

MASTERARBEIT | MASTER'S THESIS

Titel | Title

Holobiontic Earth: Artificial Intelligence meets Biological Machines
A Futures Study investigating the Impact of Current Technological Developments
in Information and Biochemical Sciences converging the Natural and Artificial
Realm

verfasst von | submitted by

Patrick Schimpl BA BSc

angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of
Master of Arts (MA)

Wien | Vienna, 2024

Studienkennzahl lt. Studienblatt |
Degree programme code as it appears on the
student record sheet:

UA 066 810

Studienrichtung lt. Studienblatt | Degree pro-
gramme as it appears on the student record
sheet:

Masterstudium Kultur- und Sozialanthropologie

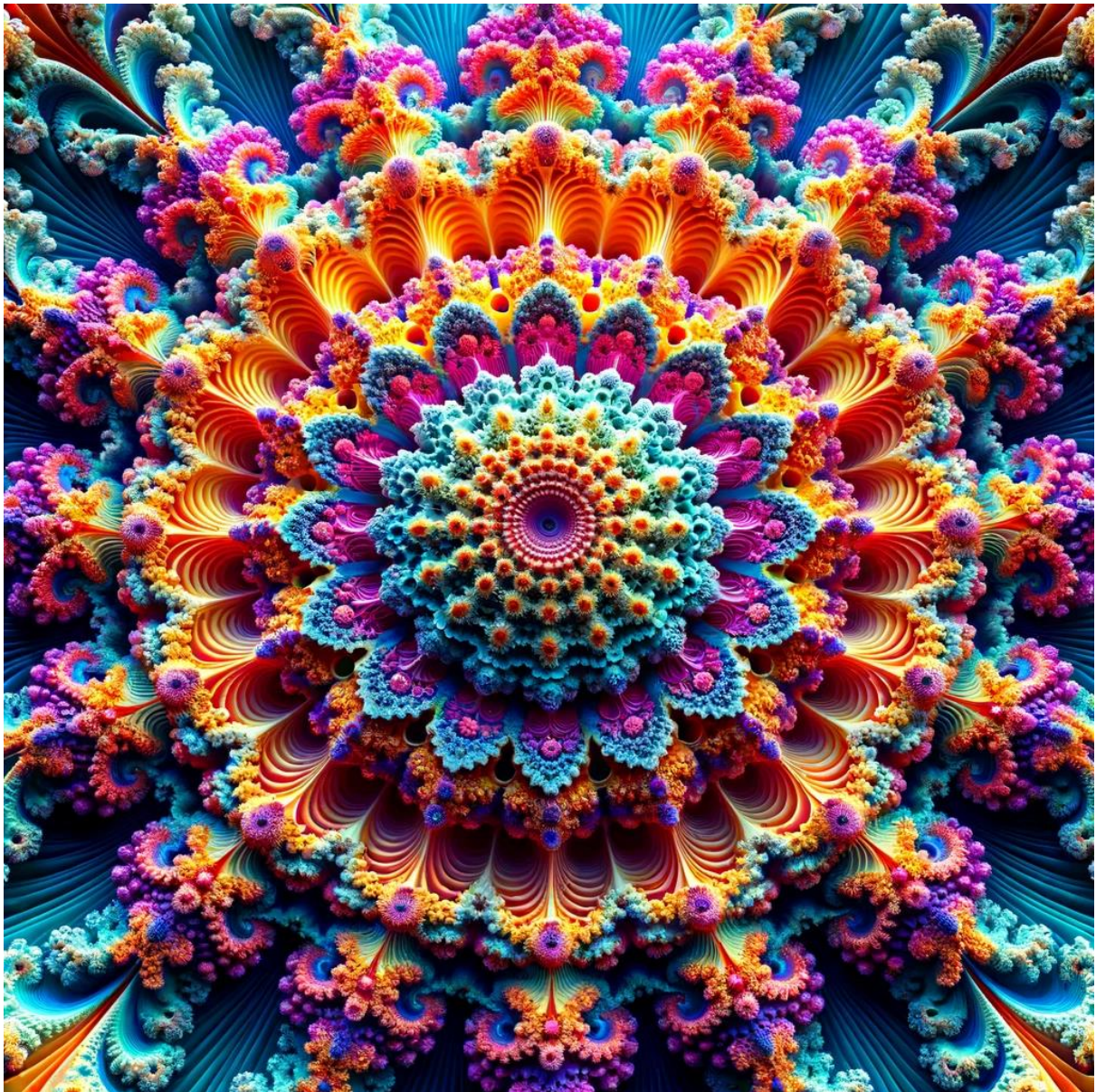
Betreut von | Supervisor:

ao. Univ.-Prof. Mag. Dr. Hermann Mückler

Holobiontic Earth

Artificial Intelligence meets Biological Machines

A Futures Study investigating the Impact of Current Technological Developments in Information and Biochemical Sciences converging the Natural and Artificial Realm



Cultural- and Socialanthropology, University of Vienna

Master's Thesis, 2023/2024

Patrick Schimpl

Acknowledgments

I want to thank my mentor Univ.-Prof. Mag. Dr. phil. Hermann Mückler for his guidance, my parents for their life-long support and love and above all my two wonderful sons, Nalin and Malu, who are my greatest sources of joy and motivation and for whom this thesis was written. May they look forward to a bright and prosperous future.

Figure 1. Artistic Visualization of Mandelbrot set and Feigenbaum set generated with DALL-E3 (above on first page)

The author

Patrick Schimpl currently works at University of Vienna's Faculty of Organic Chemistry. He conducts original research in the field of Medicinal Chemistry, developing Homotaurine derivatives with a focus on Blood Brain Barrier permeability strategies and modulation of GABAergic activity, leveraging endogenous transporter mechanisms.

He was recently awarded the **Fundamental Milestone Award** of the **2023 Exner Lectures** by the Wilhelm Exner Medal Foundation for his work 'Total Synthesis of the potent Siderophore Pyochelin *via* a novel general route to aldehydes'.

Table of Contents

Acknowledgments	2
The author.....	3
Table of Contents.....	4
0.1 Introduction	7
1.0 Theoretical framework	10
1.1 Structure	10
1.2 Methodology	11
1.2.1 Futures Studies	12
1.2.1.1 Relevance and Key dimensions of Futures Studies for Quality Assertion	13
1.2.1.2 Fundamental Modalities of Futures Studies.....	14
1.2.1.3 Validation by Argumentation	16
1.2.2 Future-oriented Technology Analysis and Backcasting	17
1.2.3 Explicit Research Methodology	18
1.2.4 Definition of the underlying structural and content-related scope	19
1.3 Intention of Present Work.....	21
1.4 Hypothesis and Research Questions	22
1.5 Related research.....	23
1.5.1 Regarding the specific Content and Narrative of Present Futures Study	23
1.5.2 Regarding Cultural and Social Anthropological Discourse	24
2.0 Argumentation	29
2.1 Underlying Dynamics and Factors of the Configuration of Advancement	30
2.1.1 Fundamental Tendencies.....	30
2.1.2 Megatrends, Human Needs and Dispositions	31
2.2 Current challenges.....	33
2.2.1 Climate Change	33
2.2.2 Petroleum industry, Plastic Pollution, Production and Energy	34
2.2.3 Biodiversity Loss and Loss of Ecospheres (Deforestation, Land Degradation)	35
2.2.4 Water Scarcity, Food Security, Population Growth, Aging Population	35
2.2.5 Global (Mental) Health Challenges, Pandemics, and Antimicrobial Resistance.....	36
2.2.6 Socio Economic Inequality, Social Injustice, Education, Political Polarization; General Ethics.....	38
2.2.7 Other challenges.....	39
2.3 current technology	40
2.3.1 Biology-Oriented Science and Technology	40
2.3.1.1 Synthetic Biology	40
2.3.1.1.1 Biotechnology, Biofactories	42
2.3.1.1.2 Microorganisms and Carbon and Nitrogen Fixation, Added Value Chemicals Production, Photovoltaics, -catalytics, and -synthesis; Artificial Enzymes	43
2.3.1.1.3 Biofilms, -structures, and -composites	45
2.3.1.2 Biocomputing.....	46
2.3.1.2.1 Organoid Intelligence	47
2.3.1.3 Bioengineering.....	48
2.3.1.3.1 Engineered Living Materials.....	48

2.3.1.3.2 Bioelectronics, -photovoltaics.....	50
2.3.1.3.2.1 Protein- and Oligonucleotide Bioelectronics	51
2.3.1.3.2.2 Microbial Nanowires	52
2.3.1.3.3 Biomolecular Nanotechnology	53
2.3.1.4 (Bio)chemistry and Analytics	55
2.3.1.4.1 Reticular chemistry	55
2.3.1.4.2 Analytics	56
2.3.1.4.2.1 Metabolomics	56
2.3.1.4.2.2 Fully Automated High-Throughput Multiomics	57
2.3.1.4.2.3 Microfluidics.....	59
2.3.1.5 Microbiology	60
2.3.1.5.1 Microbiome.....	61
2.3.1.5.2 Microbial Interactions	62
2.3.1.5.3 Therapies.....	63
2.3.1.5.4 Systems Biology and Metabolic Engineering	64
2.3.1.6 Genetic Modification	65
2.3.2 Information Science centered current developments.....	67
2.3.2.1 Computational Hardware	69
2.3.2.1.1 Conventional and unconventional Computation Hardware	69
2.3.2.1.2 Supercomputer	74
2.3.2.1.3 Bio-computer	79
2.3.2.1.3.1 Population based microbial -, cell -, and membrane computing.....	80
2.3.2.2 Computational Software	81
2.3.2.2.1 Natural Computation	81
2.3.2.2.2 Bio-inspired Computation	82
2.3.2.2.3 Artificial Intelligence	83
2.3.2.2.3.1 LLMs and MLLMs.....	85
2.3.2.2.3.2 LMMs and AGI	91
2.3.2.2.3.2 Agent Oriented Programming.....	92
2.3.2.2.3.3 Polymorphic Applications and Mission-driven programming.....	105
2.3.2.2.3.3.2 Service Providing and polymorphic agential networks.....	107
2.3.2.2.3.5 Robotics and Autonomous Devices	108
2.3.2.2.3.6 Sensors	115
2.3.2.2.3.7 Engines and Virtual Reality	116
2.3.2.2.3.8 AI and Open-source.....	127
2.3.2.2.3.9 Computing the biological realm	129
3.0 Futures Visions.....	140
3.1 Imminent Developments	141
3.1.1 Agents	144
3.1.1.1 Scientific Assistant	144
3.1.2 Metaverse, Mixed Reality, and Robotics.....	146
3.1.2 Medicine	149
3.1.3 Materials, Production	150
3.1.4 Education, Specialists, Creative industry, Service Industry	151
3.1.5 Logistics and Mobility	152
3.1.6 Challenges.....	152
3.1.7 Essential prerequisites to reach a desirable future	154
3.2 A medium-term Futures Vision	155
3.2.1 Commentary	160
3.3 A long-term Futures Vision	161
3.3.1 Commentary	161
3.3.2 Resource feasibility for presented futures vision	162
4.0 Conclusion	164

4.1 Summary	164
4.2 Outlook.....	164
5.0 Mediography	166
5.1 Table of Figures	166
5.2 Internet resources	166
5.3 Bibliography.....	170
6.0 Appendix	220
6.1 Abstracts.....	220

0.1 Introduction

*"Des ersten Lagerfeuers aufstobende Funken gebaren die Sterne,
deren nasser Glanz sich hinab zum ersten Kind formte.
Dessen erstem Lachen entstiegen die zwei Ältesten,
deren Vereinigung wiederum die Vielfalt des Seins entstammt."*¹

Current scientific insights and technological advancements are characterized by both an increasing computability and, consequently, an increasing malleability of biological life. Concurrently, there is an increasingly biological design of computational and generally artificial systems, owing to the dramatic escalation in computational power.

Two seminal events predominantly laid the inspirational foundation for this work. The first was IBM's Deep Blue defeating one of my then heroes, Grandmaster Garry Kasparov, the reigning chess world champion at the time, in 1997. The other was witnessing the magical powers of microorganisms when producing the beautiful bright purple-reddish *angkak*, red koji rice, by cultivating rice with *Monascus purpureus*, and brewing beer with another yeast, *Saccharomyces cerevisiae*.

The expert system Deep Blue made me realize that computational power saw a steady increase by virtue of progressing hardware, and instilled the belief, that consequently an increasing scope of phenomena would become computable, therefore reproducible and constructible. Witnessing microorganisms at work deepened my already existing interest in biology and was a tangible illustration for the complexity, diversity, and sophistication of biological machines and technology.

In the early 2010s it became apparent that a high-resolution understanding of biological systems was within reach and that subsequently industrial processes would increasingly

¹ The cosmogonic citation portrays the two relevant phenomena of this work, logos and bios, in paradoxical symbiosis. The first bonfire - fire, a conventional metaphor for logos is here employed with a humanist twist - incepting existence and life, bears the implication of being human-made, thus inviting the eternal questions of philosophy, especially asking for the nature of reality reminiscent of Berkeley's riddle of the falling tree, the Buddhist concept of *maya*, or the simulated universe hypothesis, toying with the anthropic principle [The text was taken from a myth the author wrote for his sons; ensuing, all quotations of the author will be listed without citation].

transition to biotechnological methods of production. This shift was anticipated to encompass all industrial sectors in the end, including construction, as well as heavy- and energy industry. The remarkable capabilities of biology were evident in phenomena such as cells directing thousands of chemical reactions simultaneously and in close proximity. In contrast, chemists usually aim to isolate their experiments to a single reaction to achieve acceptable results. Biological systems operate under mild conditions yet adapt to Earth's most extreme environments. They create materials with superior properties and exhibit highly sophisticated, complex and adaptable organizational structures, like the brain or ant colonies. It was becoming evident that biological machines and technology were the timespan of evolution ahead of current human technology.

The concept of transitioning to a biologized industry and environment was initially termed *organotechnology*² by the author. This term was intentionally chosen to distinguish it from the established term *biotechnology*, which already carried specific connotations. *Organotechnology* was envisioned to address critical global challenges like climate change and social inequality, primarily through its inherent sustainability and support for autonomy. Central to this concept is the idea of symbiosis. Despite its anthropocentric design, it aims for every participating to thrive within a framework of common prosperity.

Building upon these normative implications, the present work focuses on demonstrating that the futures visions presented are not merely idealistic projections intended to inspire desirable developments. Rather, they are depictions of probable outcomes, firmly rooted in a rigorous methodological analysis of current technological advancements. This approach elucidates underlying general tendencies of advancement, lends credence to the envisioned futures and illustrates necessary precautions for a desirable future.

The fields of information science are examined to highlight the current significant progress in computational capacity and capabilities and increasing adoption of biological traits. Developments in both by conventional von Neumann- and unconventional hardware architecture, like quantum and neuromorphic computing, are showcased through recent

² The term *organ* derives from Greek *organon*, which encompasses meanings such as "implement", "tool for making or doing", "musical instrument", and "organ of sense or the body." It literally translates to "that with which one works." This term is closely related to *ergon*, meaning "work," and *orgia*, signifying "religious performances". These terms can further be traced back to the Proto-Indo-European root **werg-*, which means "to do". The author appreciates the sum of the connotations, especially those associated with an instrument, particularly the idea of all parts working in unison to generate a harmonious tune.

academic literature. Similarly, software advancements are explored, with a focus on deep learning models and intelligence architectures. These examples not only illustrate the rapid progress currently being witnessed but also highlight a trend towards biological-like properties and characteristics.

While proofreading this work during the winter season, several predictions about imminent developments had already begun to materialize. This observation underscores the incredible velocity at which the fields discussed herein are currently evolving. Notable developments include the emergence of specialized large language model assistants, as exemplified by OpenAI's GPTs; the clear shift towards polymorphic operating systems, as announced by Microsoft and evidenced by the development of the open-source project OpenInterpreter; and the advent of widespread robot employment, a trend extrapolated from numerous recent announcements by companies like Tesla, Amazon, or Google, amongst others.

1.0 Theoretical framework

1.1 Structure

Initially, the theoretical framework will be outlined by providing a concise overview of futures studies. This will be followed by an explanation of the methodology adopted and applied within this work, as well as a discussion on the relevance of these studies to anthropological research regarding futures studies and their significance for the discipline.

The main body of the work will offer a succinct examination of general tendencies, megatrends, and human dispositions underlying, shaping, and directing current developments and influencing their trajectories. This will include a selective overview of relevant academic and technological advancements in contemporary times. These will be loosely structured around the two partially overlapping thematic areas of information science and molecular biology³, forming the argumentative backbone for the futures visions elaborated and proposed.

Futures images and visions, derived from current developments, megatrends, and human dispositions will be presented across three distinct temporal frames. This approach aims to aptly illustrate the trajectory of current advancements and shed light on emergent phenomena.

Initially, imminent developments will be discussed to underscore the direction of current advancements. The centerpiece then will focus on medium-term developments, portrayed through literary narration, offering iconic and desirable visions of the future, anchored in what is probable. The futures vision is intentionally crafted to retain current concepts of human society and the individual entity. This approach is aimed at facilitating a better connection and engagement with the reader.

³ For reasons of readability and succinctness, the term is used here as a *pars pro toto* for several inter- and related disciplines within the natural sciences, which in turn display fluid boundaries, substantial overlaps, parallels, and equivalents, encompassing key academic fields such as chemistry, biological chemistry, synthetic biology, bioinformatics, and biology, amongst others. They also include a myriad of established disciplinary branches and specializations.

Finally, a vision of a more distant future will be presented, aiming to depict fundamental tendencies and provide an iconic and inspirational image. This section aims to inspire reflections and discussions that go beyond anthropocentric views. It highlights how recent developments not only demonstrate the potential to transform current human conditions, but also suggest a general trend towards heterogenization and 'fractalization' on one side, and extensive cooperation and interconnectedness on the other. These trends challenge our existing definitions and conventional concepts of individual entities, accentuating the need for pluralistic, holobiontic systems as the appropriate framework for describing biological systems at various levels.

Commentary on necessary steps and prerequisites to achieve a desirable future, as well as the challenges that arise, will be provided subsequent to the discussion of imminent developments. Each of the three visions of the future will be accompanied by its own commentary.

1.2 Methodology

This thesis positions itself within the realm of futures studies and adopts a multi-method approach within this framework. The information presented herein was predominantly gathered through a review of relevant, recent academic literature. Additionally, a smaller portion of the data was collected through participatory observation in the scientific fields relevant to my master's studies in chemistry and biological chemistry. This was complemented by a review of current media and supplemented indirectly by numerous informal conversations with academic experts during my prolonged engagement with and interest in the subject matter.

Section 1.2.1, spanning from *1.2.1.1* to *1.2.1.3*, will provide a concise overview of the key dimensions and characteristics of futures studies. This is aimed at elucidating the relevant aspects of the methodology, acknowledging the inherently interdisciplinary nature of futures studies. While the field straddles various disciplines, the author contends that it is deeply rooted in, and pertinent to, cultural and social anthropology, marking its unique position within the social sciences.

Chapter 1.2.2 will outline the specific futures studies approaches applied in this work. *Chapter 1.2.3* will detail the explicit research methodology employed. Finally, *Chapter 1.2.4* will define the thematic and structural scope adhered to in this thesis.

1.2.1 Futures Studies

Futures studies represents a systematic and interdisciplinary examination of technological and sociocultural advancements. The field can also encompass trends in individual and environmental spheres. Due to its interdisciplinary and multifaceted nature, as well as the inherent complexities of researching the future, it is challenging to ascribe a definitive general definition to futures studies (Grunwald, 2009).

This is reflected in the discipline's diverse nomenclature and the varying definitions attributed to it (Sardar, 2010), as well as in the multitude of different subfields, concepts, methods and techniques, which are interpreted and employed variably over time and by different researchers (Slaughter, 2002). The field's opacity is further compounded by unique methods and subfields defined by individual researchers, in addition to the more widely used and accepted systems (Mittelstaedt, 2009). Moreover, many methods and techniques substantially overlap.

The inherent interdisciplinarity of futures studies can be considered threefold. Firstly, the real-world object of study necessitates a multidisciplinary approach. Secondly, the diverse backgrounds of researchers influence their concepts and perspectives within the field's dynamic framework. Thirdly, complementary or substituent fields like complexity theory or transitions research further enrich futures studies (Köhler et al., 2019, Vasileiadou and Safarzyńska, 2010, Zolfagharian et al., 2019, Baker, 2020, Boisot and McKelvey, 2006, Horton, 2012, Miller, 2010, Presti, 1996).

Efforts to establish standards and explicate methods in futures research are ongoing (Gerhold et al., 2022, p. 84).

Amara outlines the three principal objectives of futures research:

"Exploring paths of possibilities (the art of the 'possible'), examining specific paths and their likelihood (the science of the 'probable') and expressing preferences for, and implementing,

certain paths (the politics of the 'preferable') (Amara, 1991)." This resonates with Appadurai's assertion that to understand the future systematically, anthropologists should examine the interplay of imagination, anticipation, and aspiration, which shape the future as a cultural fact (Appadurai, 2013, p.p 286f).

Essentially, this can be distilled to mapping change and influencing it (Bishop and Hines, 2012, p. 194).

To emphasize the epistemic immanence of the present, the term *futures* will be used in present work to denote present imaginations of future phenomena, since futures and pasts are necessarily always parts of the present regarding conventional human perception of time and space, (Grunwald, 2018, pp. 51f). This implies, that shaping the future equates to influencing the present through the creation and reflection of futures (Grunwald, 2019, pp. 18f).

Futures visions, with their four important practical dimensions of producing interfaces, serving as communication media, providing guiding visions, and exerting normative force, along with visionary practices, can both impact and be affected by current power dynamics. Therefore, it is crucial to be cautious not to reinforce existing power structures underlying current sociotechnical arrangements (Lösch et al., 2019, pp. 69, 72-78).

1.2.1.1 Relevance and Key dimensions of Futures Studies for Quality Assertion

Forecasts and scenarios are fundamentally constructed images of the future

The evaluation of scientific relevance is always embedded within its historical context, shaped by current social and scientific values, especially the standards prevalent in the scientific community. Consequently, they are subject to variations in sentiment and perception (Weimert and Zweck, 2022, p. 101). This historical embedding gives rise to unique challenges in assessing the scientific relevance and rigor of claims in futures studies.

Academic claims in future studies are distinct due to their inherently conjectural nature, focusing on events that have not yet occurred and thus are beyond empirical verification. This is aptly encapsulated by the notion that forecasts and scenarios are fundamentally

constructed images of the future⁴. The challenge lies in evaluating the academic rigor of claims about contingent developments before their actual occurrence. To address this, four key dimensions are vital in assessing the quality of futures research: content, normativity, certainty, and time-boundness (Neuhaus, 2022, p. 5).

Content covers the subject matter of the future image and its temporal distance from the present. Futures studies research may encompass developments across various areas and timeframes (Neuhaus, 2022, p. 5).

Normativity pertains to the interests, goals, and values influencing the future image. While explicitly normative images dictate how the future should be, descriptive images aim to depict probable or possible futures. However, even descriptive claims bear implicit normativity, influenced by underlying desires, values, and norms. It's essential to differentiate normativity from judgments about desirability (Neuhaus, 2022, p. 5).

Certainty, like normativity usually a matter of degree, refers to the expectation of predicted future events occurring. Strong claims of certainty are typically associated with studies concerned with probable futures (Neuhaus, 2022, p. 5).

Time-boundness acknowledges that each image of the future is a product of its time, shaped by contemporary values and historical context. Understanding the construction of a future vision requires awareness of these influencing factors (Neuhaus, 2022, pp. 6f).

1.2.1.2 Fundamental Modalities of Futures Studies

In futures research, modality refers to whether given scenarios are intended to represent possible, probable, or desirable developments. The modalities of possibility and probability are explorative, while the modality of desirability is inherently normative. Adhering to good research practice necessitates making a clear distinction between these three modalities, particularly between explorative and normative aspects (Steinmüller, 2022, p. 13).

⁴ Edward Norton Lorenz famously demonstrated that even with the most detailed atmospheric modelling, long-term predictions remain elusive. This illustrates, that forecasts about even larger and more complex systems, regardless of their deterministic nature, exceed the limits of formal predictability (LORENZ, E. N. 1963. Deterministic nonperiodic flow. *Journal of atmospheric sciences*, 20, pp. 130f). Moreover, these predictions are fundamentally subjective transpositions, highlighting the intrinsic uncertainties in such forecasting endeavors.

Value judgments play a pivotal role in this context, as identifying desirable developments is inherently based on subjective preferences, social norms, and values. Thus, it is crucial to differentiate clearly between expectations and preferences (Steinmüller, 2022, p. 14).

This distinction is necessary to avoid conflating factual judgments of possibility and probability with value judgments of desirability, thereby protecting the work from succumbing to wishful thinking or fatalism (Steinmüller, 2022, p. 14).

The work presented here will clearly state and elaborate the underlying axioms, assumptions, and valuations shaping the exemplary vision of the future. This approach aims to provide a precise understanding of which aspects are desired and which are based on factual evidence, emphasizing potential objective arguments for the desired modalities.

Regarding the modality of possibility, it is important to clarify that mere speculation does not suffice. The envisioned future should be within the realm of concrete possibility, compatible with expected societal conditions, and traceable from current circumstances or based on reasoned disruptive events. Researchers must be careful not to overly focus on the present state, thereby reinforcing constraints, nor should they allow their imagination to drift too far from empirical reality without critical reflection (Steinmüller, 2022, p. 14).

To address the feasibility of the futures visions presented in this thesis, a broad spectrum of current research fields is explored. This includes innovations on the cusp of commercial or academic application, as well as those already in use. The thesis provides arguments to distinguish between advancements that are foreseeable and those that remain speculative.

Regarding the modality of probability, this thesis explicitly presents one probable future. This choice is based on a preliminary selection of probable futures, centering the vision on the developments in the increasing computation and manipulation of biology. This focus is argued to be the most significant influence on future developments, thereby narrowing the range of probable futures considered.

The medium-range futures vision in this thesis will contain a brief section on other probable fundamental developments. This aims to provide the reader with a contextual understanding of the relational framework of potential developments. However, specific technological advancements will not be the primary focus, due to the difficulty in accurately predicting their trajectories and emergent properties. Additionally, the aim is to describe the future vision in terms that are relatable to the reader.

The central vision presented will depict an optimistic and desirable future scenario. It will also discuss the necessary prerequisites for its realization and potential threats that could impede its manifestation.

Throughout, careful attention will be paid to rendering modalities as transparent as possible and avoiding implicit value judgments (Steinmüller, 2022, pp. 16f).

1.2.1.3 Validation by Argumentation

As previously mentioned, the principle of falsifiability, a cornerstone of scientific hypotheses and theories as proposed by Karl Popper, is inherently unattainable in futures studies due to the lack of empirical verification of knowledge about the future (Popper, 1963).

Consequently, other methods of validation are necessary. This thesis aligns with Armin Grunwald's perspective, which posits that "Knowledge about the future arises through a process that incorporates a broad series of elements, including disciplinary knowledge, causal relationships, model assumptions, value judgments, assessments of relevance and irrelevance, and, in the case of great uncertainty, more or less plausible, partially implicit assumptions. These elements are combined through specific procedures and according to specific rules to form statements about the future. [...] In this way, scientific knowledge about the future emerges from individual components ("ingredients") that are put together ("composed") in a specific way and in a controlled process" (Grunwald, 2022, pp. 22f).

This approach renders the knowledge of the future and its presentations falsifiable in the present through criteria of argumentative validation. It underscores that futures studies, rooted in the present, must rely on justifying claims based on current assessments and the overall soundness of the argumentation, rather than the eventual materialization of the proposed theories (Knapp, 1978).

Following Armin Grunwald's guidelines, this work will adhere to principles of consistency, coherence, and transparency (Grunwald, 2022, pp. 24-26).

Consistency is a fundamental requirement in scientific examination, necessitating the avoidance of self-contradictory information. This thesis presents a consistent vision of the future by synthesizing heterogeneous fields and trends into a cohesive narrative. This amalgamation is supported by several megatrends, as identified by Kreibich *et al.* (Kreibich et

al., 2011), which include overlapping trends towards automation, interconnectedness, autonomous and intelligent agents and intelligence architectures, and an increasing mastery over biological life (Grunwald, 2022, pp. 24f).

Beyond mere consistency, the integrity of internal coherence is another epistemological demand. This work will focus on explicitly highlighting the logical interconnections among individual elements that form the empirical basis for the future vision. Robust, up-to-date knowledge from the most recent academic literature and media about developments and advances in the informational- and biochemical- centered sciences provides a solid foundation for extrapolating future models (Grunwald, 2022, pp. 25f).

External coherence and adequacy are ensured by distinctly categorizing world phenomena and the technological landscape into three domains: matter, information, and energy. This thesis focuses on developments in the bio- and infosphere while deliberately setting aside energy-focused technological advances (Grunwald, 2022, pp. 25f).

Epistemological, normative, and procedural transparency are paramount. The knowledge base, extrapolations, and assumptions will be rigorously examined. Normative premises, values, and interests will be clearly stated to ensure verifiability. Moreover, the approach to argumentation and justification will be communicated transparently, for reasons of clarity and understanding (Grunwald, 2022, p. 26).

In all aspects, the goal is to maintain the utmost transparency with the given assumptions and aim for precise definitions, relationships, and proposed implications in the argumentation.

1.2.2 Future-oriented Technology Analysis and Backcasting

This work employs a multi-modal futures studies approach with a focus on foresight, primarily through future-oriented technology analysis (FTA). FTA is dedicated to analyzing future technology and its consequences. An informed understanding of current trends and imminent advancements lays the foundation for assessing future developments. This aligns with Halicka's definition of FTA as a process aimed at predicting the future of technology through evaluation and detailed analysis (scanning) of its current state and identifying strategic factors for its future development (Halicka, 2016). This approach is structured around megatrends

and world concepts of the sustainable society and the science society respectively (Kreibich et al., 2011).

Within this framework, two specific areas will be of special relevance: technology forecasting and technology assessment. Technology forecasting is devoted to illustrating future characteristics of technology through extrapolation from historical and current developments. Meanwhile, technology assessment focuses on studying and evaluating new technologies, considering their potential impacts and implications (Zweck, 2009, pp. 199-202). Additionally, an element of backcasting is incorporated, where necessary factors for the emergence of a desirable future are identified and discussed. This approach involves envisioning a preferred future and working backward to determine the steps required to achieve that future state.

1.2.3 Explicit Research Methodology

The methodology of this thesis will be articulated following the research onion model, as outlined by Melnikovas and Zolfagharian (Melnikovas, 2018, Zolfagharian et al., 2019). This model provides a structured approach to detailing the research methodology.

The underlying research philosophy of this work aligns with the paradigms of positivism and pragmatism. It focuses on positivist events, observations, and perceived tendencies, which form the basis for the futures images. However, subjectivist ontological assumptions also demonstrate implicit relevance. The importance of discourse and social constructions, among other interpretive factors, is not only integrated into the described phenomena but is also inherent in the author's process. This introduces a phenomenologically-based element to the research.

The approach to theory development in this work is predominantly deductive, as hypotheses are proposed and tested. However, these hypotheses are generated from the author's prior observations and experiences. The presented futures visions serve as plausible explanations and specific conclusions, lending an abductive quality to the research.

The research strategy primarily involves archival research, gathering, analyzing, and synthesizing relevant and current academic literature through purposive non-probability sampling methods. This is complemented by many years of informal interviews, observation, and participation in the field (Popp and Schüll, 2009). While the primary focus of this research

lies in the natural sciences, the methodology employed nonetheless is qualitative. The author plays a crucial role, leveraging personal experiences, knowledge, and insights to generate logic and structure. This approach is predominantly descriptive, incorporating explorative elements and underlying normative aspects. One reason for this is the perception that the discussed developments are driven by common problem recognitions and the subsequent creation of corresponding solutions. Additionally, the illustrations presented here are shaped by the author's desire to provide an exemplary vision of the future, grounded in principles of sustainability, autonomy, and equality.

T Regarding the time horizon for information gathering, this study adopts a cross-sectional approach. It is less focused on deriving conclusions from historical developments, providing only essential quantitative context and relevant theories, such as Moore's law. Instead, it deduces anticipated developmental landscapes by examining the scope, focus, and success of current research and, to a lesser extent, industrial realizations. The timeframes for the future scenarios presented are short-term, highlighting imminent developments; long-term, as defined by Kreibich et al. to be 20-50 years - though strict adherence to this timeframe is not critical in our context, as the goal is to illustrate tendencies and possibilities - and an even longer timeframe, which is unconventional for futures studies (Kreibich et al., 2011).

1.2.4 Definition of the underlying structural and content-related scope

Information is the fractal interface mediating between energy and matter⁵

A brief description of the underlying structural classification will be given to better illustrate the scope and boundaries of presented topics without delving too deep into the mechanics and definitions of the related discourses (Floridi, 2008, Richmond, 2020). The concept of above quote sets the stage for this work's foundational tripartition of perceivable phenomena. This delineation establishes the broader scope of fields and developments considered in constructing future scenarios.

The term 'infosphere', as used in this study, aligns with Floridi's definition: a comprehensive system encompassing services, documents, and all entities that process data, information, and

⁵casual representation

knowledge (Floridi, 2002), including informationally embodied organisms (Floridi, 2014). This definition extends to all information-processing mechanisms (Van der Veer Martens, 2015). The concept of biosphere is used here as a *pars pro toto* for the physiosphere. It loosely includes Boulden's other five physical spheres (Van der Veer Martens, 2015). While the biosphere's informational aspects, such as social organization, genetic makeup, or protein conformations, can be conceptualized within the infosphere, this work primarily focuses on the biosphere's 'raw' physical nature.

In the fundamental triad of matter, information, and energy, this study will not explore emergent developments in energy. It assumes continuity in the known and established forms of energy harvesting and conversion. The future scenarios developed herein extrapolate current energy needs, presuming they can be met sustainably utilizing known technologies. Just as this work does not delve into the emergence of energy conversion as it is anticipated to fundamentally transgress the current nature and focal point of human perception akin examinations of the trans-dimensional, so reflections on artificial general superintelligence with potential incomprehensible agendas are omitted. Such explorations, which might involve radically different understandings of chemistry or complexity in intelligence, are more suited to metaphysical discussions, including considerations of superpositions and coexisting reality layers.

Definitions of technology-specific terminology within this research will primarily rely on extensively referenced literature, serving as a basis for explanation. Exceptions to this approach will be made only when it is deemed absolutely necessary or particularly beneficial to the understanding of the content.

The interdisciplinary selection of fields and topics in the theoretical literature has been carefully and purposefully curated. This selection is driven by inherent thematic necessity, greatly influenced by my hands-on practical experience and long-standing theoretical engagement with the subject. My practical experience stems primarily from my pursuits in obtaining Master's degrees in Chemistry and Biological Chemistry, with a focus on bioinformatics. The curricular activities undertaken during these studies were strategically chosen for their direct relevance to the research presented in this thesis.

1.3 Intention of Present Work

The current work delves into advancements in information science, with a focus on computing and computation, and natural sciences, particularly biochemistry, including molecular and synthetic biology, and bioengineering. It aims to provide a concise yet comprehensive overview of current standings and trends. This is achieved by presenting a carefully selected array of the latest developments and possible future trajectories. The intention is to foster a deep understanding and to inspire creative thought about future possibilities.

In addition, this work explores the societal impact of emerging technologies. It seeks to approximate the influence of these technologies by presenting visions of the future. These visions are designed not just to inspire but also to facilitate the identification of relevant research areas and questions, and to expedite the development of sensible strategies towards a desirable future. This includes reflecting on important developments and concepts, and encouraging proactive engagement.

Futures images are presented as guiding beacons, portraying the architecture of a desirable future that addresses current challenges through existing and anticipated technological advancements (Grunwald, 2023, p. 299). Care is taken to ensure that these depictions are not only inspiring but also grounded in probability, based on rigorous reasoning and solid extrapolations of current developments, megatrends, and underlying tendencies.

The selection of current developments aims to provide an overview of the landscape of relevant fields. The futures images intend to convey an understanding of the configuration, patterns, and tendencies of advancements, their impacts, and the resulting architecture of social, individual, and environmental assembly and organization. This is particularly aimed at enabling the reader to identify pertinent exploratory fields of research, providing orientation, and preparing anthropologists for emerging phenomena (Grunwald, 2023, pp. 316f).

While a brief reflection on potential dangers and necessary prerequisites is included for thoroughness, the work consciously avoids dystopian visions. The focus is predominantly on presenting probable and desirable futures visions derived from resolving current challenges and deducing from trajectories of current developments and underlying megatrends. The objective is to direct the reader's view and engagement towards constructive and fruitful discourse and actions related to shaping the future.

1.4 Hypothesis and Research Questions

The current advancements in information and natural sciences, particularly at the intersection of computing, computation, and molecular and synthetic biochemistry, hold the promise of enabling humanity to compute, design, and summon artificial intelligence and artificial life. These creations are anticipated to become increasingly indistinguishable from biological intelligence and life, in parallel with the growth in computational power and technological sophistication.

Moreover, the technological progress being made heralds the potential to catalyze a prosperous future, potentially even inaugurate a *technospiritual golden age*. This era is envisioned to be characterized by sustainability, complexity, adaptability, and efficiency, driven by human efforts to address global challenges and human nature's fundamental needs and dispositions. These include necessities such as food, clothing, housing, and social contacts, as well as desires for mobility, meaningful experiences, playfulness, and an inherent drive for exploration and expansion. Current megatrends like automation, interconnectedness (including virtual reality), and the emergence of increasingly capable and versatile technologies and entities also play a significant role. Thus, the ensuing research questions form the core of this work's research interest.

What are the relevant current scientific and technological advancements in the fields of information science and molecular biology?

How can these developments provide solutions to current global problems and which prerequisites have to be fulfilled?

How will these developments impact and shape global society and which underlying tendencies can be anticipated?

1.5 Related research

1.5.1 Regarding the specific Content and Narrative of Present Futures Study

Since the first conceptualization of present work a bit over 11 years ago, much has happened in the respective fields, which rather brought them from the periphery to the forefront of scientific and technological discourse.

The past 15 years have seen a resurgence of techno-visionary futures, particularly with the advent of new and emerging sciences and technologies. These include areas like nanotechnology, converging technologies, synthetic biology, human enhancement, autonomous technologies, various omics technologies, climate engineering, robotics, artificial intelligence, and neuro-technologies (Grunwald, 2023, p. 309). Additionally, there has been considerable discussion on the transformative potential of biology-centered technologies (McKinsey - Bio-Revolution, 2023) as well as those centered around artificial intelligence (Gruetzemacher and Whittlestone, 2022). While there is a rich tradition and extensive body of work concerning futures visions in artificial intelligence (Kurzweil, 2000), comprehensive futures visions focused on advancements in biochemical sciences remain notably scarce. This is the case even though there is a longstanding appreciation of biology as a superior technology (Rinaldi, 2007), and an increasing orientation of industry towards biological methods (Voigt, 2020).

Recent efforts have been made by numerous researchers to offer a panoramic view of the emergent technological landscape. However, these efforts have not provided a synthetic visionary image, nor have they explicitly connected the impact of new computing technologies with an emerging mastery over biology. While they do provide adequate clustering and a good understanding of the impact of the topics discussed, they fall short of offering a comprehensive and biology-centered vision of an artificially designed world (Betz et al., 2023). The discourse surrounding emergent technologies is as varied as the technologies themselves, with reflections on their positive transformative potential being as numerous as those on their potential threats. Foresight, a method widely used by academic, private, and public institutions, plays a crucial role in generating novel insights and gauging these dangers (Nelson et al., 2021).

In their work, Nolin *et al.* explore ten influential concepts of technology-rich futures that have emerged since the beginning of the century. These include System of Systems, Ubiquitous Computing, Pervasive Computing, Semantic Web, Ubiquitous Web, Internet of Things, Ambient Intelligence, Smart Environment(s), Web of Things, and Real World Internet (Nolin et al., 2019, pp. 236-241). Each of these concepts has been integrated into the present work's futures studies to varying degrees, reflecting the breadth and depth of technological advancements and their potential impact on society.

1.5.2 Regarding Cultural and Social Anthropological Discourse

This section provides a selective overview of anthropological discourses related to futures studies and the futures visions presented in this work. Anthropology offers a rich array of perspectives on the concept of the future, each exploring it in distinct ways.

Anticipatory Anthropology, for instance, focuses on empowering people to actively shape their future. This discipline seeks to understand and learn from the possible worlds of future generations (Strzelecka, 2013, p. 267).

Participatory Futures represents a notable intersection between futures studies and anthropology, highlighting their shared use of interdisciplinary approaches and multidisciplinary knowledge. Both fields are, in various ways, anthropocentric. Stefanie Ollenburg, for example, proposes a futures-design-process model for participatory futures. This model integrates communication processes from human-centered design with concepts from participatory normative futures studies. The goal is to generate knowledge and action aimed at forging a more sustainable future (Ollenburg, 2019, pp. 55f).

Digital Anthropology and Material Culture research also play a significant role in the discourse on futures. This research is particularly concerned with representations, as the digital realm fundamentally operates as a representational system (Dourish, 2016, p. 31). It explores the relationships between local and global scales of futures visions, aiming to steer the digital-material world towards the development of affordable technology, accessible in the broadest sense (Lanzeni, 2016, p. 45).

Matthew Gladden employs a qualitative phenomenological and posthumanist anthropological approach to analyze Japan's Society 5.0 paradigm. He delves into the interactions between a diverse array of human and non-human entities. Gladden suggests that new types of technologically posthumanized beings have parallels in earlier, non-technologically posthumanized societies. This comparison offers robust insights into Society 5.0, including the behaviors and interactions of its participants. He argues that intelligent technology in post-digital organizations will predominantly assume managerial, supervisory, and advisory roles (Gladden, 2019c, Gladden et al., 2022).

Peter Pels echoes similar sentiments, when he states "(...) multitemporality underscores the need to recuperate the insights of classical anthropology into practices of classification, kinship, religion, and gift giving, not only to restore to them futures that were long denied but also to help us to cope with a world where modern temporal classifications seem to be as salient as they are under siege" (Pels, 2015, pp. 789f).

Arjun Appadurai highlights that the future is neither a neutral nor a purely technical space, especially for those living in the realm of the possible rather than the probable. He views the future as a trauma inflicted on the present and urges those designing for the future to recognize it as a cultural fact. This recognition is essential to address present inequalities and to design a democratic and equal future (Appadurai, 2013, pp. 298f).

Space colonization offers a unique context for anthropological research. Researchers like Eller use analogies of terrestrial migration and colonialism to explore potential new identities, independence movements, and how space settlement will reshape the definition of humanity and, consequently, the practice of anthropology (Eller, 2022).

At the 2014 Conference of The European Association of Social Anthropologists, the Future Anthropologies Manifesto was established (Pink and Salazar, 2020, p. 2). This manifesto serves as a pivotal reference for the study of future societies and the evolving role of anthropology:

1 We are critical ethnographers engaged with confronting and intervening in the challenges of contested and controversial futures.

2 We are stubbornly transdisciplinary and transnational: we collaborate, hybridize and compromise. We break boundaries and network without fear of incapacity or contamination.

3 We de-centre the human, embracing larger ecologies and technological entanglements.

4 We probe, interrogate and play with futures that are plural, non-linear, cyclical, implausible and always unravelling.

5 Anthropology of the future is accretive. It builds on traditions, reflects on pasts.

6 We are bold enough to engage with complexity and stay with differences and uncertainties. We traverse the macro, mundane and minute and embrace the chaotic, multisensory, performative and material dimensions of social life in the Anthropocene.

7 We understand and are understood. We foster a politics of listening attuned to a diversity of voices and we tell stories that are imaginative, illustrative and informative. We create and design a variety of materials and processes that are provocative, disruptive, adaptable and reflexive.

8 We get our hands dirty. We are ethical, political and interventionist, and take responsibility for interventions.

9 We may be epistemologically filthy, improvisational and undisciplined. We may struggle, and fail and transform.

10 Anthropology of the future supports current and future members to be part of a strong and recognizable community of practice.

The Future Anthropologies Manifesto encapsulates several key positions frequently encountered in anthropological futures research. It asserts that anthropologists engaging in futures studies must maintain a critical stance, recognizing that futures images are often shaped by cultural biases and are rooted in both the present and the past. Such engagement necessitates an awareness of ethical dimensions and a proactive approach to shedding light on them. Constructing and reflecting upon futures images involves various dimensions and angles, acknowledging the need for transdisciplinarity. This approach is especially pertinent given the inherent complexity, plurality, and uncertainty in futures studies, often leading to engagement filled with doubts and questioning.

Sarah Pink's research within anthropology actively explores energy futures. She collaborates with others to investigate relevant images within this context, everyday futures, spaces, and mobilities, as well as the energy politics of digitalization (Abram et al., 2022).

Olivia Macovei offers an anthropological perspective on synthetic biology. She delves into its mythological dimension, portraying humans in a demiurgic role and synthetic biology as a spiritual marker of the Anthropocene. Her work covers regulatory issues, the importance of open-source approaches, the transformation of nature into an artifact, and the ethical dimensions of these changes. She also discusses the distinct trends of techno-optimism and techno-pessimism within the anthropology of synthetic biology (Macovei, 2022).

Nelson and Selin propose a systematic framework for innovation processes, particularly in human genome editing. Their framework involves broad expert and public consideration, formulated through seven questions to discern plausible futures of this technology (Nelson and Selin, 2023).

Sarah Pink, in her work on Digital Futures Anthropology, emphasizes that technology design and realization are influenced by both global imaginaries and local or personal visions of the future. She advocates for applying anthropological understandings to grasp the relationship between the specificity and diversity of everyday sites where futures are imagined. This approach aims to shift and shape these narratives towards ethical and responsible human futures (Geismar and Knox, 2021, pp. 321f).

Matthew Gladden applies Ingarden's conceptual framework to view computer games as organic works of art, contributing significantly to the field (Gladden, 2020).

Jared Farmer explores the concept of future fossils of the Anthropocene. He metaphorically uses the imprint of a mobile phone to symbolize the anthropogenic effects, representing elusive hyperobjects like global warming and biodiversity loss (Mitman et al., 2018, p. 198).

On a sidenote, this concept resonates with the Silurian Hypothesis, which suggests the potential for a prior industrialized civilization on Earth, evidenced by large-scale anoxic events (Schmidt and Frank, 2019).

Generative artificial intelligence raises questions about originality and copyright issues (Fenwick and Jurcys, 2023). This is one of many emerging topics in the field of human-computer interactions (Gladden, 2019b). Gladden notes that these interactions are increasingly occurring within cyber-physical-social-intentional systems, involving workforces operating in larger cyber-physical entities such as spaces, organizations, ecosystems, and societies (Gladden, 2019a).

Paul Rabinow's concept of biosociality refers to the increasing tendency for biological categories and markers, like genes, to form the basis of social organization (Rabinow, 1997) p.99f. Catherine Waldby introduces the concept of biovalue, arguing that it is primarily generated through the manipulation of biological fragments' time scales and trajectories in biotechnological strategies. She suggests that technologies like stem cell research reveal the human condition as a status emerging from a complex network of technobiological production, rather than a mere natural, biological category (Waldby, 2002, pp. 314, 319). A crucial question in this context relates to biological reproduction (Waldby and Cooper, 2008).

Paul Rabinow and Gaymon Bennett delve into the coevolution of ethical, social, and cultural dimensions with technological advancements in synthetic biology. They advocate for a design approach that centers biological systems around the human systems they will interact with, emphasizing the interconnectedness of technology and society (Rabinow and Bennett, 2012, pp. 1-9).

Matthew Gladden explores the design of neuroprosthetic supersystems, organizations comprising neuroprosthetically augmented human members. He focuses on ensuring these systems respect human dignity and empower creativity (Gladden, 2017b, pp. 15-23). Additionally, Gladden highlights the challenges posed by neuroprostheses in terms of information security (Gladden, 2017a).

Donna Haraway, from a social-feminist perspective, calls for a reevaluation of the concept of nature in the context of modern biotechnology. She discusses the human body and narratives imposed on it, viewing the invention and reinvention of nature as arenas for hope, oppression, and contestation (Haraway, 2013b, pp. 1-4, 230). She advocates for the cyborg imagery as an icon symbolizing the variability of biological entities and the responsibility entailed in the social relations of science and technology (Haraway, 2013a, pp. 67f). The cyborg metaphor has also been applied to organizations, described as entities continually creating, transforming, and dissolving internal units (Modliński and Gladden, 2022, pp. 387f).

Art and popular culture offer a rich tapestry of interpretations and visions of the future, significantly contributing to the public discourse on technological advancements and future possibilities. Films like 'Tron,' 'The Matrix,' and 'Avatar' have played pivotal roles in shaping societal perspectives on technology and the future. 'Tron,' particularly the original version, was one of the first movies to immerse viewers in a digitized universe, influencing early concepts of virtual reality and digital worlds. 'The Matrix' represents a nexus of artificial intelligence within a dystopian vision, exploring themes of reality, control, and resistance. 'Avatar' can be interpreted as a utopian vision of the biology-centered nexus, highlighting themes of ecological harmony and the intersection of technology with natural systems. 'The Simpsons' deserves a special mention for its decades-long depiction of a multitude of intriguing future visions. The show has offered a satirical and often surprisingly accurate portrayal of societal trends and potential technological developments.

'Rick and Morty' stands out for inherently thematizing futures and technological advancements. The show delves into complex scientific and philosophical themes, often with a humorous twist. Notably and relevant to our context, it features the character Unity, an entity, that colonizes inhabited planets, taking control and unifying all inhabitants, an interpretation of the holobiontic topos. This depiction serves as a compelling narrative tool for discussing themes of autonomy, identity, and the impact of technology on society.

2.0 Argumentation

"It is not a bad definition of man to describe him as a tool-making animal. His earliest contrivances to support uncivilized life were tools of the simplest and rudest construction. His latest achievements in the substitution of machinery, not merely for the skill of the human hand, but for the relief of the human intellect, are founded on the use of tools of a still higher order." Charles Babbage (Purbrick, 1993)

The argumentation for the futures visions presented in *Chapter 3*, will consist of highlighting the underlying dynamics directing innovative developments in *Chapter 2.1*. This includes a brief illustration of key fundamental tendencies, such as the law of increasing functional information, and currently relevant megatrends. These are portrayed against the backdrop of fundamental human needs.

Subsequently, *Chapter 2.2* will present current global challenges. Addressing these perceived fundamental problems is recognized as a primary driver of progress and a strong determinant of the specific distribution of innovative efforts. Clarifying current challenges is also necessary to sharpen our understanding of the elements that constitute a desirable future vision.

The majority of the argumentation will be in *Chapter 2.3*. This chapter aims to portray a selection of current technological developments. It seeks to convey an understanding of the landscape of relevant fields and disciplines, as well as the velocity and intensity with which certain fields are progressing. Specifically, it will focus on areas like artificial intelligence, processing hardware, and robotics in *Chapter 2.3.1*. Furthermore, it will explore how these advancements accelerate progress in fields such as synthetic biology and biochemistry, as discussed in *Chapter 2.3.2*.

The fields are selected in such a manner as to provide the most concise and relevant information necessary for an informed understanding of the tendencies and developments shaping the future. This selection process aims to ensure that the discussion is both comprehensive and focused, highlighting the most influential factors in current technological progress and their potential impact on future advancements.

2.1 Underlying Dynamics and Factors of the Configuration of Advancement

2.1.1 Fundamental Tendencies

In this chapter, selected concepts of fundamental underlying tendencies are presented to provide a theoretical toolset useful for approximating future visions. The basis for this discussion is the observation that the universe constantly generates time-dependent, ordered structures and patterned systems. This observation supports the fundamental temporally asymmetric law of increasing complexity through the accumulation of functional information in evolving systems. The primary sources of selection for diverse components are identified as static persistence, dynamic persistence, and novelty generation (Wong et al., 2023)⁶.

This fundamental law bears a conceptual similarity to the thermodynamic entropy as defined by Ludwig Boltzmann and Josiah Willard Gibbs. Central to the second law of thermodynamics, this principle states that the entropy of a closed system – defined as the measure of microstate freedom over which energy is dispersed – cannot diminish in a closed system. Information entropy, quantifying the uncertainty associated with a set of possible outcomes and serving as an index of the information contained in a dataset, combines with physical entropy to form the total entropy. This combination creates additional information microstates superimposed onto the existing physical microstates, a concept established by Claude Shannon and Ralph Hartley. Vopson proposed that the information entropy of systems containing information must remain constant or decrease over time, contrasting with physical entropy. This has profound implications for evolutionary biology, as it suggests mutations occur in a way that

⁶ Persistence as fundamental momentum of the law of increasing complexity sees its analogy regarding thermodynamic entropy in the barriers brought by fundamental laws like Coulomb repulsion and the slow rate of weak-interaction events amongst others, which leads to pockets of long-lived disequilibria in the universe.

minimizes information entropy (Vopson, 2023). Furthermore, described the biosphere as retarding the global increase in entropy (Ayres, 1997, p. 116).

The complexity of a system, defined by Sabirov and Shepelevich as a combination of information entropy and semantic information (Sabirov and Shepelevich, 2021), reaches its lowest point both when entropy is at its minimum, such as at the universe's Big Bang, and when entropy is at its maximum, as the system becomes simpler to describe. This complexity behaves akin to the time derivative of entropy (Modis, 2022).

Within the scope of this work, emergent properties will be treated as manifestations of increasing complexity. Specifically, consciousness and intelligence are defined as emergent phenomena arising from complex, multilayered interactions among physical, neuronal, and environmental agents (Sharma et al., 2023, Standish, 2001, Arsiwalla et al., 2023, Baker, 2020, Larson et al., 1988, Whiten, 2000).

An interesting sidenote is the characterization of complexity itself as an emergent property, particularly in relation to the Boltzmann-Gibbs entropy concept (Standish, 2001). This perspective underscores the interconnected nature of emergent phenomena and foundational physical principles.

Extrapolating from the advent of the first biological autogenetic information systems, represented by reproducing nucleic acids (Wills, 2023), to the evolution of single-celled and multicellular organisms with increasingly complex processing units, a discernible trend towards the emergence of a global processing unit becomes apparent. This trend is accompanied by a general increase in the diversity of functional information. However, predictions beyond this scope venture into the realm of speculation, as they exceed the bounds of reasonably probable estimations.

2.1.2 Megatrends, Human Needs and Dispositions

This section aims to succinctly present the underlying drivers of current and general developments, as well as human aspirations, to contextualize current technological progress and offer insights into probable patterns and structures of advancement.

Megatrends represent complex dynamics of change, characterized by four key attributes: duration, ubiquity, globality, and complexity. They typically span at least several centuries,

impacting all societal levels globally, albeit in varying degrees. These trends are complex and interrelated, creating dynamic tensions and mutual interdependencies (Megatrends, 2023).

Current megatrends include globalization, mobility, connectivity, global health, sustainability (alternatively framed as the threat of climate change), urbanization, digitalization, automation, an aging population, gender shifts, and the rise of emerging markets, among others (Haluza and Jungwirth, 2023, Megatrends, 2023).

Globalization and connectivity, key trends in this study, are subsumed under the broader concept of interconnectedness. This illustrates the increasing connectedness of societies worldwide, including the integration of humans and objects into shared spaces, both physical and virtual. The trend towards automation stands out as a fundamental driver and characteristic of technological innovation, increasingly realized across a wide array of fields and phenomena.

The challenges posed by aging populations and urbanization serve as attractors for innovation, reflecting societal needs and priorities. Mobility and emerging markets are intrinsically linked to sustainability, underlining the urgency of meeting growing energy demands through sustainable means. The ongoing shift in gender dynamics is poised to significantly influence the design and deployment of artificial intelligence and robotics, especially in the context of rising employment and interaction.

Global health has emerged as a potent driver for advancements, with extensive research focused on health-related improvements, including the use of artificial intelligence for mental health (Graham et al., 2019). The need for continuous discourse and reflection is paramount to ensure just and desirable development in these areas (Gupta et al., 2023, Gabriel, 2020, Kim et al., 2021b, Kaack et al., 2022). Digitalization, particularly grassroots movements enabled by it, offers a platform for wider engagement and amplifies diverse voices (Artero et al., 2020).

Furthermore, basic human needs such as food, clothing, housing, social contact, and meaningful experiences, alongside the advent of increasingly capable technologies, serve as consistent drivers of innovation, shaping the direction and structure of advancement.

It's also important to note that human ethological traits like curiosity and playfulness (Kobayashi et al., 2019), encompassing exploration and sensory expansion (Hamou, 2022,

Svechtarova et al., 2016, NASA Science Instruments, 2023), as well as problem-solving orientation (Wang and Chiew, 2010), are integral to technological innovation. Acknowledging humans as innate explorers and problem-solvers is essential (Rahman, 2019).

Consequently, intelligence architectures are being designed to exhibit these characteristics, reflecting and leveraging these fundamental human qualities. (Kim et al., 2020, Gelernter and Rochester, 1958).

2.2 Current challenges

The elucidation of current global challenges holds a twofold importance in the field of futures studies. Firstly, when engaging in normative approaches to develop visions of desirable futures, it is imperative to clarify existing values and preferences. These must be reflected upon in the context of current conditions to make informed decisions about whether advancements should aim to change the status quo or maintain it. This process of aligning proclaimed values with current circumstances also serves to evaluate the consistency of these values and preferences, especially when juxtaposed with perceived negatives.

Secondly, applicable to all futures studies, is the understanding that conditions, phenomena, and circumstances viewed as troublesome—whether by directly obstructing the fulfillment of desires or by creating conditions that make fulfillment more challenging—will inevitably lead to efforts aimed at resolving them within a prioritized framework. Given that identifying and solving problems is a fundamental human trait, a detailed examination of perceived current global issues will enhance the accuracy of assessing probable future scenarios.

Accordingly, a list of current problems, drawn from the United Nations' compilation of global issues, will be presented in a subsequent section (UN Global Issues, 2023).

2.2.1 Climate Change

Global warming, primarily driven by human-induced emissions of greenhouse gases, is impacting weather and climate extremes globally. This phenomenon leads to a range of adverse effects, including compromised water and food security, economic and societal

disruptions, and losses and damages to nature and human populations. Vulnerable communities, often those contributing least to current climate change, are disproportionately affected (Aldunce, 2023).

Greenhouse gas emissions have continued to rise over the past decade, fueled by unsustainable energy consumption, land use changes, lifestyle and consumption patterns, as well as production and transport practices within and between countries (Aldunce, 2023).

While global warming may not pose a direct threat to life on Earth or the survival of humanity, it significantly challenges the prospect of a sustainable and prosperous future for humanity. Rapid climate changes are leading to abrupt shifts in the distribution of hospitable regions, necessitating urgent action to mitigate these effects (Radunsky and Cadman, 2020). The tendency for human settlements in coastal areas and along waterways exacerbates the risks, as rising sea levels, increasing desertification, and changing arid regions' distribution patterns could lead to heightened human migration, unrest, and potential conflicts over resource redistribution.

2.2.2 Petroleum industry, Plastic Pollution, Production and Energy

Our dependence on oil not only contributes to climate change but also poses downstream problems, as petroleum products are fundamental to current industrial processes. The increasing demand for crude oil is set to collide with a predicted decline in overall crude oil production starting from the 2030s (Rech et al., 2021). This impending shortage is likely to cause significant conflicts and turmoil, given the widespread reliance on crude oil not only for energy production but also as a raw material in various industries. The chemical industry, for instance, utilizes refined crude oil products extensively, impacting sectors like pharmaceuticals and materials, among many others.

Furthermore, current production methods reliant on the petroleum industry led to ecological challenges such as marine pollution, pervasive microplastics, and infertility issues linked to plastic pollution (Angelo and Meccariello, 2021). The absence of a natural ecological cycle for the numerous artificially produced carbon derivatives and associated chemicals results in not only the accumulation of plastics but also toxic effects through the biomimetic actions of many compounds used in design, production, and the final products.

2.2.3 Biodiversity Loss and Loss of Ecospheres (Deforestation, Land Degradation)

In addition to the aforementioned chemical pollution and climate change, which contribute to biodiversity loss and the degradation of ecospheres, agriculture-driven deforestation is a primary cause (Ellwanger et al., 2020, Pendrill et al., 2022, Veldkamp et al., 2020). Addressing deforestation could yield significant global savings, estimated at 3.7 trillion US dollars, just by avoiding greenhouse gas emissions, as calculated in 2010 (TEEB, 2010). Furthermore, it can be argued that the biogenetic diversity of Earth is its most valuable resource, offering untapped potential for energy production, computing, and advanced materials. This perspective will be elaborated upon later. There is a broad consensus on the link between biodiversity and ecosystem services, underscoring the importance of preserving biodiversity for sustainable development (Cardinale et al., 2012).

Estimates suggest that approximately 30%, with an uncertainty range of 16-50%, of species have been threatened or driven to extinction since the 16th century. This loss in global biodiversity is believed to diminish ecosystem functioning and nature's contributions to humanity (Isbell et al., 2023). Notably, larger-bodied species with slower life histories are more vulnerable to extinction, while smaller-bodied species, which are more likely to transmit zoonotic pathogens, tend to increase in abundance. This shift poses direct negative effects on human health (Keesing and Ostfeld, 2021). Moreover, biogenic-based sequestration is recognized as an immediately deployable, highly sustainable approach to mitigate climate change to some extent (Fawzy et al., 2020).

2.2.4 Water Scarcity, Food Security, Population Growth, Aging Population

The increasing frequency and consequences of outbreaks of emerging infectious diseases can be attributed to a combination of factors, including climate change, biodiversity loss, habitat degradation, and more frequent wildlife-human interactions. These are exacerbated by the synergies between persistent intense poverty and a growing human population (Schmeller et al., 2020). In addition to the factors already mentioned, population growth and increasing urbanization significantly contribute to escalating water scarcity and diminishing food security

(He et al., 2021). Currently, 22 % of global food production relies on unsustainable uses of blue water resources, highlighting the gravity of the situation (Rosa et al., 2020).

The current global population growth rate stands at approximately 0.837 % per year, with estimates suggesting the world population will peak at around 11 billion during this century. Notably, much of this growth is concentrated in the world's poorest regions, particularly in Africa, while many industrialized nations face challenges associated with an aging population. These demographic shifts will exacerbate global inequalities in wealth distribution and necessitate solutions for supporting aging populations in developed countries⁷.

2.2.5 Global (Mental) Health Challenges, Pandemics, and Antimicrobial Resistance

Globalization has significantly contributed to the spread of antimicrobial resistance (AMR), with enzymes conferring broad resistance against antibiotics rapidly disseminating worldwide. The World Health Organization has warned that AMR is poised to become the leading direct cause of death by 2050, surpassing current leading causes such as diabetes, heart diseases, and cancer (Morrison and Zembower, 2020).

Additionally, the global increase in AMR is fueled not only by travel and trade but also by imprudent use of antibiotics in agriculture, veterinary, and medical sectors. This has raised concerns about the environment acting as a reservoir for AMR, highlighting the urgent need for regulatory frameworks in pharmaceutical manufacturing, agriculture, and aquaculture (Ahmad et al., 2021).

Pandemics further compound the issue of AMR, as evidenced by the rise of multidrug-resistant organisms during the COVID-19 pandemic (Lai et al., 2021).

Novel influenza viruses represent a significant threat to national security and public health, as they can emerge unexpectedly. Although all countries have shown vulnerabilities in pandemic resilience and preparedness, with issues such as vaccine hesitancy in industrialized nations, effective responses have been linked to factors like good governance and substantial health system investment, which are less prevalent in disadvantaged parts of the world (Coccia, 2022). Despite the recent pandemic raising awareness for preparedness, it has been concluded that the world remains unprepared for future pandemic threats (Clark et al., 2022).

⁷ values taken from Wolfram alpha, 04.08.2023

Disasters and other traumatic experiences often lead to emotional instability, anxiety, trauma, stress reactions, and other psychological symptoms. Given the anticipated impacts of climate change and other global issues that could lead to mass migrations and potential conflicts, an increase in these psychological conditions can be expected (Makwana, 2019).

The challenge of addressing mental health extends beyond marginalized groups struggling to find treatment or prevention. In wealthy, industrialized nations like the United States, there has been a dramatic increase in mental illnesses, contributing to a decline in life expectancy due to rising rates of suicides, opioid overdoses, and alcoholic liver cirrhosis. This trend underscores the need for multifaceted approaches to tackle physical and mental health issues, considering the complexities of modern lifestyles and changes (Zeira, 2022). The demand for mental health services is predicted to continue outpacing supply (Lattie et al., 2019).

There is growing evidence of direct relationships between nutrition, mental health, stress susceptibility, and mental functioning throughout the lifespan. This issue is pertinent in regions experiencing recurrent famines as well as in industrialized countries facing health concerns related to processed foods (Adan et al., 2019).

The Global South faces systemic challenges in training and retaining competent researchers and practitioners (Reidpath and Allotey, 2019).

The interconnected nature of malnutrition, stress, lack of physical activity, and inflammation—which is a significant contributor to depression—is concerning. This is especially troubling given the rise of such pathologies in the industrialized world (Lee and Giuliani, 2019) and the steady increase in depressive symptoms since the 1990s (Keyes et al., 2019).

Lifestyle changes contributing to these trends include increasing sedentary behaviors and nutritional challenges. Emerging evidence also links increased time spent on social media with a modest rise in depression, conduct problems, and episodic heavy drinking (Brunborg and Burdzovic Andreas, 2019).

Additionally, it has been argued that the surge in depression among U.S. adolescents between 2011 and 2018 may be linked to increased time spent on technology and the overall technological environment (Twenge, 2020).

2.2.6 Socio Economic Inequality, Social Injustice, Education, Political Polarization; General Ethics

This complex and far-reaching topic requires a succinct presentation of key facts and regional examples to illustrate the broader challenges of inequality.

While the gross domestic product (GDP) of the United States stands at approximately 23.32 trillion US dollars, India, with over four times the population, has a GDP of just 3.18 trillion US dollars, less than a seventh of the US figure⁸. The World Inequality Report 2022 highlights a stark disparity: the poorest 50% of the global population earned about 8% of the total global income in 2021, while the richest 10% received around 52% (Chancel et al., 2022).

Low-income countries (LICs), despite contributing the least to climate change, are projected to bear the greatest costs, with the poorest segments of their populations suffering the most (Global Inequality, 2023). This pattern of crises disproportionately affecting LICs was also evident during the Covid-19 pandemic, which further exacerbated global wealth disparities (Global Inequality, 2023).

Inequality tends to compound and intersect within countries, with the greatest income disparities observed in poorer nations. Marginalized groups face double jeopardy, as children are more likely to live in poverty than adults, and women and persons with disabilities face additional disadvantages (Global Inequality, 2023).

Selected examples further illustrate the pervasive effects of wealth-related inequality. In India, unemployment was significantly associated with insomnia and the risk for pediatric obstructive sleep apnea (Zoukal et al., 2023). In China, less wealth correlated with an increased risk of obesity among school girls (Liu et al., 2023b). A multi-country analysis revealed that children aged 6-23 months from low-income families received fewer vegetables, fruits, and animal-source foods than those from wealthier families (Ricardo et al., 2023). In Italy, regions experiencing faster precarization, lower incomes, and lower university education levels tended to give more votes to polarizing political parties (Bloise et al., 2023).

Social injustice manifests in various forms worldwide, encompassing gender inequality, systemic racism, economic disparity, and other forms of discrimination and marginalization deeply ingrained in societal norms, policies, and habits. These factors have manifold effects,

⁸ values were taken from Wolfram alpha, 04.08.2023

including significant impacts on physical well-being. For instance, racism and social injustice have been identified as prominent determinants of child health (Abman et al., 2020).

Limited healthcare literacy (LHL) is more prevalent in socially disadvantaged populations. Increasing research suggests that LHL is a key factor in creating health disparities (Schillinger, 2020). Additionally, socioeconomic status has been positively correlated with intelligence across all ages, highlighting wealth-induced developmental advantages (von Stumm and Plomin, 2015). Educational opportunities and home environment quality, both influenced by socioeconomic status, play significant roles in the development of educational inequalities, underscoring a loss of academic potential in less privileged children (Paulus et al., 2021).

2.2.7 Other challenges

Beyond the aforementioned issues, other critical current challenges include general warfare, nuclear proliferation, cybersecurity threats, the unsustainable methods of resource harvesting and utilization, and animal suffering.

Technological disruptions and emergent technologies also present significant challenges. Advances in synthetic biology raise fundamental bioethical questions and potential risks to existing biological entities or biotopes, necessitating alignment and containment strategies. Similarly, the rise of artificial intelligence brings challenges like deepfakes and the potential risks associated with misaligned or malicious artificial general intelligences. These require safety approaches analogous to those used for designed biological entities. Furthermore, advancements in automation carry the potential for social upheaval, while space exploration presents the risk of fueling conflicts over valuable resources in a largely unregulated environment.

2.3 Current Technology

This chapter will provide a concise overview of the most relevant current research advancements and technological developments impacting human society and the environment.

2.3.1 Biology-Oriented Science and Technology

2.3.1.1 *Synthetic Biology*

Synthetic biology, an interdisciplinary field merging biology, chemistry, engineering, and computational sciences, aims to design and construct new biological parts, devices, and systems. It also seeks to redesign existing natural biological systems for practical applications. This field can be seen as a driving force in the biologization of material sciences. The central concept involves regulating material synthesis and processing by engineering biological systems to interpret both synthetic and natural instructions, thereby achieving desired synthesis, modulation, and expression of materials or energy (Burgos-Morales et al., 2021). The significance of biologization in current and emerging avant-garde technologies cannot be overstated. For instance, 3D printing is rapidly evolving with research yielding diverse methods and materials. The scale of this technology is also expanding, evidenced by commercially available printers capable of micro-scale resolution. A recent project involved the author using a printer, costing less than 200 €, to create a microfluidics gradient generator. This project pushed the printer's limits, achieving channels as fine as 100 micrometers. Impressively, recent advancements have achieved resolutions in the single-digit micrometer range at a cost of only 1€ per piece (Hsiao et al., 2022). There is a growing trend to utilize proteins and other biological molecules as versatile materials. A notable example is a study by Jia et al., which demonstrated 3D printed complex protein-based micro-robotic structures. These structures, powered by a minimal actomyosin exoskeleton, converted chemical energy into work, exemplified by contracting microhands. This self-powered system, assembled from biomolecules in a bottom-up approach, marks a significant leap towards sophisticated soft robotic systems (Jia et al., 2022). It is conceivable that this trend will advance towards the design and creation of specific engineered biological systems.

It is crucial to note that humanity's reliance on fossil fuels for energy generation is not only an ecological concern but also a looming threat to our supply chain. This dependence extends to the chemical industry and, by extension, to the production of vehicles, electronics, medical equipment, and pharmaceuticals, among others. The increasing demand juxtaposed with a potential decline in supply presents a dire scenario (Rech et al., 2021).

As a participant in the iGem 2023 competition with the BOKUiGem team, I define synthetic biology as a discipline grounded in modularity, standardization, and iterative design. This approach aims to create a systematic framework for engineering biology, involving the design of standardized biological parts, known as BioBricks. These parts can be assembled to construct more complex systems (Endy, 2005).

Our team's project involves genetically modifying the yeast model organism *Pichia pastoris* to express cholesterol instead of ergosterol, subsequently used to produce testosterone derivatives. The previous year's BOKUiGem team developed *Escherichia coli* strains expressing spider silk genes, potentially replacing concrete in certain applications.

A groundbreaking publication from last year demonstrated a significant advancement in agricultural biotechnology. Researchers successfully expressed the Fe protein of nitrogenase in transgenic rice, marking a major step towards engineering functional nitrogenase in cereal crops. This achievement involved expressing NifH in rice plants, which actively transferred electrons to the NifDK unit and initiated iron-molybdenum cofactor biosynthesis (Baysal et al., 2022, He et al., 2022).

I am particularly excited about recent developments in bio-computation, especially those utilizing spatial diffusion and engineered bacteria. Drawing inspiration from the adage 'The world is a large-scale laboratory,' the initial concept of this work a decade ago contained a comprehensive chapter dedicated to exploring the use of diverse biological phenomena and complex systems as computational media. It encompassed multiple scales – from subcellular components to individual cells, from consortia to societies, and from ecological biotopes to the Earth as an integrated system. The chapter delved into the application of automata theory in understanding and harnessing these levels for computational purposes, illustrating the vast potential of biological systems in computing. (Lloyd, 2013, Mainzer and Chua, 2012). Given that a single cell possesses numerous feedback loops enabling fine-tuned modulation and

adaptation, a biotope amplifies this computational capability through complex microbial interactions (Simpson et al., 2001, Goñi-Moreno and Nikel, 2019, Karkaria et al., 2020). By feeding the system defined inputs, like sonar waves or chemical compounds, and decoding its output, we can access a vast, multilayered computational system akin to superposition in quantum computing.

Recent research in 2023 has made a significant contribution to biocomputing. It involves engineering bacterial colonies to process information through spatial patterning. The computation is determined by the physical locations of morphogen input sources and output receiver colonies, opening new possibilities in bioengineering, biomaterials, and biosensing (Fedorec et al., 2023).

Another innovative approach involves using orthogonal light-activated DNA for patterned biocomputing within synthetic cells (Hartmann et al., 2023).

Biofoundries, which are integrated molecular biology facilities equipped with automated robotic handling, high-throughput analytics, and biomanufacturing capabilities, are attracting increasing investment and interest. They are rapidly becoming an industrial cornerstone (Hillson et al., 2019, Holowko et al., 2020, Holub and Agena, 2023, Kitney et al., 2021, Dixon et al., 2022).

However, it is important to address the concerns regarding the containment of genetically modified organisms and the prevention of biosafety risks, such as horizontal gene transfer. This could lead to genetic contamination or the disruption of ecological niches and ecosystems. Various biocontainment strategies have been developed to address these concerns, surpassing the international standard of controlling escape rates below 10^{-8} . These strategies include chemically regulated transcriptional switches (Cai et al., 2015), the use of tough, encapsulating hydrogel biofilms (Tang et al., 2020), and designing non-natural amino acid auxotrophic organisms (Pei et al., 2022) amongst others.

[2.3.1.1.1 Biotechnology, Biofactories](#)

As our understanding of natural biosynthesis pathways deepens and our metabolic models become more sophisticated, our ability to engineer cells at multiple levels is also advancing.

This progress allows for the design of cells to produce molecules and materials with desired properties. Such engineered products aim to replace materials currently derived from energy-intensive, non-sustainable, and wasteful processes, like those based on petroleum and metals. Moreover, this approach enables the creation of materials with novel functionalities that were previously unattainable through conventional mechanical or chemical production methods (Wang et al., 2019).

An example of the shift from petrochemicals to bio-generated materials is evident in the development of biotechnological strategies for nylon production. Nylon, a widely used synthetic polymer, can now be produced entirely through biosynthesis or by using biological precursors. These innovations represent a significant move towards sustainable production of commodity materials (Li et al., 2020a, Lin et al., 2023b, Turk et al., 2016, Burgos-Morales et al., 2021).

Furthermore, the scope of biotechnology now extends to inorganic materials and structures, such as amorphous glass-like or crystalline structures, achievable through biomineralization processes (Durak et al., 2019, Li et al., 2020b, Chellamuthu et al., 2019, Cheung et al., 2009, Delalat et al., 2015, Griffiths, 2022, Liang et al., 2018, Xiong et al., 2016).

2.3.1.1.2 Microorganisms and Carbon and Nitrogen Fixation, Added Value Chemicals Production, Photovoltaics, -catalytics, and -synthesis; Artificial Enzymes

Many microorganisms, such as the microalgae *Nannochloropsis oceanica*, exhibit a remarkable capacity for carbon fixation and biomass production. These organisms can utilize high concentrations of carbon dioxide, offering a sustainable solution for carbon management (Feng et al., 2023). Additionally, by feeding on phosphates and nitrates, these microorganisms can combine carbon fixation with the purification of various water sources, including viaduct rainwater, demonstrating a multifaceted approach to environmental sustainability (Bi et al., 2023).

Nitrogenase, a unique natural enzyme capable of fixing nitrogen from atmospheric elemental nitrogen—one of the most stable and inert natural compounds—is responsible for fulfilling half of humanity's annual nitrogen fixation needs. This enzyme has existed for over 2.5 billion

years, originating in a reducing, almost oxygen-free environment from tetrapyrrole-reducing, maturase-like ancestral enzymes (Garcia et al., 2022, Garcia et al., 2020, Ghebreamlak and Mansoorabadi, 2020). It is closely related to enzymes involved in the biogenesis of methionine, ethylene, and methane (North et al., 2020) and possesses a highly sophisticated and unique structure. The functional nitrogenase complex consists of a mirrored dimer, with each MoFe protein bonded to an Fe protein via ATP induction (Einsle and Rees, 2020, Martin del Campo et al., 2023). This bonding initiates an electron transfer cascade involving a complex relay mechanism that delivers electrons through multiple FeS clusters to the FeMoCo enzymatic center. This center is unique in nature, with a centrally coordinating carbide, rare use of molybdenum and homocitrate (Burén et al., 2020, Pérez-González et al., 2021). Here, an elegant multi-step reduction of dinitrogen to ammonia occurs (Hoffman et al., 2014).

This overview of nitrogenase's sophisticated mechanics provides context for understanding its economic and ecological advantages over the Haber process, the only other significant nitrogen-fixing method currently in use. The Haber process, a key factor in the population boom of the 20th century and a notable contributor to climate change, consumes about five percent of the world's annual gas production. It operates at several hundred degrees Celsius and under immense pressure, releasing substantial amounts of CO₂ (Song et al., 2018). In contrast, the nitrogenase process operates below 38°C, at atmospheric pressure and does not release CO₂. Consequently, there is a strong interest in augmenting or introducing nitrogenase expression in natural systems, such as coupling with carbon-fixating photosynthetic pathways, and in creating artificial mimetic systems (Baysal et al., 2022, Bennett et al., 2023, Eseverri et al., 2020, He et al., 2022, Layer et al., 2017, Okada et al., 2020, Rapson et al., 2020, Wang and DeBeer, 2021, Xiang et al., 2020). This trend towards designing semi-biological, artificial hybrid, biomimetic, modified natural, and structurally embedded enzymes is particularly evident in fields like photosynthesis, bioelectrocatalysis, photocatalysis, and added-value chemical production (Albero et al., 2020, Arif et al., 2022, Bellardita et al., 2020, King et al., 2021, Kou et al., 2021, Nguyen et al., 2020, Wang et al., 2022c, Zhang et al., 2020a, Zhang et al., 2022a, Wan et al., 2020, Yi et al., 2019, Cai et al., 2021).

2.3.1.1.3 Biofilms,-structures, and-composites

Biofilms are three-dimensional bacterial structures that adhere to both abiotic and biotic surfaces. These structures, often initiated by single cells or small clusters, are characterized by extracellular matrices consisting of water channels, embedded proteins, lipids, nucleic acids, and predominantly carbohydrates formed by polymeric substances. Beyond promoting adherence, these matrices play crucial roles in environmental protection, survival, communication, and food acquisition strategies. The characteristics of biofilms can vary significantly across different species and genera, and they often exhibit increased resistance to antibiotics, competition, heat, physical forces, desiccation, and UV radiation, among other environmental challenges (Kassinger and van Hoek, 2020). The development, formation, and persistence of biofilms are intricately regulated by signaling molecules and complex interactions (Fang et al., 2020a). Biofilms are a prime focus in synthetic biology. With an expanding understanding of microbial community interactions, the potential for manipulation grows. This is exemplified by electroactive biofilms, which are garnering attention in environmental engineering, particularly in the study of conjugative plasmids and non-exoelectrogens in consortia (Fessler et al., 2022).

Engineered biofilms are already finding applications in biomedical, electromedical, and environmental fields. For instance, the biofilm developed by the Joshi group for mercury bioremediation (Tay et al., 2017) showcases the potential in bio-manufacturing. Future advancements are supported by tools such as optogenetic control of biofilm behavior, the use of non-model organisms, and the functionalization of the biofilm extracellular matrix (Tran and Prindle, 2021).

There is also significant interest in the medical application of engineered biofilms for microbiome diagnostics and therapeutics. Strategies range from transplanting beneficial gut microbiome bacteria via self-coating biofilms to programmable and printable *Bacillus subtilis* biofilm production platforms with self-healing and evolvable functionalities. These platforms are engineered to produce therapeutic and signaling biomolecules (Huang et al., 2019, Wang et al., 2020, Chen et al., 2014) and are being coupled with bioelectronics applications (Chen et al., 2021b). An intriguing study highlighted the potential of microorganisms in designing the structural and mechanical properties of materials with unconventional phases, enabling the creation of thermally inaccessible structures in a chiral fashion. This allows for highly

sophisticated and tunable aggregates, gels, and reticular structures with non-conventional mechanical and rheological properties (Grober et al., 2023).

The trend towards utilizing biology in the materials sciences is further illustrated by the bacteria-induced 3D printing of living structural biocomposites, such as bone-like structures with highly desirable properties for a range of applications (Grober et al., 2023), and the production of high-strength, ultra-tough whole spider silk fibers from transgenic silkworms, surpassing the mechanical properties of materials like Kevlar (Mi et al., 2023).

Significant progress has also been made in three-dimensional bioprinting, as demonstrated in eye tissue engineering (Ruiz-Alonso et al., 2021).

2.3.1.2 Biocomputing

Biocomputing, which involves using biological substrates as computation hardware, has seen numerous innovative efforts. The field of molecular computing has advanced to the stage where virtually any computation can be implemented using standard DNA oligomers and DNAzymes. Multi-input systems employing these elements are currently in clinical trials for therapeutic applications (Benenson, 2012, Jaekel et al., 2021). Programmable intracellular biocomputing circuits have been developed for precise cell recognition (Gong et al., 2019). Additionally, hybrid synapses based on various metals or metal oxides on silk protein substrates have demonstrated exceptional analog switching capabilities with high reliability (Dang et al., 2018). Other approaches include utilizing transcriptional and metabolic pathways for high-performance computing (Goñi-Moreno and Nikel, 2019), as well as cell consortia (Simpson et al., 2001, Karkaria et al., 2020). There are many approaches involving DNA computing (Fan et al., 2020, Mondal and Ray, 2022) (Wang et al., 2022a), like for example based on strand displacement (Lv et al., 2021) and already mentioned orthogonal light-activated DNA within synthetic cells (Hartmann et al., 2023) or recombinase assisted transcriptional effectors in mammalian cells (Letendre et al., 2022). DNA is not only an efficient data storage medium with a significantly longer half-life than conventional digital storage media, but it also offers enhanced data security, especially in cloud environments (Namasudra et al., 2020).

Notably, the use of photonically enabled chiral bio-organic structures for optical computing (Han et al., 2022b) and cilia biocomputing (Mayne and den Toonder, 2018) represent particularly intriguing approaches. The integration of biocomputing within smart nanomaterials holds great promise, especially for therapeutic and diagnostic applications in internally applied nanorobots (Tregubov et al., 2018).

2.3.1.2.1 Organoid Intelligence

The human brain is an exemplar of biological machines, surpassing artificial systems in complexity and computational power. It can be regarded as the most sophisticated computational system in use, processing vast amounts of information with exceptional adaptability. The brain effectively filters noise, discerns signals, and performs various other complex functions, all while operating on merely 10-20 watts of power (Morales Pantoja et al., 2023).

Organoid intelligence refers to the use of brain organoids, which are three-dimensional structures grown artificially from stem cells. These organoids aim to replicate aspects of intelligence and memory. The potential applications of this technology are vast, ranging from biocomputing and disease modeling to drug development (Smirnova et al., 2023a, Smirnova et al., 2023b).

A key advantage of biological systems over current technological approaches is their ability to lower activation energies for chemical reactions through structural enzymology.

The efficiency of biological systems is starkly illustrated when comparing the human brain to modern supercomputers. While a single brain, operating at an estimated speed of 1 exaFLOPS, uses only 10 to 20 watts of power, the supercomputer Frontier, with a similar computational speed of 1.102 exaFLOPS, requires a staggering 21 megawatts. Additionally, the spatial requirements are vastly different: Frontier occupies 680 square meters, whereas the human brain has a volume of just over 1000 cubic centimeters. Frontier comprises 58 billion transistors, in contrast to the brain's 125 trillion synapses (Smirnova et al., 2023a, Smirnova et al., 2023b).

Organoid intelligence is acknowledged as a potential game-changer in understanding the human brain and addressing current computational limitations. However, concerns about

brain organoids developing consciousness have been raised, leading to ethical debates and the establishment of guidelines, such as those outlined in The Baltimore Declaration on the exploration of organoid intelligence (Friston, 2023, Lavazza and Reichlin, 2023) and the related dangers and ethical concerns, which resulted in *The Baltimore declaration toward the exploration of organoid intelligence* (Hartung et al., 2023). Recently, research interest has increased to explore leveraging artificial intelligence for bioprinting organoids (Lee, 2023a). This topic is well suited to illustrate the trend towards an amalgamation of natural and artificial intelligence.

2.3.1.3 Bioengineering

Bioengineering denotes the application of biological principles and phenomena with the tool- and mindset of engineering, encompassing and overlapping a wide array of pure and applied sciences due to the immense power of biological technology and the characteristics of human practical approaches leveraging the apparent teleonomy of biological phenomena (Clawson and Levin, 2023).

The field of bioengineering is diverse, covering areas such as biomedical engineering, which includes the engineering of human organs, environmental health engineering like bioremediation, biotechnology, bioinformatics, and bioprocess engineering including biocatalysis. These areas represent just a few examples of the fruitful interaction between biology and engineering (Eskandar, 2023).

2.3.1.3.1 Engineered Living Materials

Engineered Living Materials (ELMs) represent a pioneering class of materials, defined by their composition of living cells that either form the material itself or modulate its functional performance. This concept reimagines living systems as dynamic, responsive entities with emergent and programmable functionalities. The advantages of ELMs are evident when considering the attributes of natural materials, which display properties like programmability, multifunctionality, self-growth, self-healing, self-adaptation, and self-assembly. In this

context, the living cell is seen as the archetypal synthesis machine—a living chemical factory and the epitome of a biological machine (Burgos-Morales et al., 2021).

Current methodologies for the spatiotemporal development of ELMs encompass genetic and/or chemical engineering of cell-cell interactions, utilizing techniques such as optogenetics or nanobodies. Biofilms engineering is also increasingly significant in this area (Burgos-Morales et al., 2021). Regarding practical production processes, 3D printing and electrospinning are currently the predominant fabrication strategies (Rivera-Tarazona et al., 2021). The engineering efforts extend beyond mere structural formation to create responsive materials that proactively engage with environmental stimuli, such as inducing biofilm formation upon detecting a triggering signal (Tay et al., 2017). The application of optogenetics is one such example, where microorganisms like *Escherichia coli* are engineered to distinguish colors and respond by adapting genetic and substance expression (Fernandez-Rodriguez et al., 2017, Moser et al., 2019). This is just one instance of creating an input-output interface in ELMs.

Stimuli-responsive ELMs are poised to play a critical role in environmental applications, particularly as biosensors. They can be used for monitoring and directing environmental conditions, with the capability to detect a wide range of pollutants and nutrients, such as copper, estrogen, and hydrocarbons. Various model organisms, including *Escherichia coli*, *Saccharomyces cerevisiae*, and *Pseudomonas fluorescens*, can respond to these substances with optical signaling (Rivera-Tarazona et al., 2021).

In the biomedical field, ELMs have been developed for applications like wearable biosensors. For instance, *Escherichia coli* wearables can detect chemical inducers like N-Acyl homoserine lactone with a sensitivity of 100 nM or monitor gut biomarkers such as heme with a resolution of up to 32.5 ppm, responding with bioluminescence. Additionally, drug-delivery applications have been explored, such as using *Lactococcus lactis* to control the behavior of human mesenchymal stem cells in response to Nisin. This control induces the production of fibronectin for stem cell adherence and bone morphogenic protein for osteogenic differentiation (Rivera-Tarazona et al., 2021).

The profound significance and extensive reach of these biological applications cannot be overstated. They represent the cornerstone of future technology, engineering interactive materials and systems that respond to inputs and produce desired, appropriate outputs—whether it be information, materials, or energy. Currently at an early stage of research, the

focus is on understanding single, direct causalities. However, as research progresses, these materials are expected to intelligently sense a variety of complex stimuli and generate a wide range of adaptive outputs. While the primary emphasis is on fundamental research, the engineering of cellular signal sensing, processing, and actuation is already making a substantial impact across various fields, including biomedical, energy, fine and bulk chemicals, agriculture, and environmental sectors (Burgos-Morales et al., 2021). Proof-of-concept applications have been convincingly demonstrated, indicating imminent commercial adoption.

The biomedical applications of Engineered Living Materials (ELMs) are particularly promising. Innovations in wearables and enterically introduced symbionts could allow for the monitoring of health parameters and response to specific stimuli, such as pathogenesis-associated proteins, by releasing drugs and antigens. This, however, is likely just the beginning. As technologies evolve, a sophisticated symbiosis between wearables and enterically integrated ELMs is conceivable, with far-reaching implications.

2.3.1.3.2 Bioelectronics,-photovoltaics

Bioelectronics, a field at the intersection of biological systems and electronic devices, traces its origins to Luigi Galvani's groundbreaking experiments in bioelectromagnetics at the University of Bologna in the 1780s (Berggren and Richter-Dahlfors, 2007). Recent advancements have seen the rise of plastic bioelectronics, offering mechanical flexibility, large-area and facile thin film processing, controlled biological properties, and mixed electronic and ionic conductivity. These attributes are crucial for applications involving direct contact with living organisms, such as skin or heart tissue (Someya et al., 2016).

In the realm of bio-photovoltaics, photosynthetic organisms are being harnessed by rewiring photosynthetic electron transport chains for solar energy conversion (Lawrence et al., 2023). The integration of nanoelectronics into synthetic or in vivo three-dimensional tissues is a subject of intense research, focusing on the development of nanoelectronic devices within cellular circuitry. This integration is anticipated to merge seamlessly with biological information processing systems, such as the brain. Such advancements could revolutionize our understanding of the interaction between nanostructures and biosystems. For example,

this technology could be used to map brain activity *in vivo* with high spatial and temporal resolution, significantly impacting both fundamental research and healthcare sectors (Zhang and Lieber, 2016). Recent progress in the field of soft bioelectronics, such as the use of hydrogels combined with conductive polymers, has enabled new applications including continuous intrathecal drug release, spinal and neurostimulation, closed-loop neural and cardiac interfaces, skin-mounted electroencephalography sensors, and even biomimetic soft robotics (Fang et al., 2020b, Phillips et al., 2022, Sunwoo et al., 2020).

There is also considerable interest in establishing closed-loop systems that utilize the body's warmth for energy and artificial intelligence for smart adaptability. These systems aim to develop increasingly smaller, smarter, and more capable devices to address unmet clinical challenges in monitoring and modulation (Cho et al., 2021).

Moreover, research is not limited to *in vivo* systems; *in vitro* applications are gaining momentum. These applications are at the forefront of revolutionizing research, serving as an ideal interface between automated nanoscale microfluidics systems and biological tissue. Their potential for bidirectional interfacing, through continuous, label-free monitoring and precise control of biological activity, is a driving force in the effort to render animal testing obsolete (Pitsalidis et al., 2021).

2.3.1.3.2.1 Protein- and Oligonucleotide Bioelectronics

Recent advancements have brought significant attention to bioelectronic systems based on amino acids, nucleic acids, oligonucleotides, and proteins. These systems are being developed for applications such as logic gates, memory devices, processors, and sensors (Ramesh et al., 2022).

They offer advantages in terms of versatility, flexibility, and adaptability in dimensions, morphologies, and functions, surpassing the limitations of current synthetic materials. Their production is not only cost-effective but also environmentally friendly. Current research is exploring the self-assembly capabilities of proteins, presenting vast opportunities ranging from delivery systems to modulation. Furthermore, leveraging the intrinsic electronic properties of proteins, such as semiconductivity and piezoelectricity, is another area of focus. The potential applications of peptides as semiconductors and active components in fields like

optoelectronics and as reducing agents are comparable to the functionalities of enzymatic centers or synaptic action potential generation (Chen et al., 2021b, Ha et al., 2021, Zhang et al., 2021a).

2.3.1.3.2.2 Microbial Nanowires

The blurring of boundaries between biotic and abiotic realms at the interface of biological entities and an increasingly interconnected, biologically integrated technology is exemplified by microbial nanowires. As previously discussed in the context of nitrogenase, living organisms extensively utilize the redox potential of metals for respiratory processes. Although most of this utilization occurs within cells through complexes and ions acting as cofactors, certain bacteria—particularly those from the *Geobacter* and *Shewanella* genera—have developed electrically conductive appendages known as microbial nanowires. These nanowires are composed of stacked cytochromes, redox-active proteins containing a heme group with a centrally coordinated iron atom. They have diameters in the single-digit nanometer range and can transport electrons over micrometer distances. Recent theories also suggest that some archaea, specifically anaerobic methanotrophic archaea, may use archaeella as electrical conduits *via* tightly packed phenylalanines for electron transfer to sulfate-reducing partners (Lovley and Holmes, 2020). Microbial nanowires are being utilized in microbial fuel cells and are gaining attention as key components in the development of the Internet of Things. Unlike the energy-intensive and environmentally harmful processes required to synthesize artificial nanowires, biological nanowires can be sustainably grown, even from waste. Innovative applications have emerged where microbial nanowires generate electricity from ambient humidity, offering the potential to design wearable devices capable of electricity generation comparable to solar panels but without the need for sunlight (Lovley, 2022). Additionally, microbial nanowires have been used in creating memristors, integral to the development of self-sufficient, long-lasting environmental and biomedical implants, functioning similarly to neurons and sensors. Remarkably, these protein-based electronic materials exhibit stability and high conductivity even in very low pH environments. Recent studies have even suggested quantum-coherence effects in the conductivity of OmcS type nanowires.

Therefore, microbial nanowires stand as a pivotal technology at the crossroads of synthetic biology and semiconductor technology. Their applications span energy harvesting, sensor development, ultra-low power computing, and bioelectronics, including living transistors and super-capacitors (Yalcin and Malvankar, 2020).

2.3.1.3.3 Biomolecular Nanotechnology

Biomolecular nanotechnology illustrates how human innovation, often sparked by curiosity and playful experimentation, can lead to practical applications. The field of molecular machines is a prime example. Initially regarded as toys or artworks, these molecular machines soon proved their utility as tools, given that biological organisms themselves can be viewed as networks of highly sophisticated biomolecular machines. This realization opened up vast potential for refined applications, either by integrating artificial molecular machines into biological systems or incorporating biomolecular machines into artificial supramolecular structures (Ariga, 2020).

A notable biomimetic artificial system is one developed by Li, Feng, and colleagues. They loaded ATP-synthase into proteoliposomes as a motor protein on an artificial membrane. This membrane, containing a photoacid generator and a proton conductor, was structured as a bi-layer to create a photoactive ATP producer (Feng et al., 2016).

The world of molecular biological machines is vast, encompassing well-known examples such as kinesin molecules walking on microtubules, ribosomes assembling proteins, the DNA replication and translation apparatus, ATP synthase, and CRISPR-associated proteins. Enzymes, which consist of a discrete number of molecular components and produce mechanical movement in response to external stimuli, thus initiating their enzymatic activity, also meet the definition of molecular machines.

The field of molecular machines reached a significant milestone with the awarding of the 2016 Nobel Prize in Chemistry for the design and synthesis of molecular machines. This field, a central theme of supramolecular chemistry, involves molecular self-assembly, folding, recognition, and dynamic interactions such as host-guest chemistry, mechanically-interlocked architectures, and dynamic covalent chemistry. There is a visible trend towards biomimetic architectures as the field advances in sophistication (Nicoli et al., 2021).

It is important to note that nanoscale machines differ fundamentally from their macroscopic counterparts, as their operation is influenced by the energetics of random thermal motion (Nicoli et al., 2021).

Current research in artificial molecular machines (AMM) mirrors chemistry's focus on reducing reactants and reagents to achieve reproducible and desired outcomes, analogous to the myriad of chemical reactions occurring within a single cell. Types of AMM, such as molecular balances, hinges, logic gates, motors, necklaces, propellers, shuttles, switches, tweezers, and nanocars, hint at our emerging ability to manipulate biological systems. This capability will be further enhanced as computational power advances, allowing for *in silico* understanding and *in vivo* production. Modeling is leading the way in understanding self-assembly processes, and several proof-of-concept realizations have been achieved in the last two decades. For instance, semi-biological AMMs with integrated and-logic gates for protein folding regulation have been developed. This was achieved by genetically engineering the chaperonin GroEL to have cysteine residues at both entrances of its cylindrical cavity, which were then functionalized with azobenzene derivatives to create photoresponsive mechanical gates. The engineered chaperonin, as an example of the complexity in biological systems, trapped denatured green fluorescent protein (GFP), preventing its refolding. Upon simultaneous detection of ATP and UV light, it rapidly released GFP. In contrast, with only one of these stimuli present, it released GFP slowly or not at all. This demonstration of a system's ability to respond to multiple diverse stimuli was achieved as early as 2006 (Muramatsu et al., 2006). Further developments include motor-polymer conjugates with varying PEG sizes that polymerize under click-chemistry conditions and contract upon UV irradiation, as well as covalent polymer networks in the form of daisy chain rotaxanes, which polymerize upon light irradiation and contract in acidic conditions (Moulin et al., 2020). With the current surge in artificial intelligence technologies, this field is expected to experience rapid advances, first in computational modeling and then in manufacturing capabilities.

The complexity within a single cell is immense, as evidenced by the enormous number of RNAs and their functions, exemplifying emergent complexity where information and physical function converge. Another illustration of complex multilayered functionality is membrane patterns carrying ontogenetic information, independent of DNA (Wells, 2014). This concept aligns with the hypothesis that DNA's origin can be traced back to viruses hijacking RNA-protein-based entities in the early stages of life (Ribas de Pouplana et al., 2004).

2.3.1.4 (Bio)chemistry and Analytics

2.3.1.4.1 Reticular chemistry

Reticular chemistry focuses on constructing extended crystalline structures by connecting molecular building units through strong bonds (Yaghi, 2020). Prime examples include metal-organic frameworks (MOFs) and covalent organic frameworks (COFs), with recent advancements leading to bio-MOFs. These structures are three-dimensional, porous, and have multivariate functionality and mixed metals, allowing for the incorporation of various functional groups and metal ions. This versatility extends to physical properties like rigidity and pore size, as well as catalytic capabilities. Recent developments have even seen frameworks used as photocatalysts, among other applications.

There is a significant emphasis in this field, as in all materials research and development, on data-driven science (Zhou et al., 2019a). The advent of Big Data and artificial intelligence has led to the emergence of 'digital reticular chemistry' (Lyu et al., 2020). Materials genomics has become increasingly important given the synthesis of thousands of porous and non-porous MOFs, COFs, porous polymer networks (PPNs), zeolites, and other porous materials in the past decade. This is out of millions of potential materials, each with a plethora of possible applications. The vast landscape of possible structures, combined with the limitations of practical synthesis and property examination, make reticular chemistry particularly suited for machine learning and deep learning approaches (Jablonka et al., 2020).

In summary, reticular chemistry is about creating enclosed environments, akin to cells and their compartments. The field is expected to continue producing materials with a wide range of applications. These materials can be functionalized with enzymatic, catalytic, and separating properties, serving as hosts that provide protected microenvironments with high surface area and acting as the catalytic 'inhabitant,' similar to a coral and its microbial consortia.

Bio-metal organic frameworks (bio-MOFs) are a class of MOFs synthesized using cost-effective and environmentally friendly biomolecules such as porphyrins, proteins, peptides, or amino acids. A significant body of research is focusing on carbon capture and storage via bio-MOFs. These frameworks offer solutions to the limitations of traditional methods like amine scrubbing, which is known for high energy consumption, environmental damage, and health

risks. Moreover, bio-MOFs are characterized by their large surface area, thermal and chemical stability, and moisture resistance, making them highly efficient in these applications (Zulys et al., 2020).

Materials discovery and science are undergoing a revolution driven by in silico deep learning methods. An example of this is DeepMind's GNoME, which has expanded the known material space by 2.2 million crystals, including 380 thousand stable materials. This expansion represents a significant leap forward, equivalent to hundreds of years of conventional human research, and offers a wealth of possibilities for future technologies (Merchant et al., 2023, Zhongming et al., 2021, Szymanski et al., 2023).

2.3.1.4.2 Analytics

Analytical chemistry, often described as 'the eyes and ears of chemistry,' is crucial for unlocking a deeper understanding of our world. Recent advancements in analytical chemistry have catalyzed further developments across various scientific fields.

Notably, the rise of omics sciences represents a significant trend in molecular biology and chemistry. These fields, including genomics, transcriptomics, proteomics, metabolomics, epigenomics, and pharmacogenomics, utilize high-throughput techniques to analyze biological data on a large scale. The term 'omics' is derived from the Greek word 'ome,' meaning group or whole. The advancement of these fields is largely attributable to improvements in analytical detection technologies and informatics, enabling the generation and processing of vast, often heterogeneous, biological datasets. While these fields have traditionally been studied individually, there is an increasing emphasis on integrating these data to gain a more comprehensive understanding of biological systems (Manzoni et al., 2016).

2.3.1.4.2.1 Metabolomics

Metabolomics involves the global identification and quantification of metabolites, typically small molecules with a molecular weight under 1500 Da. As an omics technology, metabolomics provides critical insights into the state of biological systems that may not be

evident from other data types. It has become a pivotal tool in systems biology, personalized medicine, and the rapid, non-invasive detection of specific markers and pathologies. Due to the vast scope of data generated, metabolomics heavily relies on databases and computational assistance (Abram and McCloskey, 2022, Dmitrenko, 2022). High-throughput, nanoscale, and automation techniques are extensively used in the analysis of biological samples (Cai and Zhu, 2019, Deborde et al., 2019, Malinowska et al., 2022, Vignoli et al., 2019, Zampieri et al., 2017).

One notable application is the metabolomic fingerprinting of sweat, which has been successfully used to detect caffeine consumption. This demonstrates the potential of non-invasive analytics in healthcare and the opportunities it provides for metabolic biomonitoring (Brunmair et al., 2021).

Recent advancements in informatics and analytical technologies have expanded the scope of metabolomics beyond biomarker discovery, enabling system-level analyses of metabolite effects. The inherent sensitivity of metabolomics allows for the detection of subtle changes in biological pathways, providing deeper insights into the mechanisms behind physiological and pathological conditions (Johnson et al., 2016, Khanijou et al., 2022).

In cancer research, metabolomics has been instrumental in shedding light on the complex biological characteristics and dynamics of the disease. It has been used to examine the interactions between cancer, cancer therapies, and metabolism at both cellular and systemic levels (Lei et al., 2021, Liesenfeld et al., 2013, Schmidt et al., 2021).

The field of personalized medicine has also seen the introduction of gender medicine, which considers the interplay between biological markers like sex and psychological/cultural indicators like gender. This approach is vital for effective disease prevention, clinical sign identification, prognosis definition, and therapy optimization. The omics approach has become a potent tool in identifying sex/gender-specific disease markers (Gemmati et al., 2020).

2.3.1.4.2.2 Fully Automated High-Throughput Multiomics

Fully automated high-throughput multiomics represents a significant advancement in data science, enabled by machine learning and increasingly sensitive analytical instruments. This

technology allows for the comprehensive analysis of cells and biological substrates like blood, brain, or muscle tissue. Techniques like liquid chromatography coupled with mass spectrometry generate millions of data points. Machine learning algorithms then structure, filter, and organize this data, providing detailed insights into the ensemble of lipids or peptides, the landscape of the metabolome, specific compounds or markers such as alkaloids or eicosanoids, and novel relationships through the application of volcano plots, heatmaps, or principal component analysis.

While these workflows are substantially aided by machine learning models, they remain complex and labor-intensive, often resembling a multidimensional sudoku puzzle for researchers.

Deep learning models, particularly those based on multimodal knowledge-driven or representation learning, are poised to overcome one of the major bottlenecks in high-throughput analytics: data analysis. The other bottleneck being the measurement itself (Shu et al., 2023, Xiong et al., 2023, Wu et al., 2021, Xu et al., 2022b, Guo et al., 2021c).

Techniques like mass spectrometry and nuclear magnetic resonance spectroscopy, considered the gold standards in high-throughput analysis, are continually improving and being integrated into fully automated systems (Corsaro et al., 2022, Deborde et al., 2019, Vignoli et al., 2019, Wishart et al., 2022, Ali et al., 2019, Cai and Zhu, 2019, Dmitrenko, 2022, Hall et al., 2022, Holbrook-Smith et al., 2022, Janzen et al., 2019, Zampieri et al., 2017).

Microscopy, historically limited by the diffraction limit, is undergoing transformative advancements. The development of super- and hyperlenses, not constrained by the wavelength of visible light, has made significant progress, offering practical solutions for overcoming the intrinsic losses of plasmonic systems (Guan et al., 2023). These lenses are invaluable for high-throughput single-cell multiomics and metabolic engineering analytics, and represent a cornerstone for spatial profiling and modality measurements. They enable increasingly accurate reconstructions of gene-regulatory and signaling networks that drive cellular identity and function (DeLaney et al., 2019).

2.3.1.4.2.3 Microfluidics

Microfluidics technologies and their applications epitomize the trend towards automation and high-throughput efficiency in research and development. These technologies, focused on manipulating and controlling fluids at the micro- and nanoscale, have facilitated remarkable advancements in miniaturization. Recent progress in microfluidics is set to play a crucial role in imminent technological advancements by accelerating analysis, research, production, and a broad spectrum of applications. These range from personalized medicine, drug discovery and development, environmental monitoring, to complex biochemical research. The technology's applicability extends to modeling brain functions, understanding particle dynamics in viscoelastic flows, developing new materials, and exploring the microbial universe. The synergy of microfluidics with advancements in automation, robotics, and artificial intelligence is significantly enhancing its capabilities (Ali et al., 2019, Alsaeed and Mansour, 2020, Aubry et al., 2023, Battat et al., 2022, Galan et al., 2020, Goda et al., 2023, Grebenyuk et al., 2023, Guo et al., 2021b, Liu et al., 2021b, Mogera et al., 2022, Wu et al., 2023b, Zhou and Papautsky, 2020, Zhu et al., 2023c).

The miniaturization and automation of biochemical, synthetic, and analytical laboratory setups are drastically accelerating the generation of practical data for deep learning models. This acceleration is providing insights into biological mechanisms at a molecular level. Flexible microfluidics devices are being experimentally applied in areas such as energy storage, sensors, and wearable devices. For example, plasmonic paper-based microfluidics are used for continuous sweat analysis, vital sign monitoring, biomarker detection, and even in the regeneration of neuronal tissue (Mogera et al., 2022, Xu et al., 2018, Guo et al., 2021a). The integration of various sensors into microfluidic systems is also increasing (Buttkewitz et al., 2023).

Furthermore, the modular and dynamic properties of microfluidics make them ideal for assembling human brain organoids in a controlled, high-throughput manner. This approach is advancing realistic human brain models and assembloid models for studies in neuronal development, disease modeling, and drug screening (Zhu et al., 2023c). Synthetic 3D soft microfluidics offer solutions to challenges like vascularization of engineered tissues and organoids (Grebenyuk et al., 2023). The merging of microfluidics with artificial intelligence marks a significant shift in lab-on-a-chip technologies (Goda et al., 2023, Galan et al., 2020).

Applications of microfluidics extend to diagnostics, therapeutics, genomic screening, and microbiome profiling for disease marker identification. They are also employed in consumer product safety, such as identifying foodborne bacteria and producing active pharmaceutical ingredients (Battat et al., 2022). The versatility of microfluidics is further supported by advancements in 3D printing technologies, integration with various other technologies such as acoustic microfluidics, and their modular design (Nielsen et al., 2020, Raj M and Chakraborty, 2020, Zhang et al., 2020b, Wu et al., 2023b). Microfluidics is poised to be at the forefront of an explosion in data generation and interconnectedness, particularly in the era of the Internet of Things.

The significance of high-throughput automated microfluidics systems in drug discovery and development is immense. These systems are vital for both screening and synthesis processes, significantly contributing to the rapid increase in the discovery of new drugs. When combined with *in silico* modeling, these technologies are revolutionizing the landscape of drug development, enabling more efficient and targeted approaches to new pharmaceuticals (Liu et al., 2021b).

2.3.1.5 Microbiology

Microorganisms encompass a diverse range of microscopic life forms, including bacteria, archaea, various eukaryotic clades, fungi, and viruses—the latter not considered living organisms by current biological definitions. These organisms are ubiquitous in all ecological niches and represent the oldest forms of life, forming the foundation of Earth's trophic systems.

While current estimates suggest that plants, with 450 Gt carbon, represent the most abundant group in terms of biomass compared to 70 Gt C for bacteria (or 100 Gt C collectively for bacteria, fungi, archaea, protists, and viruses), this comparison requires further context. Approximately 70 % of plant mass consists of woody stems and tree trunks, which are relatively metabolically inactive compared to the generally highly active mass of microorganisms. For perspective, animals contribute around 2 Gt C to the Earth's biosphere (Magnabosco et al., 2018).

There are estimated to be approximately 10^{30} cells of bacteria and archaea on Earth. Although the total number of individual plants is challenging to estimate due to their vast size and mass variation, it is undoubtedly much lower than that of microbial cells (Cavicchioli et al., 2019). To put this in context, the human population, approaching 10^{11} individuals - a value reached by just 1 gram of soil (Rosselló-Mora and Amann, 2001) - is far surpassed by the microbial population in a single human's intestines, which is about 10^{13} cells, slightly more than the number of human cells in the body (Abbott, 2016). While fewer microorganisms inhabit the sea surface layer or the atmosphere compared to within humans alone, the major habitats for microbes include the deep oceanic subsurface, soil, the ocean, and the deep continental subsurface. Most of these microbes reside within biofilms, creating their own habitats and interfaces with the environment (Flemming and Wuertz, 2019). Organisms like corals or sponges have evolved to contain vast surface areas within protected microenvironments, populated with microbial biofilms, forming holobionts.

2.3.1.5.1 Microbiome

*"We are but mere sacks of meat, transportive vehicles
for the rulers of Earth residing within us."*

The human body contains approximately as many bacterial organisms as it has endogenous cells, with these bacteria encoding about 150 times more genes than the human genome. These genes have the capacity to change in composition, forming what is collectively known as the holobiome, which also includes a vast number of active and dormant viruses (Shine and Crawford, 2021). The recent surge in microbiome research is a result of advancements in bioinformatics and analytical chemistry capabilities (Arnold et al., 2016).

The human microbiome functions akin to an organ, influencing various aspects of human physiology. It affects development, body functioning, nutrition, metabolism, behavior, and disease occurrence (Hoffman et al., 2022, Natalini et al., 2023, O'Donnell et al., 2023, Pennisi, 2020, Sánchez-Pellicer et al., 2022, Tan et al., 2022). Notably, it plays a significant role in modulating the GABAergic and dopaminergic systems (Mazzoli and Pessione, 2016, Hamamah et al., 2022). This has led to numerous clinical studies that focus on administering engineered

bacteria or viruses for treating various diseases (Bai et al., 2023b, Rutter et al., 2022). Engineered probiotics are being used to deliver CRISPR-Cas9 systems for precise microbiome editing, particularly against antibiotic-resistant strains (Neil et al., 2021). The microbiome-shaping function of bacteriocins is another area of intense research (Heilbronner et al., 2021). Efforts are underway to enable real-time profiling of the gut microbiota to modulate the microbiota-gut-brain axis (Yang et al., 2022), and there has been success in genetically modifying the mobilome through *in situ* conjugation (Ronda et al., 2019). Dietary measures to engineer the gut microbiome have also been explored and demonstrated (Volter et al., 2021). The increasing resolution in understanding cellular composition and function opens new avenues for modulation and manipulation. This is exemplified by the rise of RNA and biomolecular condensate drug targets (Arunachalam et al., 2022, Banani et al., 2017, Shin and Brangwynne, 2017, Barraza et al., 2022, Chen et al., 2022, Loganathan and Doss C, 2023). Analogously, these insights are applicable to all ecosystems, with efforts to develop precision microbiome management strategies in diverse agroecosystems (French et al., 2021).

2.3.1.5.2 Microbial Interactions

Microbial environments are densely populated with a wide array of competitors forming diverse consortia and communities. These include different strains, species, and genera in varying physiological and phenotypic states, from dormant to proliferating cells and from stationary to motile organisms. The interactions within these microbial communities are mediated by an array of agents, such as metabolites that serve as communication signals, trigger factors, cargo transporters, lubricants, toxins, and weapons. The effects of these metabolites are as multifaceted as their roles, influencing not only a microbe's interactions within its own mutualistic and competitive network with their next of kin, predators, prey and viruses but also its impact on hosts, including humans. This understanding is crucial for considerations in human health (Böttcher, 2020).

2.3.1.5.3 Therapies

The complex relationship between multicellular organisms and their unicellular counterparts is exemplified in plants living in symbiotic associations with mycorrhizal fungi and rhizobia. These beneficial microbial relationships enhance the plants' innate immune systems and help ward off pathogens (Nishad et al., 2020, Hassani et al., 2018).

Equally important for the health of multicellular organisms in this respect is the ambivalent relationship between different microbes, shaped by the pressures of competition. These interactions have been harnessed for therapeutic purposes, giving rise to antibiotics among other treatments. Interestingly, antibiotics are used by microbes at far lower concentrations for various modulatory functions, such as inhibiting the swarming behavior of competitors, rather than just for plain extermination (Rütschlin and Böttcher, 2020).

A highlight in this regard is the selective prophage induction by pyocyanin, one of the many toxic compounds produced by the Gram-negative pathogen *Pseudomonas aeruginosa*. It is a chemical multi-talent, as it is not only a potent weapon in redox warfare, but an exuberant blue-colored phenazine, both with a plethora of technological and economical applications (Mavrodi et al., 2001).

Bacteriophages, which are viruses infecting bacteria, are the most diverse and abundant biological entities on our planet. The human microbiota harbors an enormous diversity and their composition has been linked to human diseases and contributions to the maintenance of intestinal immune functions. While in a dormant state as prophages integrated into the host's genome, they can confer benefits to the bacterial population, such as competitive advantages against non-lysogenized bacteria (Jancheva and Böttcher, 2021). Selective prophage induction is only one way of many to manipulate and alter the microbiome, in addition to completely designing it, yet certainly a highlight. The author has generated pyochelin, a potent siderophore of *Pseudomonas aeruginosa* by means of total synthesis, which is currently investigated for its promising selective prophage induction potential, which would make it another example for a compound that developed to serve secondary functions, especially in regard to interactions with surrounding organisms, by means of fierce evolutionary pressure.

The intricate interactions between microorganisms underscore the importance of computational assistance in deepening our understanding of these complex microbial networks, a dense microcosm (Faust and Raes, 2012).

2.3.1.5.4 Systems Biology and Metabolic Engineering

Automated high-throughput analytics, enhanced by deep learning for microorganism identification, are significantly accelerating the exploration of Earth's largely unknown biological realms. The application of multiomics approaches facilitates the detailed elucidation of cellular components at a molecular level. This provides comprehensive insights into a vast array of lipids, proteins, sugars, and their interrelationships. Deep learning architectures are instrumental in determining the three-dimensional structures of these molecules and modeling their potential interactions. This information is crucial for AI-assisted prediction of metabolic pathways and for the *in silico* modeling of these systems. The rapidly increasing use of AI-guided enzyme and pathway design is expected to expand the range of synthetic pathways and enzymes for diverse chemical production (Jang et al., 2022).

Figure 1 showcases an interactive metabolic pathway map for the model organism *Escherichia coli*. This map illustrates all major metabolic pathways and dynamically adjusts to show varying pathway activities under different conditions, such as changes in oxygen availability. (Pathway Map, 2023).

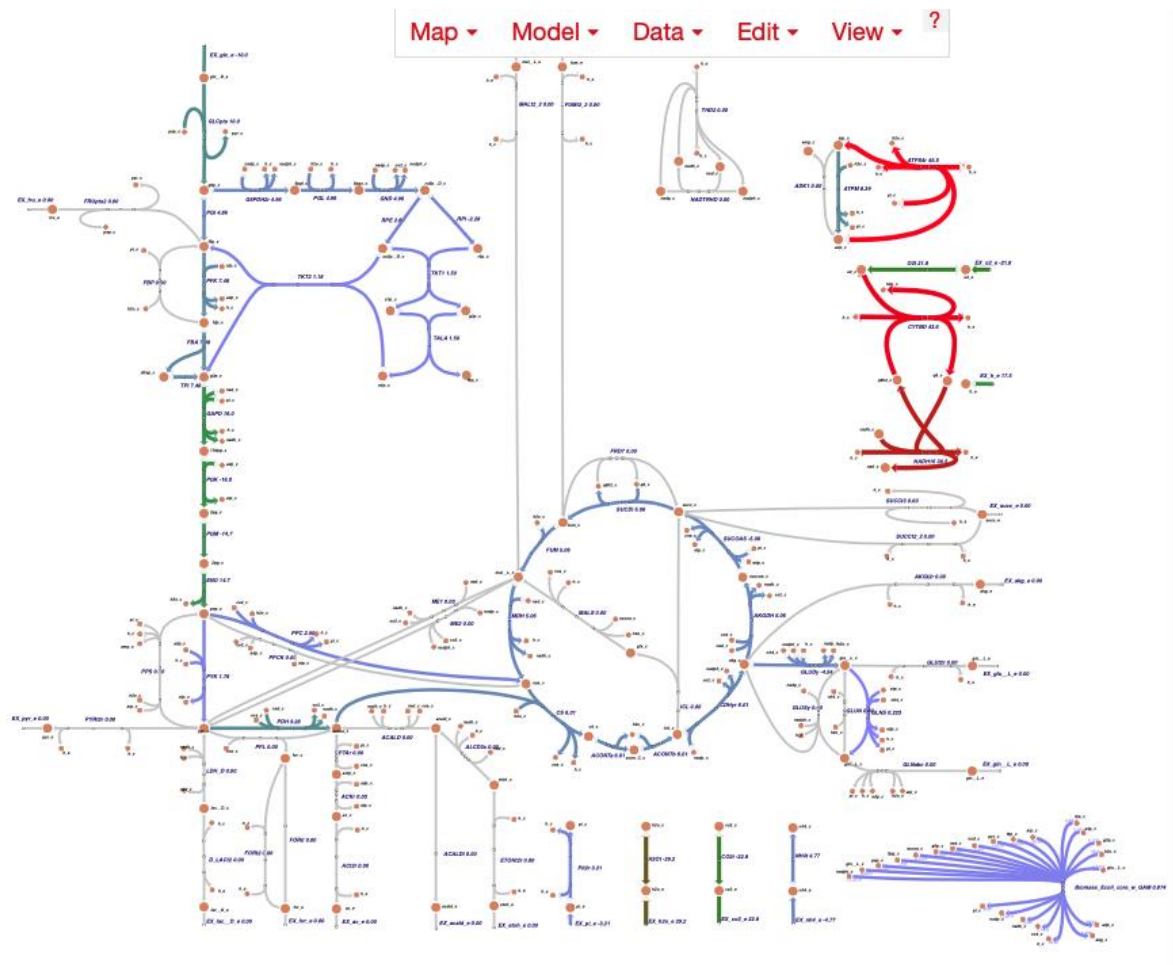


Figure 2. Interactive Metabolic Pathways Map for *Escherichia coli*

The advancements in this field are moving towards an ever-increasing resolution of metabolic interactions. Similar to how deep learning enables the live resolution of complex, dynamic datasets like weather patterns or the Earth's surface, we are approaching a future where models will be capable of simulating living systems with high precision and resolution.

2.3.1.6 Genetic Modification

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) is a family of DNA sequences found in prokaryotic organisms such as bacteria and archaea. These sequences originate from DNA fragments of bacteriophages that have previously infected the prokaryote. Functioning as a form of memory and immune system, CRISPR allows prokaryotes to recognize and destroy foreign DNA.

The CRISPR system is an adaptive immune system. It works in conjunction with CRISPR-associated proteins, or Cas proteins, whose origins can be traced back 2.5 billion years (Alonso-Lerma et al., 2023).

To clarify the mechanism of the CRISPR system, here a brief step-by-step explanation:

The first phase, called adaption, happens upon entry of a plasmid or bacteriophage infection, when incorporation of a segment of the foreign DNA into its own DNA at the CRISPR loci is initiated by the bacterium. This new segment becomes a new spacer in the CRISPR array.

The second stage is constituted by the production of CRISPR RNA, which matches a complementary foreign DNA sequence, *via* transcription and splicing of the CRISPR array.

The third stage is marked by interference, when the so produced CRISPR RNA complexes with a Cas protein and guides it to invading RNA.

In gene editing, the cut sequence is repaired by the cell's repair machinery. Research in this field includes various strategies for insertion, deletion, and base editing. Notable developments include programmable base editing from adenosine to thymine and guanosine to cytosine in genomic DNA without DNA cleavage (Gaudelli et al., 2017). This is particularly significant as over half of human pathogenic genetic variants are due to point mutations (Rees and Liu, 2018).

CRISPR RNA-guided integrases are employed for one-step, efficient genomic integration of ultra-long RNA sequences, where for example Bxb1 integrase is complexed with a Cas9 protein *via* M-MLV RT, which offers simultaneous, multiplexed insertions in three genomic loci and facile, multi-loci deletions by combining orthogonal integrases and recombinases (Vo et al., 2021, Yarnall et al., 2023).

The Protospacer Adjacent Motif (PAM) is a short DNA sequence required for the CRISPR-Cas9 system to bind and cut DNA. SpyCas, the most commonly used Cas9 protein, from *Streptococcus pyogenes*, requires 'NGG' as a PAM sequence, where N is allowed to be any base, which limits the number of targetable sites in the genome. Different Cas protein systems exhibit different PAM requirements, like PAM-less, meaning requiring less specific bases, like for example a Cas9 from the bacterium *Staphylococcus aureus* recognizing 'NNGRRT', with R allowing for A or G, up to engineered, completely PAM-less systems, which of course offer freedom of targetable sequences yet come at the price of increased off-target activity, which need to be taken care of by modulating R-loop formation or the structural enzymology of the Cas protein itself, for example (Collias and Beisel, 2021, Wu et al., 2022, Zhou et al., 2022).

Genetic modification has become a staple in the daily work of many geneticists and molecular biologists. The CRISPR-Cas9 system and Goldengate cloning are robust techniques with high success rates, marking them as crucial tools in the current research landscape. The future importance of genetic modification is underscored by the significant number of academic publications, increasing investments, and the founding of new companies in this field (Brinegar et al., 2017).

The application of large datasets and machine learning algorithms is becoming increasingly important in gene editing. They are used for predicting repair outcomes post-editing (Leenay et al., 2019) and refining the CRISPR system's on-target and off-target effects. The latter is especially critical in therapeutic applications, such as potential anti-cancer strategies, highlighting the value of artificial intelligence-assisted research in this domain (Bhat et al., 2022).

A recent discovery that exemplifies the vast, largely unexplored potential of microorganisms is fanzors—eukaryotic programmable RNA-guided DNA endonucleases found in the diverse domain of protists. These molecules have only recently garnered attention, yet they promise a multitude of applications and enhancements in highly specific gene editing. Fanzors represent not just a technological marvel from the biological realm but also signal that our understanding and utilization of such biological systems are just beginning. The discovery of fanzors suggests a wealth of yet untapped resources and tools for genetic manipulation and opens new avenues for research and application (Awan et al., 2023, Saito et al., 2023, Jiang et al., 2023c, Patinios and Beisel, 2023, Yoon et al., 2023).

2.3.2 Information Science centered current developments

We are currently witnessing an era defined by the burgeoning fields of computation and automation, characterized by a rapid proliferation of discoveries, advancements, and innovations. Among these developments, the rise of versatile, all-purpose networks, agential frameworks, and mission-oriented polymorphic computing stands out. These seem predestined to be retrospectively viewed as hallmarks of the initial disruptive wave of technological emergence.

A pivotal moment in this trajectory was the introduction of the transformer model architecture by Vaswani *et al.* in 2017 (Vaswani et al., 2017), building upon earlier attention-based models (Luong et al., 2015, Bahdanau et al., 2014). This marked the onset of the current AI spring (AI spring - Stanford, 2023). While many in their respect equally capable and heavily utilized deep learning architectures exist, and the transformer architecture sees employment in a broad range of machine learning fields with great success (Chen et al., 2023c, Esser et al., 2021, Kamath et al., 2022, Le et al., 2021, Liao et al., 2023, Ma et al., 2023a, Micheli et al., 2022, You et al., 2023), its exceptional proficiency for natural language processing is currently the center of attention.

Transformer models offer several significant advantages, including parallelization, improved capability to capture long-range dependencies and thus better contextual understanding. Their scalability presents a major advantage, as it allows for efficient handling of large datasets and complex tasks. Transfer learning has also proven highly effective, which involves pretraining the models on extensive datasets and fine-tuning them for specific tasks. In comparison to previous language models, like Recurrent Neural Networks or Long Short-Term Memory networks, these models can effectively harness the capabilities of conventional GPU and TPU infrastructure, which proved convenient for development and industrial scalability (Lecun et al., 1998, Sutskever et al., 2014, Chellapilla et al., 2006).

The transformative aspect of such advanced language models is the ability to use natural human language as a high-level programming language. This provides an intuitive, easy-to-use, versatile, and flexible user interface with a low barrier to entry.

Its revolutionary quality was quickly recognized, as evidenced by the widespread use of tools like ChatGPT. This tool has demonstrated its capability in autonomously writing functional scripts, aiding experienced programmers in increasing efficiency by handling routine tasks and drafting initial versions. Moreover, it has proven to be an invaluable aid for beginners, enabling them to quickly learn, understand theoretical concepts, and write functional scripts tailored to their goals (ChatGPT coding March, 2023).

The widespread adoption of interfaces enabling high-level command interactions will have a profound impact, revolutionizing fields such as education, finance, and research, and further accelerating the pace of technological innovation.

First and foremost, artificial intelligence can serve as an empowering and equalizing tool, when reflecting on the technology and momentarily setting aside the real-world issues of

discrimination, disadvantages, marginalization, and bias - such as underrepresentation in datasets and model conceptions of populations already marginalized. These issues stem from barriers to full participation in scientific and economic arenas. This can be starkly illustrated by the fact that as of today not a single supercomputer in the TOP500 is in Africa (TOP500, 2023).

Artificial intelligence diminishes barriers and restrictions that arise from the need for expert knowledge. It provides a low-level entry point and supportive access to an extensive range of human knowledge. Moreover, it enables individuals to be productive across various fields by fostering critical thinking, creativity, and problem-solving skills.

2.3.2.1 Computational Hardware

The current AI revolution is deeply rooted in advancements in hardware, particularly in the efficient utilization of accelerators, such as graphics processing units (GPUs). This boom was sparked significantly by the paper '*Attention is all you need*', which introduced the transformer model running on conventional GPUs instead of custom-built solutions. This innovation greatly facilitated ease of development and deployment (Vaswani et al., 2017). Currently, GPUs are predominant in AI-related deployment. However, there is a general trend towards heterogeneous computing architectures in AI acceleration. This trend is evident in various projects, ranging from specialized tensor processing units to RISC-V architectures (Ganahl et al., 2023, Huang et al., 2023, Lotti et al., 2023, Peserico et al., 2023, Fritscher et al., 2023, Ngo et al., 2023). Contrasting with the internet revolution, which relied on the cheapest possible computing parts, AI computing favors capital-intensive enterprises. Despite this, current trends in open-source, embedded, and distributed computing suggest that advancements in computing can meet demands for empowerment and equality.

2.3.2.1.1 Conventional and unconventional Computation Hardware

While general practical limits of computation are derived from physical principles, such as Bremermann's limit (which describes the maximum computation rate in a self-contained system), the Margolus-Levitin theorem (limiting the maximum computational speed per

energy unit in conventional computing), and the von Neumann-Landauer limit (setting a theoretical minimum for energy dissipation per irreversible bit operation), current conventional computing is approaching its physical boundaries. Based on metal-oxide-silicon semiconductors, this form of computing is nearing the limits of semiconductor scaling, signaling a potential end to Moore's Law. Moore's Law predicts the doubling of the number of transistors on integrated circuits every two years, a trend now constrained by physical limitations.

Consequently, there is an increasing focus on revising processor architectures, such as system-on-chip designs, and exploring unconventional computing methods that operate on different principles, each presenting unique limitations and opportunities. These approaches can complement conventional computing architectures. Current trends are leaning towards the miniaturization of mobile computing devices, specialized computing devices for distinct tasks, and the enhancement of cloud computing power. The cloud computing market is projected to experience the most significant growth trajectory this decade (Cloud Computing Growth, 2023). Additionally, there is a focus on increasing computational efficiency, primarily by reducing the energy required for computation, as this area offers the most significant margin for improvement (Computation Efficiency, 2023).

Currently, photon-based quantum computers are at the forefront within the alternative computing cosmos, having made significant advances over the last decade (Cheng et al., 2023a). However, inherent noise remains the greatest challenge on the path to realizing the full potential of quantum computing. While the implementation of fault-tolerant quantum circuits and error correction is seen as the ultimate solution to this issue, utility in the pre-fault-tolerant era has been arguably demonstrated (Kim et al., 2023a). Projects are underway to unlock the potential of noisy quantum computers (Egger et al., 2023). Several approaches to error mitigation have been proposed and successfully implemented, improving the approximation to ideal quantum computation (Kim et al., 2023b, Nation and Treinish, 2023, Temme et al., 2017, Tran et al., 2023, Vallury et al., 2023). New models offering increased accuracy are being published continually, pushing the frontier (Kim et al., 2023b) and providing methods for measuring noise-free observables, even in larger circuit volumes (van den Berg et al., 2023). There is a strong sense of optimism within the research community, with efforts being invested in theoretical optimization of early fault-tolerant quantum

computers (Ding and Lin, 2023) and the proposal of various architectures for optimization (Bartolucci et al., 2023). Algorithms are improving not just in noise reduction but also in their theoretical capacity to tackle classical problems (Jumade and Sawaya, 2023). This transformative technology is expected to significantly impact many industry sectors, with the financial industry showing particular interest (Herman et al., 2023). However, the most naturally suited field is quantum chemistry. Numerous advancements across various sciences, industries, and applications have benefited from quantum chemical computations, which are currently emulated by supercomputers using vast resources. These tasks could be more efficiently performed by smaller quantum computers (Shang et al., 2023). IBM, one of the industry leaders, has dubbed this era the Quantum Decade. They anticipate fundamental breakthroughs in quantum computing within the next ten years, completing the trinity of bits, neurons, and qubits that will revolutionize computing. IBM highlights the chemical industry - which provides 120 million jobs and contributes to approximately 7 % of the global domestic product - as a prime candidate for quantum computing. For instance, the simple hydrocarbon naphthalene could be modeled with around 116 qubits but would require 10^{34} bits, which is 7.1 billion times the amount of data predicted to be electronically stored in 2025 (Quantum Decade IBM, 2023, pp. 3, 87).

Recently, phonons have been shown to be a viable source for operating hybrid linear mechanical quantum computing (Qiao et al., 2023).

Within quantum information science, the subfield of quantum sensing has achieved early successes, notably in enhancing the detection limits of gravitational waves. Quantum sensing is poised to explore theoretically predicted phenomena and matter. The anticipated use of paramagnetic molecules as highly selective sensors, akin to drug targets, promises a wide range of applications in molecule-based quantum sensors (Yu et al., 2021).

Beyond chemistry, quantum computing holds significant potential for biology and machine learning. These fields are interlinked and promise to advance the control of quantum systems (Baiardi et al., 2023, Cerezo et al., 2022, Krenn et al., 2023b, Lamata, 2020, Marchetti et al., 2022, Martín-Guerrero and Lamata, 2022, Marx, 2021). Quantum biomimetics, encompassing quantum memristors and quantum artificial life, and quantum machine learning, particularly in quantum artificial networks, share many parallels. Both draw inspiration from biological systems and establish analogies (Lamata, 2020).

Pioneers of Quantum Mechanics, including Erwin Schrödinger, believed that quantum mechanics plays a vital role in biological processes and that biological systems may utilize non-trivial quantum mechanical effects (Danylova and Komisarenko, 2020, Moberg, 2020). Quantum Biology, merging biochemistry and physics, aims to explore these mechanisms - deepening our understanding of biological processes, energy conversion, and computation, among others. Significant progress has been made in this young field, with *in vitro* studies of ion channels, DNA pair-building, and photosynthetic porphyrins, along with theoretical work on neurophysiological electrical fields (Kim et al., 2021c).

The ever-growing demand for computing resources, particularly for deep learning applications, challenges in sub-10 nm CMOS nodes, and the 'memory-wall' inherent in von Neumann architecture have created a negative imbalance between computing resource demand and its practical growth rate. This gap is increasingly being bridged by novel architectures and materials. Neuromorphic computing, especially those utilizing memristive-dynamics, has gained prominence (Yan et al., 2023a), enabling massively parallel computing (Tang et al., 2019).

Neuromorphic computing draws inspiration from the human brain to develop hardware that is energy-efficient and capable of handling sophisticated tasks. This approach includes imitating the probabilistic and stochastic nature of synapses, potentially leading to optimizations in the information transfer-to-energy ratio. Concepts inspired by neuroscience are ideally implemented using bioinspired algorithms and computing models, developed in tandem with suitable physical substrates (Marković et al., 2020). The significance of algorithm-hardware co-design is frequently emphasized in this context (Roy et al., 2019). The field is dynamic, exploring a variety of concepts to emulate brain-like dynamics, complexity, and efficiency through diverse mechanisms and materials for artificial synapses and neurons (Zhu et al., 2020a). One notable effort involves the development of self-organized networks of nanoparticles, exhibiting brain-like criticality through power law distributed switching events (Mallinson et al., 2019). Third-generation neural networks, classified by the use of spiking neurons, primarily function through an 'integrate-and-fire' model of information exchange (Roy et al., 2019).

Brain-like spatiotemporal correlations have been observed in distributed, self-organized networks of nanoparticles, especially when fabricated at a percolating phase transition. The sizes and durations of these networks' avalanche switching events follow a power law distribution, satisfying stringent criteria for criticality in such multi-agent evolutionary networks (Xu et al., 2022a).

Parallel to this, the use of quantum mechanical effects in biological systems, like the porphyrins active in photosynthesis (Kim et al., 2021c), is gaining increasing recognition. This reinvigorates the longstanding debate about neurobiological quantum effects in cognition and consciousness (Swan et al., 2022). Recent studies suggest the possibility of consciousness-mediated entanglement, adding a fascinating dimension to our understanding of cognitive processes (Kerskens and López Pérez, 2022).

Perovskite can find parallel employment harvesting solar energy and providing memristive functionalities for computational purposes (John et al., 2022, Rogdakis et al., 2022). Additionally, hydrogen-doped perovskite-nickelates, known for their inherent stochastic properties, have been identified as promising and scalable candidates for probabilistic computing (Park et al., 2022). Reconfigurable halide perovskite nanocrystal memristors, which allow for electrochemically controlled switching between volatile and non-volatile modes, further demonstrate the material's versatility (John et al., 2022).

Graphene, due to its high surface area, ease of conductance regulation, and advantageous thermal properties, has emerged as a promising material for sensors, actuators, and processors. Its applications span across devices that mimic human sensing and actuation, including models of the five senses, nervous systems, muscle tissues, as well as in biosensors and ultrafast light-based logic gates. Graphene's potential in neuromorphic computing is underscored by its use in metaplastic, energy-efficient, biocomputable artificial synaptic transistors for enhanced accuracy in neuromorphic computing (Ahmed and Mohamed, 2023, Balan et al., 2023, Cheraghi et al., 2022, Dejpasand et al., 2021, Pang et al., 2023, Peña-Bahamonde et al., 2018, Tielrooij, 2023, Zhu et al., 2023a, Kireev et al., 2022, Schranghamer et al., 2020).

It is crucial to note that bio-informational engineering extends beyond processing architectures. It encompasses the continuous development of interfaces for two-way communication across organic, inorganic, and biological substrates, integrating biological, digital, and cyber-physical systems. This field also explores a vast array of potential sensing substrates and architectures, with numerous avenues currently under investigation (Dixon et al., 2021).

Analog computer will see wide employment in edge computing and IoT infrastructures, which will exhibit a high density of sensors, as analog units can be built to resonate solely upon certain analog signals, allowing for continuous monitoring with minimal computing and energy investment. Furthermore, analog signals can be dealt with highly energy efficient compared to digital processors, which will only be activated when an analog sensor and processor unit registers 'wakes' them with information.

The examples provided illustrate just a small yet significant segment of the diverse approaches to computation hardware. Other important areas of research include photonic processors, analog computers (Ambrogio et al., 2023, Li et al., 2023c, Ulmann, 2022, Zangeneh-Nejad and Fleury, 2019, Zangeneh-Nejad et al., 2021), and combined strategies like analog nanophotonics (Giamougiannis et al., 2023), as well as probabilistic computing architectures (Misra et al., 2023), among many others.

The diversity indicates that various computing architectures will likely be employed in parallel, either in combined devices or for specific use cases.

2.3.2.1.2 Supercomputer

Technological advances, often products of problem-solving tasks, can generally be viewed as successful computations. These are typically understood in mathematical or algorithmic terms, as they represent the essence of rational abstraction in problem-solving. The term 'computer,' derived from the Latin '*computare*' meaning 'to calculate, count, think, sum up,' has evolved significantly over time. Initially used from 1613 on to refer to individuals performing calculations, the need for computational skills has been prominent since the

advent of sedentary agriculture and metallurgy. This need arose primarily due to administrative tasks in accounting, taxation, (re-)distribution, and judicial matters.

Throughout history, various devices have aided in computation. The Lebombo Bone, found at the archaeological site Border Cave in South Africa's Lebombo Mountains, is a compelling example. Dated to approximately 44,000 years old, its 29 notches suggest use for monitoring lunar phases (Beaumont, 1973, d'Errico et al., 2012). However, this interpretation is debated, as the bone is broken at one end, and tally sticks and bones have been used in various contexts throughout history. Counting beads, particularly from ostrich eggshells, have been dated to around 50,000 years ago (Beaumont and Bednarik, 2013).

The practice of tracking, computing, and manipulating data related to astronomical, annual, and phenological cycles likely predates concrete evidence, as many artifacts were made from ephemeral materials. However, ancient civilizations such as Sumer and Egypt indirectly testify to a long-established tradition of engaging with natural phenomena through their sophisticated astronomical and mathematical systems. Notable archaeological sites, such as Göbekli Tepe in Turkey, dating back to the Pre-Pottery Neolithic A period around 12,000 years ago, are believed to exhibit astronomical alignments (De Lorenzis and Orofino, 2014). This suggests an ancient integration of environmental, societal, and individual transitions, documented and likely used as guiding logic for rites of passage and other significant societal structures.

Many analog and mechanical computers have been in use historically, and analog computers are garnering renewed interest, particularly as spiking neural networks are compatible with analog neuromorphic computers (Cramer et al., 2022).

The concept of the first all-purpose computer is often attributed to Charles Babbage in the early 19th century. However, the modern era of computing began with the advent of digital computers, initially electromechanical, then transitioning to vacuum tubes and digital electronic circuits, before evolving to transistors, which gained prominence from the 1950s onwards.

In our current age, systematic computation of challenges and open questions has taken a central role. Historically, having well-educated specialists provided a technological edge for war-faring courts and led to prosperous periods. Similarly, today's advancements are largely driven by an increase in computing power and enhanced sensory input detection capabilities. This trend is exemplified by the construction of research facilities aimed at detecting novel

waves and particles. The importance of data gathering is also evident, as seen in the massive sensory input generated by electric cars in pursuit of autonomous driving. This generates vast quantities of data for training machine learning models – a concept often referred to as 'Big Data'. The software aspects of this will be discussed in the chapters on computation, while the physical aspects of computing are examined here.

To foster comprehension of and appreciation for computational power, some illustrative descriptions will be provided.

To aid in understanding and appreciating computational power, some illustrative descriptions are provided. Supercomputer performance is measured in 64-bit FLOPS (double-precision floating-point operations per second). For context, a 24-bit operation computes a single visual pixel, with each 8-bit segment representing a value in red, green, or blue, capable of displaying almost 17 million different colors (Wolfram alpha, 2023). In contrast, 64-bit floating numbers, as per the IEEE 754 standard, use one bit for the sign, 11 bits for the exponent, and 52 bits for the fraction. This allows for a high dynamic range, enabling the representation of very large and small values with precision.

The TOP500 project lists the 500 largest supercomputers (Abramov and Abramov, 2023) (TOP500, 2023). However, not every powerful supercomputer is included in this list. A notable example is the Supercomputer Center at Qingdao's OceanLight, which reportedly was not submitted for ranking, possibly to avoid potential economic sanctions from the USA. At the time of its completion, OceanLight was rumored to be the largest supercomputer and the first to surpass exaflop/s performance (Matsuoka et al., 2023). Another example is Google's optically reconfigurable Tensor Processing Unit (TPU) v4 (Jouppi et al., 2023), which achieves peak performance over 1.1 exaflops. It is specialized for machine learning workloads and does not conform to the specific benchmark algorithm and numeric precision used by TOP500. Interestingly, the layout for the fifth generation TPU was designed by a novel deep reinforcement learning application (Mirhoseini et al., 2021), illustrating a scenario where an AI model designs improved hardware for its subsequent use.

The rapid automation in microprocessor production and the advancements in autonomous agents suggest an approaching event horizon where mainly inorganic machines could design, optimize, and produce their own successors.

It is important to note that the High Performance Linpack (HPL) benchmark, commonly used by TOP500, faces criticism for being outdated. A proposed alternative is the HPL-AI Linpack,

which, when tested by IBM and Nvidia, allowed them to triple the performance of their selected supercomputers (HPL, 2023).

The current leader in supercomputing is the Frontier supercomputer cluster at the Oak Ridge National Laboratory in the United States. Operational since 2022, Frontier boasts a practical peak performance of 1.194 exaflops and a theoretical peak of 1.67982 exaflops. In practical terms, this means Frontier can process 1.194×10^{18} 64bit values in a single second. Notably, the highest recorded computational performance was achieved by Folding@home, a distributed computing project, which reached 2.43×10^{18} flops during its efforts to unravel the structure of a then-unknown protein (Voelz et al., 2023).

With computing efficiency steadily increasing, requiring less power per calculation, projections from 2018 anticipated the advent of zettascale computing around 2035. This level of computing power could potentially deliver accurate global weather forecasts for up to two weeks (Liao et al., 2018). However, these predictions did not fully consider the rapid evolution of deep learning approaches, emerging hardware technologies ranging from single-chip microcomputer architecture to diverse hardware specializations, or developments in quantum computing, photonic processors, or biocomputing.

The energy consumption of supercomputers is a significant environmental concern. The top 10 largest supercomputers alone consume over 1 TWh per year (TOP500 energy consumption, 2023), roughly equivalent to the annual power usage of approximately 358,000 average European households (Wolfram alpha, 2023). In a notable development, Nvidia announced plans in March to build an 18.4 exaflop cluster, a system six times as large as the combined TOP100 listed top 10 supercomputers. This Nvidia supercomputer is expected to have power requirements comparable to the average current consumption of Austria's capital, the city of Vienna (NVidia, 2023).

To illustrate the rapid acceleration of computational power in recent times, one must mention Cerebras' Condor Galaxy-1 supercomputer network series, owned by the Abu-Dhabi based company G42. This series is centered around the Wafer-Scale Engine-2, an AI-specific processor crafted from a full wafer of silicon. This design results in significant efficiency advantages, offering increased speed with less energy consumption compared to GPUs, including NVIDIA's current H100. The first supercomputer in this series, capable of 2 exaflops, commenced service in July, and a 36 exaflop cluster network is expected to be fully operational within 18 months (Cerebras, 2023).

In another significant development, AI giant Google released an updated version of its machine learning specialized TPUs. These are enhanced with optical switching, claiming drastic improvements in efficiency, and have already been integrated into a supercomputer cluster (Jouppi et al., 2023).

The advent of cloud-based supercomputing, soon to be complemented by the widespread implementation of the internet-of-things, has democratized access to supercomputing power. Large server service providers like Azure, AWS, and Google now offer supercomputing capabilities as rentable services. This accessibility allows small start-ups and underprivileged research institutions to utilize these powerful resources. The author anticipates an unprecedented surge in technological progress as research increasingly shifts to *in silico* methods. This shift will unlock vast potential in terms of working hours and costs while significantly enhancing research efforts. For example, space exploration and colonization models can now be run with data from an expanding compendium of sensor data and automated orbital research stations. This reduces the need for specialized personnel and costly space missions for data generation, and most importantly, shortens the time required to develop and test equipment before deployment.

While large institutions still have the advantage of leveraging more computational power, the author believes these developments are reducing the need for specialized knowledge, even in complex tasks. Knowledge that was previously challenging to acquire and limited to a select few is becoming increasingly accessible, enabling cutting-edge research around the world. (Cerebras, 2023).

This trend is further supported by the efforts of the non-profit and open-source community. Their development and provision of peer-shared supercomputers and large deep learning models are rapidly closing the gap between proprietary and open-source technologies. Mustafa Suleyman, a leading figure in the field for over 15 years and currently the CEO of Inflection AI, remarked that cutting-edge technology, backed by significant investments, is only about six months ahead of open-source efforts (Suleyman - open-source, 2023).

On a related note, considering the advancements where artificial intelligence models are achieving human-level performance across a broad range of tasks, Mustafa Suleyman proposed an updated version of the Turing test. He suggests that this modern test should move beyond assessing language skills to include tasks like navigating the world in ways

comparable to humans. An example he gives is the challenge of turning a hundred thousand dollars into a million within a set timeframe (Suleyman, 2023, pp. 29, 118).

While supercomputing represents the pinnacle of current computing capabilities and accounts for a small percentage of total computing, it serves to underscore the rapid progress in the field. Equally important is cloud computing, which plays a significant role in the broader computing landscape. The current trend shows not just an increase in total computational power but also a significant enhancement in hardware efficiency at many levels. This includes improvements in processor architectures, specialization, and the implementation of new technologies.

The steep improvement curve in the models of the nascent field of LLM based artificial intelligence, coupled with the increase in high-quality in silico data production, is noteworthy. This data fuels deep learning models, enabling them to create more quality data and establish new patterns for generating insights. The proliferation of these models is empowering more people to write code and contribute to the refinement of general and deep learning algorithms. This synergy is likely to catalyze a surge in developments related to automation, artificial intelligence, and life sciences, as well as insights in natural and living sciences, already within this decade.

2.3.2.1.3 Bio-computer

The concept of bio-computers illustrates the potential of using biological entities as computing systems. These entities inherently possess computability, making them suitable for diverse applications such as production, analysis, and housekeeping. Biological systems are adaptable and dynamic autonomous systems, adjusting their physiological responses to specific environmental inputs. These adaptations can be harnessed for general computational purposes. Moreover, biological computers enable the design and implementation of operations and circular dynamics that are either unavailable or less productive in conventional hardware and software. Biological systems can simultaneously function as operators (in the form of catalysts) and operands (as substrates), thereby blurring the traditional distinction between application and data. This unique property allows for the creation of self-modifying machines that operate in circular or closed-loop systems (Gentili and Stano, 2022).

In this context, Bianchini's caution regarding the challenges of prediction in synthetic biology and artificial intelligence is pertinent. He points out that both fields aim to produce autonomous systems that interact within unpredictable contexts, namely the environmental and social world, and thus face epistemological challenges in forecasting future developments (Bianchini, 2018).

Andrianantoandro *et al.* provide a useful analogy by aligning the hierarchy of synthetic biology with that of computer engineering. They draw parallels across various complexity levels: proteins and genes correspond to the physical layer of transistors and resistors in computing, biochemical reactions to logic gates at the device level, biochemical pathways to circuits at the module level, cells to computers at the system level, and tissues, cultures, and consortia to LANs, clusters, and the internet at the network level (Andrianantoandro et al., 2006, Amos, 2014).

2.3.2.1.3.1 Population based microbial-, cell-, and membrane computing

Quorum sensing, a microbial mechanism for regulating an individual's metabolic responses within a higher-order system, has previously been discussed (Boo et al., 2021, Stephens and Bentley, 2020).

Population-based microbial computing offers significant advantages in terms of self-organization and a dense layering of complexity (Amos, 2014). Despite current challenges, such as fine-tuning the behavior of multiple microbial consortia, ensuring long-term homeostasis, engineering useful functionalities, and addressing horizontal gene transfer between populations, cell computing shows promise in computational architectures (Amos and Goñi-Moreno, 2018). Recent developments include spatial organization as a tunable parameter for microbial communication, based on the location and interaction strength of microbial strains (Venkatraghavan et al., 2022).

Gentili *et al.* highlight the advantage of cognitive artificial cells over conventional hardware: their inherent ability to function simultaneously as operators and operands. A recent study by these researchers introduced a minimal cognitive artificial cell neural network, based on transmembrane and gene expression regulation through protein phosphorylation (Gentili and

Stano, 2022). They also explore the potential of artificial cells in chemical fuzzy neural networks, where inputs can activate various enzyme systems (Gentili, 2021). The vast array of potential molecular conformation and symmetry states further enhances the capability for designing fuzzy logic systems.

2.3.2.2 Computational Software

2.3.2.2.1 Natural Computation

Natural computation represents an interdisciplinary nexus, merging computer science with the natural sciences. This expansive field encompasses computational techniques, models, and algorithms inspired by nature. It also includes exploring computation within natural systems to understand and harness the computational aspects inherent in natural phenomena. This involves using natural materials for computation as well as employing computers to synthesize natural phenomena (Song et al., 2021).

Natural computation encompasses a diverse range of fields, including bio-inspired computation, physical computing using processes like quantum and DNA computing, and the study of naturally occurring phenomena such as cellular automata or biological neural networks, like the human brain, for their computational properties. This approach views natural phenomena as computation. Other notable areas of research include artificial immune systems, fractal geometry, and artificial life, among others. Methodological approaches in this field vary from simulation and modeling to experimental computing and analytical studies, with applications in optimization problems, data analysis, cryptography, and environmental modeling. Insights from natural computing are poised to play a crucial role in the imminent developments in synthetic biology, engineering biological systems, artificial life, and intelligence. Biology, viewed as a source of inspiration, offers immense potential; for instance, evolution and epigenetics can be seen as intelligent, multimodal, polymorphic applications and regulatory regimes.

2.3.2.2.2 Bio-inspired Computation

Bio-inspired computing, a subset of computational science, develops algorithms, computational models, and hardware architectures by drawing analogies to biological systems. It aims to solve complex computational problems using paradigms, mechanisms, and principles from natural systems. This field has led to insights into behavioral patterns and social phenomena, such as the evolution of swarming behavior and its orchestration logics. Reflections on biological organization have similarly inspired the development of bio-inspired computation. Evolution has produced intelligent biological phenomena and behaviors, enabling biological entities to perform complex tasks with adaptability, self-learning, robustness, and efficiency (Del Ser et al., 2019).

Biological agents, integral to bio-inspired computation, can range from single creatures like birds, cyanobacteria, or humans to sub-entities such as Follicular B helper T cells or Betz's pyramidal cells, as well as supra-entities like ant colonies, orca pods, starling murmurations, beehives, gazelle herds, and human tribes. Additionally, complex systems like the human brain or blooms of phytoplankton exemplify supra-entities of sub-entities. Intelligent capabilities in these agents manifest at various levels and through numerous cases. For instance, Swarm Intelligence, exhibited through stigmergy or collective swarming movements, showcases how agents following local rules, without central control, can produce functionalities greater than the sum of individual actions. This leads to improved mechanisms for exploring complex search areas, akin to the human brain which inspires artificial neural networks (Del Ser et al., 2019).

There are several key features of bio-inspired computation worth mentioning:

Similar to biological neural networks, bio-inspired algorithms often operate in parallel, enhancing efficiency. This is supported by leveraging non-Von Neumann architectures, such as memristors, which overcome the Von Neumann bottleneck of sequential data and instruction processing (Mehonic et al., 2020). To facilitate adaptability and scalability, these algorithms are typically designed to be modular (Colomer et al., 2013). Bio-inspired computing is frequently used to model complex systems and processes, such as ecological and population dynamics (Colomer et al., 2013). In the realms of advanced computability and computational complexity theory, these principles are foundational, particularly in addressing Nondeterministic Polynomial time (NP) complete problems. NP-complete problems,

significant in various natural and financial systems, represent a complexity class where a problem instance can be solved in polynomial time by a deterministic Turing machine if the answer is yes, or by a nondeterministic Turing machine in polynomial time (Song et al., 2021). Turing-completeness is a crucial concept in computation, indicating that a real-world general-purpose computer or computer language can simulate the computational aspects of any other such system. The proposed concept of neuromorphic completeness, as introduced by Zhang et al., for brain-inspired computing systems, shows potential in efficiently overcoming the Von Neumann bottleneck and making significant strides in brain-inspired computing (Cheng, 2022, Zhang et al., 2020c).

2.3.2.2.3 Artificial Intelligence

*weights, biases,
summation function,
activation function,
iterations.*

Above 'poem' wants to illustrate the beauty of emergence by listing the core dimensions of neural networks. At their core, artificial intelligences consist of a library of algorithms based on weights, biases, vectors, weighted sums, and scores, forming the foundation of deep learning models.

These models encompass various architectures, such as generative pre-trained transformer models, which utilize masked self-attention and decoder-only architectures. When analyzed deterministically, these models can be seen as arrays of inputs being averaged or weighted through multiple layers to produce outputs. These models can be organized into cohorts, combining generalist and specialist models in complex arrangements of intercommunication and feedback loops.

This complexity is paralleled in the human brain and similar biological structures. Therefore, the perception of intelligence in an entity appears to rely on its complexity and capacity to compute and adapt to a range of environments and circumstances, surpassing a certain threshold that leads us to classify it as alive or intelligent.

It is important to preface this chapter by noting that the innovations described herein are illustrative of emerging trends in AI. Given the rapid pace of advancements, some details

presented may become outdated shortly after publication. The speed and unpredictable nature of these advancements make it challenging to provide a comprehensive account. For instance, the number of monthly publications on machine learning and AI on arxiv.org has shown exponential growth since 1994, increasing to over 4500 in 2023 from around 1500 in 2021 (Krenn et al., 2023a).

This unpredictability stems partly from the increasing influx of capital into AI research and development. The generation and provision of more data and computational power lead to a disproportionate increase in data availability. However, this rapid growth has also prompted critical warnings about the risks of model collapse (Shumailov et al., 2023).

Furthermore, since the advent of transformers, which enable Large Language Models (LLMs) to maintain attention-based orientation - effectively recalling the beginning of a chapter at its end (Vaswani et al., 2017) - the field is still relatively nascent. There remains an unexplored realm for the evolution of models and algorithms.

More attention than initially planned will be given to LLMs due to their pivotal role at the time of writing. However, it's crucial to recognize that LLMs are part of a broader spectrum of deep learning models, which are at the forefront of current developments. These models are characterized by a diverse array of features and find applications in numerous fields. They have become ubiquitous, influencing areas ranging from fundamental algorithm improvement (Mankowitz et al., 2023), to creative chess play frameworks (Zahavy et al., 2023), drug development and analytics (Abbasi et al., 2021, Abram and McCloskey, 2022, Alharbi and Rashid, 2022, Wu et al., 2021, Zhu et al., 2021, Zhu et al., 2020b, Zou et al., 2019), RNA-structure elucidation and engineering (Angenent-Mari et al., 2019, Angenent-Mari et al., 2020, Yu et al., 2022, Zeng et al., 2023), and various applications in agriculture, robotics, finance, construction, material development, the creative industry, urban planning, ecology research, and sensor development, among others (Abhishek Padalkar et al., 2023, Akinosho et al., 2020, Anantrasirichai and Bull, 2022, Borowiec et al., 2022, Chen et al., 2021a, Chen et al., 2023c, Christin et al., 2019, Guan, 2023, Kalva and Satuluri, 2023, Kamilaris and Prenafeta-Boldú, 2018).

2.3.2.2.3.1 LLMs and MLLMs

LLMs are AI models that generate human-like text, primarily trained on extensive text data. These models have the capability to understand and respond to prompts with coherent and contextually relevant sentences. Consequently, LLMs are utilized in a variety of applications, from drafting emails to writing code and performing at expert-level in specific examinations (Thirunavukarasu, 2023).

Despite their advancements, LLMs face significant limitations, such as the tendency to provide false or unverified information as fact (Lee, 2023b).

The capabilities of Large Language Models are being expanded through the development of Large Multimodal Models (LMMs). MLLMs are designed to process and generate information from diverse data inputs, including text and images. As of summer 2023, this field is still in its early stages, with significant research required to fully realize its potential (Paraskevopoulos et al., 2022, Yang and Hollenstein, 2023, Buch et al., 2022). By autumn 2023, it became evident that large multimodal models were set to become widely employed. The decision to retain this earlier paragraph serves to illustrate the rapid pace of developments in this field.

The transformative impact of transformer architecture in deep learning has led to substantial advancements in a relatively short time. The field of artificial intelligence, especially since the advent of ChatGPT 3 in November 2022, has witnessed a significant surge in investments. The amount of funding in AI increased tenfold, adjusted for inflation, between 2013 and 2022, with 2023 investments expected to far exceed the \$175 billion of 2022 (Investments in AI, 2023). The frequent publication of relevant papers in this field underscores its current momentum.

Continued optimization in transformer models is leading to reductions in necessary computing power and enhancements in output quality and multimodality. The potential for emergent advancements in new models is significant. This rapid, non-linear progression of innovation is also evident in the trend towards leaner LLMs that maintain performance levels. This trend could democratize education and provide digital income generation opportunities, making technology more accessible. However, disparities remain between rich and poor communities in terms of resource access, capital, and infrastructure. Nonetheless, the impact of open-source and democratization efforts in narrowing this divide should not be underestimated.

Recent examples from 2023, within just half a year of the release of ChatGPT 3, demonstrate the explosive advancements in AI, driven by exponentially increasing research and significant investment inflows.

An important arena of innovation in this regard is concerned with increasing the context length, to increase the accuracy of a model's responses as it can take a whole conversation or the like into consideration.

A key area of innovation is enhancing the context length of AI models to improve the accuracy of their responses by considering more extensive conversation histories. LongNet, a variant of the Transformer model, exemplifies this progress. It extends the context length to over 1 billion tokens, efficiently processing both long and short sequences. This is achieved through dilated attention, which reduces computational complexity from quadratic to linear, allowing LongNet to process 1 billion tokens in a single moment of attention and maintain efficiency even when zooming into details (Ding et al., 2023).

Other notable advancements include the introduction of a self-controlled memory mechanism for unlimited input length and effective historical information capture (Liang et al., 2023), and *HyperAttention*, which significantly speeds up processing for large context lengths (Han et al., 2023a).

Orca mini V2, an uncensored Llama-13b model build, demonstrates the trend towards more resource-efficient models delivering equal performance. It stands as a prime example of emergent technologies (Mukherjee et al., 2023).

By autumn 2023, *Mistral*, a 7 billion parameter model, outperformed larger models like Llama-2-34b across all benchmarks (Jiang et al., 2023a). Its fine-tuned version, Dolphin, surpassed Llama2-70b and other larger models on many tasks, raising expectations for generative agents to soon operate on average consumer hardware (Mistral benchmarks, 2023).

A significant advancement in the autumn of 2023 was marked by the introduction of SteerLLM. This model provides a framework for attribute-conditioned supervised fine-tuning, enabling end-users to tailor responses during inference to align with specific preferences. This capability is comparable to many state-of-the-art reinforcement learning models conditioned on human feedback, while being notably easier to train (Dong et al., 2023).

Self-reflective retrieval-augmented generation was demonstrated as a method to enhance large models in a variety of tasks, especially open-domain question answering, reasoning, and

fact verification. This approach addresses several current challenges faced by large models and shows significant promise (Asai et al., 2023).

Currently, many natural-language processing (NLP) tasks still benefit from large LLMs, often exceeding 100 billion parameters. Open source LLMs like BLOOM-176B and OPT-175B allow for downloading of pretrained models in this range. However, fine-tuning or even operating these models requires substantial computing power, typically available only through high-end equipment. PETALS addresses this challenge by enabling the collaborative inference and fine-tuning of large models using the resources of multiple parties. It operates on consumer GPUs at around 1 step per second and exposes the hidden states of served models natively. This feature allows users to train and share custom model extensions based on efficient fine-tuning methods. Similar to a 'torrent' model for software downloading, PETALS allows clients to form a chain of pipeline-parallel consecutive servers for model inference. For parameter-efficient adaptation, clients maintain their own trained parameters while servers host original pretrained layers. These trained modules can be shared via the HuggingFace hub, a significant development for users interested in LLMs. PETALS incorporates several optimizations for safety, speed, and reliability (Borzunov et al., 2022).

PETALS symbolizes a shift towards the democratization of LLMs, making it feasible for individuals to train, fine-tune, share, and operate custom LLMs affordably. The recognition of the necessity for legal institutions to ensure a diverse and open ecosystem for foundation models, and not one dominated by a few major players, is already underway (Schrepel and Pentland, 2023).

2.3.2.2.3.1.1 LLMs as a general-purpose interface for other applications

To integrate LLMs with databases and web applications, the appropriate use of API (Application Programming Interface) calls is crucial. An API is a set of rules and protocols for building and interacting with software applications, analogous to a user interface. This integration enables communication between LLMs and various platforms like web and operating systems, libraries, frameworks, and databases. Consequently, LLMs can access and manipulate data through natural language, much like a user would through a standard

interface. This capability allows LLMs to use tools more accurately, update frequently changing documentation, access large and dynamic knowledge bases, and perform complex computational tasks, transcending limitations like fixed sets of weights, static computation graphs, limited context, and lack of memory storage.

At the time of writing this paper, a small LLM named Gorilla, fine-tuned on a LLaMA 7B model, was introduced, excelling at writing API calls and surpassing the performance of even ChatGPT-4 in this area (Patil et al., 2023). This was soon followed by an even more capable model, ToolLlama (Qin et al., 2023). The ability to employ databases and applications marks a significant milestone in the development of polymorphic applications.

One of the most notable properties of advanced LLMs is their ability to enable natural human language as a high-level programming language and user interface. This facilitates tasks like programming applications within minutes without prior knowledge, as demonstrated by the ChatGPT App build (ChatGPT App build, 2023), and the development of 'no-code' programming apps (Flowise AI, 2023). These capabilities are expected to accelerate technological advancements significantly.

Currently, LLMs function primarily as probabilistic models. Their intelligence emerges when leveraged within an intelligence architecture framework. There have been numerous papers describing emergent behaviors in LLMs, ranging from operationalizing concepts like altruism and selfishness (Phelps and Russell, 2023) to the sudden emergence of in-context learning and recombination of abilities (Hahn and Goyal, 2023). Augmented Language Models, in particular, have been attributed with emergent properties (Bickley et al., 2023). Additionally, the SurveyLM paper exemplifies the value of LLMs in social sciences, systematically evaluating LLMs and leveraging their feedback to enhance survey and experiment designs.

Making sense of Large Language Model behavior is increasingly seen as a valuable resource for complex systems science (Holtzman et al., 2023).

2.3.2.2.3.1.2 General remarks on the limitations of LLMs

The limitations of current LLMs, as identified in the ORCA paper, are broadly applicable across the field. The term 'limitations' in this context ranges from performance shortcomings in the

best-case scenario to potential societal dangers in the worst-case scenario. The selected limitations are those with a high potential for negative impacts on individuals or society.

Data biases are a primary concern, as biases in source data can inadvertently carry over into outputs, leading to potentially biased or unfair results. A lack of contextual understanding can exacerbate this issue.

Transparency is another general problem in deep learning architectures. An entire research field is dedicated to making these models' 'reasoning' processes more transparent.

Data distribution can significantly impact model accuracy, particularly in areas underrepresented in the training data.

Content harms are also a concern, as LLMs can produce harmful content based on diverse system instructions or even present imagined data as fact during hallucinations.

Furthermore, there is significant potential for misuse of LLMs, such as in phishing attempts via calls, SMS, and emails, which are expected to increase in the near future (Mukherjee et al., 2023).

2.3.2.2.3.1.3 Surfacing problems

As LLM technology evolves, new problems emerge. One such issue is model collapse, a degenerative process where models progressively lose information about the true underlying data distribution. This occurs when models are trained on data produced by other models. The main causes of model collapse are statistical approximation error, where the model increasingly misses rare but crucial events, and functional approximation error, arising from insufficiently expressive function approximators. This problem is growing as more online data is generated by LLMs (Shumailov et al., 2023).

Many users reported a noticeable decline in the quality of ChatGPT's responses between March and June 2023. A paper by Lingjiao Chen et al. confirmed this decline via four distinct tasks. They attributed this drop in quality partly to updates, design changes, and drifts in the chain-of-thought reasoning. It was suggested that updates increasing the model's verbosity may have led to a rise in complexity, challenging the model's reasoning capabilities and adherence to protocols like chain-of-thought. Additionally, an increase in code generation issues indicated similar challenges. Another factor considered was the implementation of

enhanced safety measures and defenses against jailbreaking attacks, which led to the model's reluctance to answer certain sensitive questions, thus limiting the scope of its responses (Chen et al., 2023b).

Future developments in LLMs and LMMs are expected to address these issues and enhance the models' capabilities. This may include developing methods to reduce hallucinations in LLMs, expanding the multimodal abilities of M-LLMs, and establishing ethical guidelines for their use. As these models evolve, they are anticipated to become increasingly integral in various sectors, such as healthcare, education, and research.

To illustrate the rapid progression in this field, by autumn 2023, new efforts had emerged, such as mPLUG-Owl. This model demonstrated a significant increase in efficiency regarding inference and cost. It exhibited superior capabilities in instruction and visual understanding, knowledge transfer, multi-turn dialogue, and emerging abilities like scene text understanding, multi-image correlation, and multilingual conversation, achieved through modularization (Ye et al., 2023).

Another notable development is Visual ChatGPT, which integrates various Visual Foundation Models with a prompt manager for iterative reasoning. This enables the model to handle complex content intake and output (Wu et al., 2023a).

Current research is increasingly focused on developing efficient model compression techniques for LLMs to create compact versions suitable for mobile devices (Zhu et al., 2023b). This approach is grounded in the theory that learning, prediction, and compression are interrelated. Intriguingly, as the development of LLMs leverages this concept, these models are also being used to achieve improved compression results and to provide more accurate estimates of the entropy of the English language (Valmeekam et al., 2023).

The development of PROMPTBREEDER represents a significant stride in this area. This self-referential, self-improving system is capable of automatically evolving effective domain-specific prompts. PROMPTBREEDER not only enhances prompts but also refines its own prompt-improvement process. While it is still topologically limited and does not match the open-endedness and adaptability of human thought processes, it indicates the potential of increasingly open-ended self-improvement systems that do not rely on parameter updates.

This system could potentially employ a module dedicated to algorithmic evolution (Fernando et al., 2023).

Another innovative project is NASA-PETAL's BIDARA, which utilizes ChatGPT in conjunction with Semantic Scholar. This tool assists users in finding and applying bio-inspired design solutions to specific engineering challenges, leveraging data and information to further biomimicry research and design (Shyam et al., 2019, Whiteaker and Shyam, 2021). BIDARA exemplifies the application of LLMs in advancing research and practical applications in specialized fields.

2.3.2.2.3.2 LMMs and AGI

By autumn 2023, as this work was being finalized, there were circulating rumors about a breakthrough model developed by OpenAI, codenamed Arrakis. This model, reportedly an everything-everything model capable of handling multimodal inputs and outputs, is said to surpass the capabilities of OpenAI's own ChatGPT-V and other notable models like Google's Gemini, Microsoft's CoDi, and NExT-GPT, as well as the open-source mPLUG-Owl. Arrakis is rumored not only to excel in multimodal abilities but also to demonstrate capabilities that align with the classification of artificial general intelligence (Yang et al., 2023e, Wu et al., 2023c, Ye et al., 2023, Perera and Lankathilake, 2023, Tang et al., 2023c, OpenAI's Arrakis, 2023). Functional multimodal understanding and manipulation mark significant advancements in the utilization scope of these models. This development is crucial in the context of general intelligence structures, allowing for human-level task execution.

Moreover, these advancements represent a major stride in the field of semantic communication. This integration of communication with semantic information aims to enable more intelligent and adaptive communication services. Operating at higher levels within Weaver's communication framework, these models could play a pivotal role in the rapidly evolving Internet of Everything and in robotic prompting (Jiang et al., 2023b, Jiang et al., 2022). In January 2024, the preprint of a landmark survey, *'Thousands of AI Authors on the Future of AI'*, was published. This survey encompassed the perspectives of 2,778 researchers who had published in top-tier AI venues. The survey revealed that for 35 out of 39 tasks across various

fields - including music generation, coding, gaming, and scientific research - there was a consensus that there is at least a 50 % chance these tasks could be feasibly performed by an AI model with general human-level performance within the next ten years.

The societal impact of the widespread advent of High-Level Machine Intelligence was predominantly estimated to be neutral with a slight inclination towards positive expectations (Grace et al., 2024). Yet, the implementation of stringent precautions is imperative, given the myriad potential dangers associated with rapidly advancing technologies. This need for vigilance was starkly illustrated by the research effort *Sleeper Agents*, which explored the training of deceptive LLMs harboring hidden agendas, that persisted through safety training (Hubinger et al., 2024).

Another significant milestone on the road to AGI was presented by Meta together with the University of New York with the development of self-rewarding language models, which not only generally improved upon them judging their own outputs and providing their own rewards during training but furthermore their ability to provide high-quality rewards to themselves improves (Yuan et al., 2024).

The implications of self-improving intelligence architectures are far-reaching, as they mark the direct road to superhuman capabilities, as was demonstrated multiple times by now, for example by DeepMind's Alpha models. It further indicates the ability of first-generation AGI models being able to create even more capable AGI models.

On an inspiring sidenote, let's briefly indulge in the compelling analogies between the mechanics of games and the very fabric of reality. Just as large models have been adept at uncovering exploits within the physics generated by game engines (Baker et al., 2019), intelligent models can similarly be directed to meticulously seek exploits within the physics of our own reality, potentially unlocking abilities or phenomena originally unintended within the physics engine of our universe

2.3.2.2.3.2 Agent Oriented Programming

2.3.2.2.3.2.1 Generative Agents

Generative agents, as described in the notable paper by Joon Sung Park *et al.*, are computational software agents that convincingly simulate human behavior. These agents

utilize LLMs, possess memory capabilities to store and recall past experiences, interact with one another, form opinions, and plan future behaviors based on memories and current situations.

The architecture presented in their research, tested in a simulation akin to the game "The Sims," allows agents to maintain extensive records of their experiences using natural language. They can synthesize these memories into higher-level reflections over time and retrieve relevant past experiences to inform future actions. In the interactive sandbox game environment, these agents adapt to environmental changes and exhibit emergent social behaviors.

The potential applications of such agents are wide-ranging. They enable social prototyping, enhance human-centered design processes, and can be integrated into physical spaces as social robots. However, these advancements come with significant ethical and societal risks. Concerns include the unpredictable impacts of errors, the potential for deepfakes and misinformation, problematic user relationships and projections, and an over-reliance on these agents. To mitigate these risks, strict safety protocols and defensive measures must be implemented to ensure that generative agents complement rather than replace human interaction and to prevent other forms of harm (Park et al., 2023).

2.3.2.2.3.2.2 Generalist agents

In a significant contribution by Google's DeepMind team, the generalist agent Gato was introduced. Gato is capable of performing a wide range of multimodal tasks across various domains using a single network with consistent weights, functioning as a transformer sequence model. Demonstrating versatility, Gato has engaged in dialogue, provided captions for images, manipulated blocks with a robotic arm, achieved superhuman performance in ATARI games, and navigated simulated 3D environments, among other tasks. Despite being trained on only 1.2 billion parameters, Gato can process any data that can be serialized into a flat sequence and continues to improve with increasing data, computation, and model scale (Reed et al., 2022).

Another insight into the future of capable generalist agents is presented by MAGENTA. This agent was trained to play various multi-agent games, treating each as a distinct language. It

employs a permutation-invariant architecture, which means it does not assume any spatial relationship between features, allowing for arbitrary permutations of tokens or functions without altering their properties. This architecture is facilitated by two types of transformer models (Wang et al., 2022d). The authors of the paper underscore the intrinsic risks associated with such generalist agents, particularly when they interact with the physical world. This necessitates novel mitigation strategies. Additionally, there is a need for political efforts to ensure adequate investment in research on safety issues, as only appropriate accountability will ensure sufficient focus on these critical concerns (Reed et al., 2022).

2.3.2.2.3.2.3 Cognitive and Intelligence Architectures

The interdisciplinary field of AI has historically been characterized by two distinct research paradigms since its inception. The first, a bottom-up strategy, focuses on modeling the elemental constituents that form the foundation of human intelligence. This approach primarily studies neurons and neural networks, aiming to create intelligence as an emergent property from these basic elements.

On the other hand, the 'clean' top-down approach is concerned with modeling cognitive processes at a high level. This strategy endeavors to construct intelligence through deliberate and structured design, mimicking the cognitive functions observed in humans (Dushkin and Stepankov, 2021). Given that the concept of intelligence is largely anthropocentric, deriving from observations of natural human intelligence, the application of bionic principles to cognitive architectures is not only fitting but, in many respects, inevitable. By emulating the processes and structures found in biological systems, AI development can achieve more authentic and effective cognitive architectures, aligning closer to human intelligence (Reed et al., 2022).

Dushkin and Stepankov have highlighted several key approaches of living intelligent agents that are highly relevant for the development of cognitive architectures. These include multisensory integration, feedback mechanisms from decision-making subsystems to sensors for perception prediction, personal memory of a cognitive agent, goal setting, and internal conflict resolution. Building on earlier architectures that emphasized the importance of

pattern recognition and prediction, and utilizing various machine learning types while mirroring the human cortex's cortical columns, they propose a general scheme for cognitive architectures. This scheme integrates multisensory inputs, a proactive management system that mediates between long-term memory and current input, and a reactive management subsystem responsible for determining the necessity for immediate or managed responses. Additionally, an outcome acceptor is proposed to handle executive mechanisms (Dushkin and Stepankov, 2021).

DreamCoder, an AI system drawing inspiration from the Helmholtz machine — itself based on human learning during sleep — represents another innovative bionic approach. This system is focused on problem-solving and the development of generalizable, interpretable knowledge, characteristics intrinsic to intelligent agents (Ellis et al., 2023).

DreamCoder autonomously enhances its ability to write improved programs and search for them more efficiently by simultaneously expanding explicit declarative knowledge and implicit procedural knowledge. This process occurs through a bootstrapping approach, constructing libraries for basic operations and learning languages in multilayered hierarchies of abstraction. Each layer of this hierarchy is remarkably built from symbolic code defined by earlier code layers, making the system's representations interpretable and explainable by humans.

Meta-learning approaches are garnering significant attention in the field of AI, as they are crucial for equipping intelligent agents with the capabilities necessary for survival and autonomy. Recent studies in meta-reinforcement learning have developed methods that enable agents to discover learning rules without an explicit value function (Matsuo et al., 2022). This development is a major step forward in the design of intelligent agents, but it also introduces challenges. It highlights the importance of instilling foundational principles, such as curiosity, in artificial agents from the outset.

In a notable achievement, DreamCoder successfully rediscovered the fundamentals of modern functional programming, vector algebra, and classical physics, including Newton's and Coulomb's laws (Ellis et al., 2023)

Kumar, in his paper, discusses key concepts for artificial general intelligence, introducing an innovative concept for polymorphic intelligence and complex adaptive systems based on the collective operations of intelligent agents. This approach draws heavily on biological principles (Kumar, 2023).

Polymorphic intelligence, a critical feature of artificial general intelligence, refers to the ability to dynamically adjust cognitive structures to environmental demands through real-time algorithmic modifications enabled by meta-learning and modular neural architectures (Kumar, 2023).

Complex adaptive systems in AI are characterized by intricate algorithmic interactions and feedback loops, facilitated through interconnected neural networks and ensemble learning techniques. These systems adapt based on feedback, allowing for sophisticated, responsive behaviors (Kumar, 2023).

Collective operations are a cornerstone of intelligent architectures, involving the orchestration of coordinated functions using swarm intelligence algorithms and consensus mechanisms like Byzantine fault tolerance. This unifies heterogeneous systems for focused execution of tasks (Kumar, 2023).

Among the various modules often proposed in system architectures for autonomous intelligence, such as perception, configurator, short-term memory, actor, cost, and world model modules, the world model module stands out as the most complex. Its conception and implementation pose significant challenges due to its intricate nature (LeCun, 2022).

The ability to survive and move freely within our perceived reality relies on the selective dynamics of constructed interrelationships between actors and factors, forming a mental world model that reasonably aligns with potential interactions and experiences in an external reality. This brings up an intriguing question: can an entire system be computably represented in its entirety by a fractal representation of a partial constituent?

Jay Wright Forrester, recognized as the father of system dynamics, succinctly stated, "*The image of the world around us, which we carry in our head, is just a model. [...] We have selected only certain concepts and relationships between them, and use those to represent the real system*" (Forrester, 1971).

Yann LeCun offers a more nuanced perspective, suggesting that animals and humans are equipped with a 'world model engine.' This engine dynamically configures tasks at hand, allowing for a single, configurable model to share knowledge about how the world works across different tasks. This facilitates reasoning by analogy, applying configurations from one task to another (LeCun, 2022).

Focusing on the cost module, which closely relates to motivation and emotion in living intelligent agents, LeCun describes it as measuring the agent's 'discomfort' in the form of a

scalar quantity termed 'energy.' This module comprises two sub-modules: the intrinsic cost, which is hard-wired to measure instantaneous discomfort (akin to pain and pleasure), and the trainable critic, which predicts future intrinsic energy levels. The intrinsic cost module helps develop self-sustaining behavior and influences the nature of an agent's behavior by motivating certain actions. Meanwhile, the trainable critic module is responsible for estimating future energy costs, enabling the agent to endure short-term energy expenditure for long-term gains, thus completing larger tasks (LeCun, 2022). This module plays a crucial role not only in aligning virtual intelligent agents with human objectives but also in robotics, where proactive behavior is encouraged through movement rewards. Movement is one of many manifestations that foster proactive interaction and manipulation of the environment, with curiosity—encompassing learning, exploring, and playing—being a key element in the design of natural intelligent systems.

The principle of energy minimization, fundamental to natural sciences and particularly prominent in chemistry, serves as a driving logic in thermodynamics and kinetics. This concept is exemplified in medicinal chemistry, where reducing a ligand's entropy and enthalpy in relation to its binding to a target receptor enhances selectivity and affinity.

A promising approach that offers practical benefits in the advancement of intelligent agents, while reducing the need for computationally intensive training on whole datasets, is demonstrated by Ha and Schmidhuber. They developed an agent capable of training entirely within its own hallucinated dream, generated by its world model. The agent successfully transfers the learned policy back into the actual environment (Ha and Schmidhuber, 2018). This approach not only boosts the efficiency of intelligent model development but also provides insights into whether systems can be computed by inherent fractions.

Current challenges in the development of intelligence architectures include addressing commonsense knowledge problems, such as folk psychology, theory of mind, abductive reasoning, and naive physics. These challenges stem from difficulties in establishing functional reasoning and world model-building capabilities (Chowdhury et al., 2023, DeLong et al., 2023, Hammond et al., 2023, Hao et al., 2023, Hu, 2023, Montes et al., 2023, Ping et al., 2023, Sridharan and Mota, 2023, Wlodek, 2022, Wu et al., 2023e, McCarthy, 2022, Shanahan et al., 2020, Zhu et al., 2020c, Friston et al., 2021, Karlsson et al., 2023, Kim et al., 2020, Matsuo et al., 2022, Seo et al., 2023, Zhang et al., 2021b).

The author envisions the future development of autonomous agents possessing sophisticated intelligence architectures, extensively trained in fields such as mathematics, computer science, and natural sciences, particularly molecular biology. From this foundation, self-directed optimization and evolution of algorithms, models, and frameworks are expected to yield emergent properties and capabilities. This advancement will significantly increase computational efficiency and lay the groundwork for comprehensive computability in biology, enabling exhaustive design and control over living systems.

2.3.2.2.3.2.4 (LLM-based) Autonomous and Interactive Agents

One of the most engaging topics in the current AI boom is the programming and development of autonomous agents. Such agent is defined as *'a system situated within and part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future'* (Franklin and Graesser, 1996).

This definition encompasses a wide array of agents, including biological, robotic, and computational agents. Computational agents can be subdivided into software agents and artificial life agents, with functionalities ranging from task-specific applications to entertainment (Franklin, 1997). Autonomous agents are deemed crucial for achieving artificial general intelligence, expected to perform tasks through self-directed planning and actions (Wang et al., 2023e), as well as self-adaption (Nascimento et al., 2023).

Utilizing extensive training datasets and a significant number of model parameters, LLMs are increasingly being employed as central controllers within autonomous agent architectures. Consequently, a variety of LLM-based autonomous agents have emerged, which can be broadly categorized as general agents, tool agents, simulation agents, embodied agents, game agents, web agents, and assistant agents. The architectural design of these LLM-based autonomous agents is analogous to determining network structure in traditional machine learning, while the acquisition of agent capabilities resembles the learning of network parameters (Wang et al., 2023e).

Autonomous agents are poised to be at the forefront of the upcoming revolution in robotics and polymorphic applications, acting as the driving force behind large-scale automation. These agents, in themselves, are increasingly designed with complex architectures. Inspiration

for these designs is drawn from models of human consciousness, such as the influential workspace theory model, and traditional computer architecture principles (Hayes-Roth, 1991). Workspace theory conceptualizes human cognition as a collaboration of numerous small, mostly unconscious, special-purpose processes. In this model, coalitions of these processes gain access to the 'consciousness' or global workspace by surpassing certain thresholds. Once in the global workspace, their messages are broadcast to all unconscious processors, mobilizing additional relevant processors to address new situations or problems (Franklin and Graesser, 1999). This framework suggests that agents can recruit other agents or collaborate in cohorts, a concept increasingly reflected in the design of rational agent architectures.

The design and function of agent systems can be approached from both implementation-oriented and intentional, social perspectives. The latter views them more as organizational structures, drawing inspiration from organizational design theories (Kolp et al., 2006).

Moreover, the development of artificial intelligence *in silico* is expected to provide valuable insights into the human brain. Conversely, the rapidly evolving field of cerebral organoids — lab-grown brain tissues — is not only deepening our understanding of complex biological neurological structures but also inspiring the design of artificial intelligence architectures (Li et al., 2022).

And while there is a broad spectrum of intelligence architecture concepts, a typical current architecture design for LLM-based autonomous agents consists of four modules, the profile module, the memory module, the planning module, and the action module.

The profiling module, where basic information about the agent is written to influence the LLMs behavior by means of prompt adaptation. There are several strategies to generating this module, from handcrafting to LLM-generation or dataset alignment (Wang et al., 2023e).

The second important module is concerned with memory, where perceived information is stored from the environment, leveraging them to facilitate future actions. Due to it being essential for the agent to accumulate experiences and self-evolve, while behaving more consistent, reasonable and effective, the architecture for memory sees a steady rise in complexity and displays a multitude of differing realizations like unified or hybrid memory, which draws heavily from cognitive sciences and especially from human memory processes, with the functionalization of short and long-term memory being prominent (Wang et al.,

2023e). There are not only different concepts regarding the memory structure in use yet also various memory formats like natural languages, embeddings, databases, and structured lists. The memory operations in LLM-based autonomous agents, particularly in how they process and represent information, are a source of fascinating insights. An example is a custom instructions prompt found in a Reddit subforum, suggesting the creation of a language understandable by AI but not humans, to condense phraseology while retaining all details (Custom Instructions Prompt, 2023). This example underscores the potential developments in information representation, language, and communication that intelligent architectures could create. These systems, capable of discerning patterns and associations from extensive datasets and analyzing them through operations like principal component analysis, are likely to develop infospheres and strategies that diverge significantly from human intuition.

The main memory operations in these systems are categorized into reading, writing, and reflecting. The latter, reflecting, is particularly intriguing, as the logic behind storing and structuring information in low-level memories can yield high-level insights (Wang et al., 2023e).

The Planning Module is central to deconstructing complex tasks into simpler subtasks for individual resolution. Approaches vary, primarily in terms of whether the agent is receptive to feedback during planning. One successful method involves single-path reasoning, particularly the chain-of-thought approach, which includes reasoning steps within the prompt to break down the final task into intermediate steps. These reasoning steps can be executed in a one-shot or recursive manner (Wang et al., 2023e).

Additionally, there are numerous multi-path reasoning approaches. Tree of Thoughts models, which generate plans through tree-like reasoning structures, are gaining popularity. In this approach, each node represents a reasoning step, and the selection of nodes is based on the LLM's evaluation, following either a breadth-first or depth-first strategy (Wang et al., 2023e). The approach of planning with feedback in LLM-based autonomous agents is significantly more powerful and capable of solving complex, real-world tasks compared to more straightforward and simple planning methods. This approach, akin to human iterative strategy revision based on external feedback, not only offers insights into task conception and strategy development but also enables agents to adapt to changing circumstances during execution. Feedback is typically obtained from the environment, humans, or the model itself (Wang et al., 2023e).

A notable example is the Chain of Hindsight method, which improves the model's outputs by presenting it with past outputs annotated with human feedback. This has been effective in conditioning the agent to align with human values (Liu et al., 2023a).

The Action Module, responsible for translating the agent's decisions into specific outcomes, encompasses four aspects: action goal, action production, action space, and action impact. The agent can pursue various objectives, such as task completion, communication, or environmental exploration. These high-level distinctions often represent diverse underlying model concepts (Wang et al., 2023e).

There are two common strategies for action production: memory recollection and plan following. In memory recollection, the agent generates actions by extracting information from its memory relevant to the current task. In plan following, the agent adheres to a preformulated plan unless signals of plan failure are detected (Wang et al., 2023e). The action space is fundamentally divided between leveraging internal knowledge—guided by planning, conversation, and common-sense understanding capabilities—and external tools. These external tools might include leveraging external APIs like the LLM-powered chemistry engine ChemCrow, which utilizes multiple expert-designed tools for chemistry (Bran et al., 2023), as well as data- and knowledgebases or models (Wang et al., 2023e).

The Action Impact Module in LLM-based autonomous agents can lead to various outcomes, including changes in the environment, alterations in internal states, or the initiation of new actions (Wang et al., 2023e). This overview presents a general architecture that serves as the 'hardware' of an intelligent system, designed to accomplish specific tasks. However, akin to the need for software resources, agents may require task-specific skills and experiences that they initially lack. Therefore, agent capability acquisition is essential for creating versatile intelligent entities.

Agents can be fine-tuned using human-annotated datasets, LLM-generated datasets, or real-world datasets, equipping them with the necessary specialized resources (Wang et al., 2023e). In traditional machine learning, models acquire capabilities by learning from datasets, with knowledge encoded in the model parameters. The era of LLMs introduced new methods like fine-tuning model parameters and prompt engineering. The current era of agent development also offers the possibility of designing evolution mechanisms through 'mechanism engineering.' This broad concept encompasses the introduction of specialized modules, novel working rules, and other strategies to enhance agent capabilities (Wang et al., 2023e).

The use of human language as an operating logic in LLM-based agents opens a vast array of possibilities for fine-tuning and modeling. The abundant availability of language data, combined with its versatility, descriptive power, and inherent ambiguity, can be effectively harnessed in these agents.

To illustrate the application of mechanism engineering, several examples will be presented. These examples showcase innovative approaches to enhancing LLM-based agents beyond traditional fine-tuning and prompt engineering methods.

In the field of autonomous agent development, a variety of sophisticated strategies are being employed to enhance their capabilities. One such method is crowd-sourcing, where different agents each propose a solution to a specific question. If their responses vary, each agent then incorporates the solutions of the others to iteratively update their response. Another strategy is experience-accumulation, where the agent creates a skill library by storing necessary actions for solving specific tasks. This library is accessible for similar future tasks, with skills continually refined based on environmental feedback and the agent's self-assessment.

Self-driven evolution is another intriguing approach. In this method, agents set their own goals, gradually improving their capabilities through environmental exploration and feedback from a reward function (Wang et al., 2023e).

The implementation of curiosity in this context can introduce random yet meaningful behavior, similar to human unsupervised learning, facilitating a more natural learning process (Franklin, 1997).

To address the limitations of current supervised and reinforcement learning methods, which are prevalent in real-world applications but relatively inefficient compared to human learning, researchers are investigating latent variable energy-based models. These models are particularly promising for dealing with high-dimensional real-world data. Unlike current probabilistic models, they focus on learning the underlying data distribution, thereby fostering an understanding of data causation. This advancement is pivotal for the development of virtual and physical autonomous agents that need to grasp 'common-sense' and 'folk psychology'—essential components for exhibiting human-like intelligence in the next generation of agents (Dawid and LeCun, 2023).

LLMs have significantly lowered the barrier to writing software scripts, leading to a surge in the creation of applications, algorithms, and models. A notable example is the open-source software ChatDev, a virtual chat-powered software technology company. ChatDev follows the waterfall model, segmenting the software generation process into designing, coding, testing, and documenting phases. In each phase, multiple agents with different roles are recruited, and tasks are broken down into atomic subtasks. Here, two agents engage in context-aware, multi-turn discussions to propose and validate solutions. ChatDev has showcased remarkable efficiency and cost-effectiveness (Qian et al., 2023).

MetaGPT represents another innovative framework, introducing a meta-programming approach to LLM-based multi-agent collaboration. It incorporates standardized operating procedures into prompts to facilitate structured coordination. This system adopts an assembly line paradigm, where an anchor agent assigns diverse roles to various agents, effectively deconstructing complex multi-agent collaborative problems (Hong et al., 2023).

The open-source framework agents is designed to enable non-specialists to deploy advanced autonomous language agents with minimal coding. It offers an extensive library and promises features like long-short term memory and symbolic control. This framework encompasses agents, standard operating procedures, and environment as its major classes (Zhou et al., 2023). Similarly, Camel's role-playing framework provides a scalable method for studying cooperative behaviors and capabilities in multi-agent systems (Li et al., 2023a).

Open-source platforms like AgentSims (Lin et al., 2023a) and Gentopia (Xu et al., 2023a) are being developed to create, evaluate, and share general autonomous agents. While AgentSims serves a broader purpose, Gentopia specifically focuses on tool usage as a central feature for real-world applicability. These platforms aim to improve flexible customization, collaborative democratization, and holistic evaluation.

Virtual worlds provide ideal environments for testing autonomous agents, with human players often serving as benchmarks. One such environment is the popular game Minecraft, which has been utilized for this purpose. A significant development in this realm is Voyager, an open-ended embodied agent equipped with large language models. Designed for autonomous and continuous exploration, skill acquisition, and discovery, Voyager is built on three key components: an automatic curriculum for maximizing exploration, a skill-library of executable code for complex behaviors, and an iterative prompting mechanism. This mechanism incorporates execution errors, environment feedback, and self-verification for program

improvement. Notably, it includes a ChatGPT 4 powered agent acting as a flexible 'devil's advocate' (Wang et al., 2023a).

ConAG, a reusable framework for conscious software agents, currently in use by the US Navy, is based on workspace theory and the action selection paradigm. It features an attention manager module that gathers information and updates memory, broadcasting to various modules such as behaviors, consciousness, emotions, learning, metacognition, and perception. These modules are organized in a complex hierarchical blackboard architecture. The consciousness module further manages sub-modules like focus GUI and error handling, which, in turn, engage other modules. While ConAG presents an inspirational architecture, its actual code remains proprietary (Bogner et al., 2023).

AgentVerse, designed to orchestrate a collaborative group of expert agents, has shown improved efficiency in tasks like text understanding, reasoning, coding, tool utilization, and embodied AI compared to single-agent setups. Interestingly, it also exhibits emergent collaborative behaviors specific to its multi-agent configuration (Chen et al., 2023d).

In late September of this year, the open-source network OpenBMB released XAgent, an open-source platform for building complex task-solving autonomous agents. XAgent trained a cutting-edge BERT model using the IMDB dataset, leveraging deep learning to analyze movie reviews and assess public sentiment about specific films (XAgent, 2023).

The capability of autonomous agents to communicate *via* natural language interfaces, or other symbolic languages, paves the way for the formation of 'societies of minds.' These frameworks, which are anticipated to exhibit emergent intelligence through communicating and cooperating computational modules, can interact with independent neural network-based specialists. Consequently, autonomous agents have the potential to self-organize into complex societal structures. With an increasing number of autonomous agents, particularly those designed for generative and recruitment functions, entering the virtual domain, it is foreseeable that soon billions of agents, including humans, will form a heterogeneous society of minds (Zhuge et al., 2023). The advent of autonomous agents participating in a global 'infosphere' presents a myriad of intriguing ideas and questions. Among these, the computation of problems via 'mindstorms' of globally distributed actors stands out. This leads to broader considerations about how problems, hierarchies, and organizational structures within the infosphere will be defined and perceived. Key questions arise: What forms of hierarchy will develop? How will actors be able to 'poach' autonomous agents? How will the

concept of open-ended evolution be implemented, particularly in a manner that aligns with human needs and functionalities?

In light of these considerations, there is a growing argument that attention should shift more towards the agents themselves, rather than focusing solely on human-centered alignment. This perspective advocates for the establishment of 'agent social sciences,' a field dedicated to understanding the social dynamics and behaviors of autonomous agents within these complex systems (Bai et al., 2023a).

In January 2024, a significant step towards the widespread distribution of autonomous agents was observed with OpenAI's launch of the ChatGPT store. This platform enabled users to create custom versions of GPTs, which were minimally fine-tuned versions of ChatGPT, and make them available for wider use (ChatGPTs Store, 2024). Accompanying this development, numerous commercial products, initially starting as ChatGPT plugins, entered the market. These products, such as ScholarAI, a scientific research assistant, are designed as conventional application interfaces with ChatGPT integrated as a core component (ScholarAI, 2024).

2.3.2.2.3.3 Polymorphic Applications and Mission-driven programming

A significant advancement in AI is the emergence of polymorphic applications capable of improving upon their own architecture. These applications integrate agents that operate using various evolutionary techniques and methods already established in the field of artificial intelligence, such as Particle Swarm Optimization and Genetic Algorithms. The progression in this area is leading towards these systems writing novel, self-improving algorithms. However, this raises concerns about ensuring that such models align with anthropocentric needs and values.

Following this, an overview is presented of new paradigms driving the development of more intelligent, robust, and adaptable software systems.

The completion of the writing phase coincided with the introduction of MemGPT, a groundbreaking development in AI architecture. MemGPT features an operating system-inspired hierarchical structure, using external and main context analogously to RAM and hard disk memory. This design, combined with an event-based control flow, enables MemGPT to manage unbounded context within finite context windows. While successfully demonstrating

the potential of LLMs as interfaces for operating systems and applications, the creators of MemGPT also highlighted its value as a polymorphic application. The title of their publication, "Towards LLMs as Operating Systems," aptly encapsulates this vision (Packer et al., 2023).

January 2024 marked the debut of Rabbit R1, the first manifestation of what may be a series of polymorphic operating systems using LLMs as interfaces. The Rabbit R1 is a handheld portable device, operable via vocal interaction, designed to be a more intuitive alternative to smartphones. Leveraging a large action model, it automatically fulfills tasks, representing an early example of the widespread adoption of omnipresent personal assistants and the all-pervasiveness of LLM-enabled edge computing interfaces. The Rabbit R1's popularity and rapid sell-out after its unveiling at CES 2024 highlight the growing demand for such innovative AI-powered devices (Rabbit R1, 2023).

The open-source project OpenInterpreter, which released its second version in January 2024, serves as a compelling example of the evolving landscape in human-computer interaction. Running locally, OpenInterpreter symbolizes a significant step towards natural language interfaces becoming the next generation of human-computer interaction. This advancement underscores a pivotal shift in the nature of computing, particularly towards heterogeneous and specialized computing architectures and landscapes. OpenInterpreter's development and release illustrate the potential for more intuitive and seamless interfaces in computing (OpenInterpreter, 2024).

2.3.2.2.3.3.1 Mission-oriented Programming

transitioning from procedural to object-oriented programming. Now, with the advent of machine and deep learning technologies, another paradigm shift is emerging: the transition from object-oriented to mission-oriented programming. This new paradigm is poised to revolutionize the conception and development of software applications.

An example of polymorphic computing architectures that align with this new paradigm is the Gingko framework. Gingko is a modern C++ math library designed for scientific high-performance computing. It specializes in sparse linear algebra, particularly for graphics

processing units. However, its library design is such that it can be readily extended to other algorithms and hardware architectures. This flexibility is achieved by separating core algorithms from architecture-specific backends, making Gingko a versatile tool in the realm of high-performance computing (Anzt et al., 2022).

The concept of polymorphic computing architectures as autonomous agential frameworks is gaining clarity, as evidenced by statements from industry leaders. Microsoft CEO Satya Nadella highlighted this trend, stating that their operating system and applications are increasingly adopting the form of interfaces using natural language, backed by a reasoning engine. He also predicted a 10% increase in GDP, attributing this growth partly to the ease of application development in the future (Microsoft Inspire 2023 Keynote Speech, 2023).

2.3.2.2.3.3.2 Service Providing and polymorphic agential networks

The evolving direction of our economy can be exemplified by Amazon.com Inc., a dominant player in online retail and cloud computing. In July 2023, Amazon announced that it would not only employ a variety of generative models for powering its customer service and possibly its logistic administration but also provide access to these models for wider applications. This move is expected to facilitate the adoption of such technologies across various industries, including chatbots, virtual assistants, and content generation (Wes Roth - AI News, 2023).

Andreessen Horowitz, a renowned tech investor, has expressed a firm belief that AI will revolutionize personal finance management through consumer robot process automation. They foresee financial platforms actively managing user accounts, including bank accounts, investment portfolios, loans, and credit cards, on behalf of the user, indicating a significant shift in how financial services operate (Wes Roth - AI News, 2023).

The creation of applications based on Large Language Models (LLMs) has seen a significant uptick, thanks in part to the open-source Python package LangChain. LangChain has facilitated the rapid and easy development of prototypes. Following this, LangSmith was introduced as a unified platform for debugging, testing, evaluating, and monitoring LLM applications. LangSmith has fundamentally lowered the barrier for advancing prototypes to the production

stage. This is particularly notable in sectors demanding high accuracy, personalization, and security, such as financial products. LangSmith exemplifies how LLMs are swiftly being adopted across various sectors, offering a low entry barrier for diverse applications (LangSmith, 2023).

These developments suggest a trend towards increasingly heterogeneous yet interconnected polymorphic agential networks, operating on behalf of various clients within a global infosphere.

2.3.2.2.3.5 Robotics and Autonomous Devices

Highlighting the rapid progression in the field of artificial intelligence, Google Deepmind's Robotic Transformer 2 (RT-2) stands out as a remarkable example. RT-2 is a vision-language-action (VLA) model capable of learning from both web and robotics data, translating this knowledge into generalized instructions for robotic control. The introduction of RT-2 followed shortly after Deepmind's Gato, showcasing the incredible pace of advancements in AI. Trained on web-scale datasets, RT-2 is proficient in recognizing visual and various language patterns, representing a significant leap in the capabilities of autonomous robotic systems.

RT-2 demonstrates remarkable generalization capabilities, with enhanced semantic and visual understanding that extends beyond the robotic data it was initially exposed to. The model can interpret novel commands and respond to user instructions by performing rudimentary reasoning tasks. This includes reasoning about high-level descriptions or object categories, and the model integrates chain-of-thought reasoning, allowing it to deduce, for instance, suitable objects for improvised tools or appropriate beverages based on specific scenarios. RT-2's ability to consider an object like a rock as an improvised hammer or choose an energy drink for a tired person illustrates its advanced multi-stage semantic reasoning. The model is envisioned as the software driving a general-purpose physical robot, capable of reasoning, problem-solving, and interpreting information to execute a wide array of complex real-world tasks (Deepmind's RT-2, 2023).

By autumn, the collaborative efforts of 21 institutions globally culminated in the development of an open, large-scale dataset for robot learning. This dataset is instrumental in enabling the learning of generalized robot policies applicable across diverse behaviors, robot

embodiments, and environments. It marks a significant step towards the realization of autonomous generalist robots (Abhishek Padalkar et al., 2023).

Furthermore, NVIDIA together with Stanford University presented a highly significant model with MetaMorph, a Transformer based approach to learn a universal controller over a modular robot design space, introducing combinatorial generalization capabilities by treating robot morphology as just another modality on which the output can be conditioned (Gupta et al., 2022).

Robots and autonomous devices are poised to permeate various aspects of human society more extensively. These entities, in forms ranging from humanoids and vehicles to animal-like entities and even integral parts of buildings, are set to infiltrate terrestrial domains and space. Their presence in robotic process automation, whether as swarms or single entities, signals their imminent role as a key sector in general automation (Matthews and Greenspan, 2020). Advancements in the interconnectedness of devices, the Internet of Things (IoT), and wireless sensors, coupled with progress in artificial intelligence, blockchain technology, and robotic engineering, are driving the development and establishment of physical autonomous entities. These advancements are contributing to a growing presence of autonomous systems in various sectors (Haseeb et al., 2023, Thangavel et al., 2023, Biswas and Wang, 2023). Improvements in safe learning are particularly promising for the increased use of robots in proximity to humans (Brunke et al., 2022), and it's becoming evident that the widespread introduction of humanoid robots is on the horizon (Humanoid robots, 2023).

Autonomous driving and intelligent vehicles represent a significant market, driven by the convenience, safety, and economic benefits they promise. The interest and research efforts in this area are escalating rapidly (Chen et al., 2023a). However, challenges remain, particularly regarding privacy and security vulnerabilities in network-based systems like autonomous vehicles (Bendiab et al., 2023). Furthermore, the high safety standards required for urban deployment, coupled with the need to process and categorize vast amounts of data, are major hurdles in establishing trustworthiness in autonomous systems (Sifakis and Harel, 2023).

Specific fields and applications are witnessing early adoption of autonomous systems, such as satellites, logistics, agriculture, construction, mining, military, and industrial production. These sectors benefit from either reduced data complexity, lower security risks, or significant

efficiency gains (Deng et al., 2023a, Groll et al., 2019, Ha et al., 2019, Thangavel et al., 2023, Biswas and Wang, 2023, Marinoudi et al., 2019).

Robotic autonomous systems for earthmoving activities, for example, are leading practical applications of advancements in frontier engineering sciences. Their significant value for large-scale operations in construction, mining, and military applications has garnered considerable attention (Groll et al., 2019, Ha et al., 2019, Kim and Chi, 2019).

Urban environments present particularly challenging conditions for autonomous systems due to the intense variety of data and interactions, as well as the high density of human population. However, these environments also offer significant potential for efficiency improvements, wealth generation, and enhanced living conditions. The concept of transforming entire cities into distributed robots has been proposed, reflecting the immense scope of potential applications in urban settings (Jacob, 2015). Recent developments include the commencement of autonomous vehicle services in San Francisco and the announcement of drone delivery networks handling millions of deliveries by mid-2024, offering cost-effective alternatives to ground transportation (Wing Drones, 2023, Autonomous Taxis, 2023). Research is ongoing in areas such as collaborative fleet maneuvering to support these initiatives (Wang et al., 2023d).

In the realm of surveillance and governance, the application of robotics and automation is a sensitive issue (Macrorie et al., 2021). China is at the forefront of this, pushing the boundaries of surveillance technologies (Surveillance, 2023).

Additionally, there is a growing body of research and implementation of robots for educational purposes (Anwar et al., 2019), as well as in social and medical care (Macrorie et al., 2021).

The development and release of humanoid robots are on the rise, with an increasing number of companies investing in this area (Humanoids, 2023). Household service robots, in comparison to their industrial counterparts, face a broader range of challenges. Their roles are inherently multimodal and varied, and besides technical requirements, there are significant questions regarding their interaction with humans, including the alignment with culture-specific normative behaviors (Lee, 2021, Li et al., 2019, Zhong et al., 2021, Dorigo et al., 2020).

Swarm robotics, a field drawing significant inspiration from biological systems, is an area of particular interest due to its versatility, wide-ranging applications, and anticipated future

importance. Demonstrating self-organization through stigmergic and local interactions, swarm robotics is a clear manifestation of swarm intelligence observed in nature (Dorigo et al., 2020). The field of swarm robotics holds particular interest in the context of this work, not only because of its versatility, far-reaching applications, and future importance, but also due to its biological parallels. Analogous to the way a biological cell is represented by an agent in the virtual realm and serves as a functional unit in robotics, the concept of the swarm finds representation in both biological systems and collaborative agential frameworks in virtual reality. This parallelism highlights the emergence of holobiotic systems, characterized by their interconnected and decentralized organization, forming dynamically fragmented entities that act as collaborative components of a superorganism (Floreano and Lipson, 2021, Dorigo et al., 2021, Kolp et al., 2006, Schader and Luke, 2021). Designing and implementing effective robot swarms is recognized as one of the greatest challenges and most promising research areas in current robotics (Dorigo et al., 2021). Advances in soft robotics and the increasing deployment of drones have led to predictions of imminent widespread use of drone swarms in sectors such as agriculture, maintenance, and military reconnaissance. This is expected to be followed by maritime and deep-sea deployments for ecological monitoring and exploration. Within a decade, the urban deployment of pet- or insect-like robot swarms is anticipated, enhancing capabilities in local environments. Moreover, the first space exploration missions on the Moon and Mars are projected to include miniature rover swarms, significantly expanding the scope of exploration. Looking forward, it is estimated that within two decades, millimeter- and microscopic-scale soft-bodied robot swarms will be employed in agricultural fields for pest control, in aquatic environments for microplastics collection, and in clinical trials for targeted drug delivery in humans (Dorigo et al., 2020).

Recent developments in robotics have led to the creation of ultrafast transfer bionic vehicles. These vehicles are designed to reach interstellar space in less than six years, marking a significant milestone in space exploration technology (Karlapp et al., 2023).

Additionally, teleoperated humanoid robots are showing a wide range of potential applications, from space missions to telenursing, with the theoretical foundations already established (Darvish et al., 2023). In the agricultural sector, the application of robotics is making substantial progress. Various types of robots are performing diverse tasks, including fieldwork, husbandry, fruit picking, and crayfish processing (Cheng et al., 2023b). This

advancement continues a trend that began in the early 2000s when fully automated systems for agriculture, from seeding to harvest, were first designed.

The healthcare sector is also benefiting from robotic technologies, with applications in logistics, social care, and functional prosthetics being actively researched (Kyrarini et al., 2021).

In terms of industrial applications, the annual installation of robots has seen a dramatic increase. From 2016 to 2021, the number of newly installed units doubled, reaching over half a million in 2021. China leads this growth, accounting for about half of these installations, and is currently ranked fifth globally in terms of robot worker density in the manufacturing industry (Robot Installation, 2023, Robot Density, 2023). The automotive industry remains the largest employer of robotic labor (Cheng et al., 2019).

Furthermore, robotics and automation are increasingly being recognized as key drivers towards sustainable technology development. This has led to a growing interest in sustainable material approaches for electronic devices and robots, reflecting a shift towards environmental consciousness in the field (Hartmann et al., 2021).

The field of robotics is currently experiencing significant advancements in the fabrication of soft materials. Notably, magnetic soft materials have been successfully 3D printed, utilizing techniques based on light or extrusion with magnetization patterning or programming. Additionally, micromolding and microassembly methods have contributed to these developments. This progress has led to the creation of a diverse array of magnetic manipulation platforms, catalyzing the development of small-scale untethered soft robots. These robots are capable of various forms of propulsion and can engage in active origami and metamaterials, which have applications in unconventional soft robotics. Moreover, these advancements extend beyond robotics. They include the creation of acoustic metastructures with tunable bandgaps, programmable and reconfigurable surfaces, and soft and flexible electronic devices. One of the most notable areas of application for these soft materials is in the medical field, particularly for targeted drug delivery and minimally invasive procedures. This demonstrates the wide-reaching implications and potential of these developments in soft robotics (Kim and Zhao, 2022).

While significant strides have been made in modeling soft robotics, the full potential of real soft robots, particularly those with unparalleled motor capabilities, is yet to be fully realized (Della Santina et al., 2023).

In the realm of biological soft robotics, molecular motors have been leveraged in impressive proof-of-concept experiments, demonstrating applications across nanometer to centimeter scales (Feinberg, 2015). Notably, skeletal muscle tissue integrated within a collagen structure has been engineered in a biohybrid robot, capable of movement in air and manipulating weights (Morimoto et al., 2020).

The past decade has witnessed a surge in research on biohybrid robotics, with a focus on microorganism-bots, tissue-based biohybrid robots, and cyborgs. This field is poised for exponential growth, driven by the integration of novel materials, increased computational capabilities for modeling biological systems, and advancements in synthetic biology (Webster-Wood et al., 2023).

Recent innovations in robotics have led to the creation of *in vitro* biological robots generated from *Xenopus laevis* cells. These biological robots demonstrate coordinated locomotion and self-organization without the need for scaffolds or microprinting. They exhibit emergent group behavior and possess the remarkable ability to heal themselves, making them a promising new avenue in the field of robotics (Blackiston et al., 2021). The feasibility of simulating the combined behavior of soft components with varying material and actuation properties has opened up new possibilities. This progress, facilitated by evolutionary search methods and advancements in bioprinting, suggests a future where these biological robots can be designed and constructed with diverse functionalities.

Given the rapid advancements in machine learning, soft body simulation, bioprinting, the field of synthetic biology, as well as the ease of expressing novel proteins, synthetic biology pathways and computational circuits, the potential applications of these biological robots are extensive. They hold promise as intelligent drug delivery systems or for performing internal surgeries. When equipped with enzymatic, sensory, and deformation functions, these robots could be utilized to identify and process toxic or waste products, or even collect specific compounds of interest. The possibility of equipping them with reproductive organs could allow for their use at scale in various settings.

In a biomedical context, these robots, created from a patient's own cells, have the potential to perform intricate tasks such as removing plaque from arteries (Kriegman et al., 2020, Kriegman et al., 2021). Additionally, advancements have been made in multicellular engineered living systems, such as biohybrid flagellar swimmers actuated by neuromuscular

units, further showcasing the versatility and potential of biohybrid robotics (Aydin et al., 2019).

"Just as the deep principles of physics and thermodynamics apply across scales, from galaxies to the soft matter of cellular processes, biology is moving from zoology to unraveling the fundamental laws of life across natural, synthetic, and exobiological systems. Computer science and robotics can lead the way, with their early emphasis on functionality and realizability, not material implementation" (Blackiston, 2023).

Blackiston et al. present a compelling argument that applying the principles of computability and programmability to biological materials, akin to conventional robotic materials, has the potential to significantly expand our understanding of life. This approach paves the way for creating technological machines that leverage biology's vast library of functions and configurations, opening new frontiers in robotics and biological studies.

In the realm of biomimetics and wave utilization, recent developments have been marked by the creation of spiral-shaped microrobots. These microrobots are inspired by Spirochete bacteria and are capable of responding to sound stimuli from outside the body. They mimic the spiral motion of natural microswimmers, especially in environments characterized by low Reynolds numbers, demonstrating an innovative approach to propulsion in microrobotic systems (Deng et al., 2023b).

Another notable advancement is the development of Eureka, an LLM-powered algorithm designed for human-level reward design in evolutionary optimization. Eureka has been successfully applied to enable complex skill acquisition through reinforcement learning. A significant achievement of this technology was enabling a simulated Shadow hand to perform pen spinning tricks, a task previously unattainable by robotic systems. This represents not only a milestone in robotics but also a major advancement in addressing difficult, open-ended search problems (Ma et al., 2023b).

When revisiting the manuscript for proof-reading in January 2024, the previously anticipated fast progress and swift developments regarding humanoid robots already had been substantiated by a staccato of autonomous robots showcasing quite remarkable capabilities and feats like zero-shot abilities in real-life scenarios, giving credence to the imminent advent of wide-spread robot employment. Furthermore, Google's Deepmind together with Stanford University released their code as well as a hardware manual for their impressive and low-cost

open-source robotic system ALOHA, which will further fuel open-source endeavors and thus wide-spread distribution of diverse robotic systems (Fu et al., 2024, Tesla- Optimus, 2024).

2.3.2.2.3.6 Sensors

As virtual and augmented reality systems become increasingly accessible, affordable, and functional, there is great interest in expanding the sensory capabilities of systems taking user input, as well as in creating sensations for the user.

Various innovative approaches to haptic sensors have been brought forward, as for example in the form of washable, stretchable, ultrathin triboelectric, skin-like, and self-powered nanogenerators (Jiang et al., 2021). These soft devices are designed for textile integration and are capable of providing realistic sensations, biosensing, thermo-haptic feedback, and feel-through haptics, enhancing the emulation of tactile experiences (Yin et al., 2021). In addition to improvements in existing touch-based, wearable, and skin-attachable haptic interfaces, research is advancing in the areas of mid-air and neuro-haptic interfaces. These interfaces aim to provide contact-free transfer of stimulations and sensations, further enriching the sensory experience in virtual environments (Yang et al., 2021).

Recent developments in sensory robotics have seen the creation of neuromorphic electronic nose systems. These systems feature artificial olfactory neurons that mimic the human olfactory system, including olfactory receptors, glomeruli, mitral cells, and interneurons (Han et al., 2022a). Additionally, novel concepts have merged touch and smell in robotics, exemplified by tactile-olfactory bionic sensing arrays integrated into mechanical hands. These hands have demonstrated robust object recognition capabilities in non-visual environments (Liu et al., 2022a). The evolving complexity in odor sensing and determination is rapidly improving, opening up numerous possibilities for analytical and medicinal applications (Jirayupat et al., 2022).

2.3.2.2.3.7 Engines and Virtual Reality

In the realm of virtual reality, the convergence of learnable game engines and real-world simulators is on the horizon. Learnable game engines, which are models trained on annotated videos with conditioning signals (Menapace et al., 2023), and real-world simulators like UniSim, capable of producing realistic synthetic data through generative modeling (Yang et al., 2023c), are at the forefront of this development. The integration of these technologies with movie and audio engines is expected to give rise to a comprehensive virtual reality experience. This virtual reality, envisioned to be based on anthropocentric sensory functions, appears to be within close reach, heralding a new era of immersive and interactive virtual environments. A prime example of recent computational advancements is seen in the field of weather forecasting. DeepMind's GraphCast, for instance, demonstrates the capability to predict global weather patterns with a resolution of 0.25° over the next ten days. This advancement showcases significant progress in handling large datasets and complex interrelations. It hints at the development of models that can integrate both stochastic and deterministic elements, a crucial feature necessary for generating realistic virtual worlds (Lam et al., 2023)

2.3.2.2.3.7.1 *Game engines*

In the realm of game engines, these software products and platforms provide developers with tools and pre-made solutions for foundational programming tasks in the creation of games and digitally augmented environments. Their utility, however, extends far beyond the gaming industry. Game engines are now widely used in architecture, manufacturing, public planning, film, television, and various fields related to artificial intelligence. They play a pivotal role in the creation of a virtual metaverse, representing a significant shift in cultural and economic realms from physical to virtual spaces (Jungherr and Schlarb, 2022). Described as the engine of twenty-first-century cultural production, game engines are central to this transformation. Their status as open-source platforms has sparked discussions about business strategies and potential risks, but their contribution to democratizing game development and empowering developers is widely acknowledged and praised (Nicoll et al., 2019).

Unreal Engine, developed by Epic Games, is a renowned 3D computer graphics game engine and creation tool written in C++. It serves a versatile role, being utilized for building simulations, editing videos and sound, and rendering animations. This engine, free of cost for projects generating less than 1 million US dollars in revenue, has been the backbone of many popular games.

The latest iteration, Unreal Engine 5.2, introduces an array of tools for crafting interactive and dynamic virtual worlds. One of its notable features is chaos physics, which enhances the realism of simulations by accurately representing elements such as rocks, bending leaves, and real-time fluid dynamics. The engine's chaos implementation adeptly simulates intricate details, such as a vehicle's suspension, the operation of electric motors on each wheel, and the tire's compression and deformation. Furthermore, Unreal Engine 5.2 boasts advanced sound resynthesis capabilities, ensuring that vehicle sounds are rendered with precision.

A significant addition in Unreal Engine 5.2 is the Substrate model, which elevates the creation of materials. This model allows for the composition and layering of materials with various shading models, resulting in complex, detailed materials featuring adaptive lighting and shading that dramatically enhance realism.

Unreal Engine 5.2 also introduces an experimental suite of procedural generation tools. Procedural generation, the process of algorithmically creating data rather than manually, is refined to be flexible, deterministic, and artist-driven in this release. This feature enables different procedural elements within a scene to communicate and interact, allowing for coherent and responsive environmental changes based on object manipulation.

Moreover, Unreal Engine 5.2 provides users with enhanced control over procedural content, introducing additional customizable user interface elements for manipulating these elements. The platform's active community plays a vital role, continually exchanging tools and content, contributing to the robustness and versatility of Unreal Engine (Unreal Engine 5.2, 2023).

Just a day after discussing the Unreal Engine 5.2 demo, which had been released only four months ago, a preview of Unreal Engine 5.3 was released, marking yet another leap in technology. This update brought considerable improvements to key features such as Lumen, the fully dynamic global illumination and reflections system, and Nanite, the virtualized micropolygon geometry system. These enhancements enable the creation of hyper-realistic and finely detailed graphics. Additionally, Unreal Engine 5.3 introduced a hierarchical generation feature, allowing for varied grid sizes within the same procedural content

generation graph and support for rule processing from external data. These advancements further enable highly complex and sophisticated interactions within virtual scenes.

A notable application of Unreal Engine was the photogrammetric reconstruction of the Lofoten, creating a high-fidelity model with 16k texture sets. This task, remarkably completed in less than a day, utilized various plugins like Ultra Dynamic Sky and Gaia, along with software like Adobe Lightroom and Photo Mechanic (Unreal Engine 5.3, 2023).

The Lofoten have been photogrammetrically reconstructed as a high-fidelity model with 16k texture sets in Unreal Engine in less than a day, employing various plugins like Ultra Dynamic Sky, Gaia and additional software like Adobe Lightroom and Photo Mechanic (Capturing Lofoten in Unreal Engine 5, 2023).

The integration of Google Maps *via* API into Unreal Engine demonstrates the engine's capability to generate terrain maps within minutes (Unreal Engine 5 - Google Maps API & Cesium, 2023).

Furthermore, the ease of creating photorealistic animation of real-world people raises concerns about the potential for misuse, particularly in the creation of deepfakes (High Quality Face Mocap in Unreal Engine 5, 2023).

The rapid evolution of AI-supported generation of 3D worlds explains the sustained interest in concepts like Meta's Metaverse and the well-timed introduction of augmented reality headsets by Apple, signaling the start of society's increasing immersion into virtual reality. This transition is further evidenced by the emergence of tutorials showing the integration of ChatGPT into Unreal Engine, demonstrating how the LLM can assist users in implementing sophisticated tasks like volumetric fog and object creation with text prompts (Unreal Engine - LLM assistant, 2023) and build engine objects with text prompts (Text To Engine Object, 2023). While prominent game engines like Unreal Engine and Unity offer free usage for non-commercial users, there is also a growing interest in completely open-source engines, such as Godot, which is gaining traction among developers (Godot, 2023).

The applications of game engines extend far beyond gaming, encompassing a wide spectrum of fields. These engines are invaluable for creating immersive animations in surgical training, developing the Metaverse, conducting wind energy simulations, producing movie animations, simulating space exploration, and rendering realistic depictions of Earth, among others. Their versatility and expansive use in diverse sectors highlight their growing importance in the technological landscape (El-Wajeh et al., 2022, Jungherr and Schlarb, 2022, Marcano and

Osborne, 2023, Masood et al., 2023, Menapace et al., 2023, Sergeevna, 2023, Sørensen et al., 2022).

2.3.2.2.3.7.2 Movie Engines

Runway Gen2 is an exemplary AI-leveraging video creation software that demonstrates the potential of AI in the field of video production. It can generate video sequences from text prompts or visual inputs, including those created by Stable Diffusion XL. The software is user-friendly and capable of producing impressive effects (Runway Gen2, 2023). Runway Gen2 offers a range of features including real-time style transfer, object removal, background replacement, and more. It can automate time-intensive tasks such as video stabilization, color grading, and frame interpolation, significantly enhancing the visual quality of footage. Additionally, it supports compelling video narrative creation through scene detection, shot sequencing, and intelligent captioning. The software is compatible with popular video editing platforms and is designed to facilitate collaboration among creatives (Runway Research, 2023).

A recent development that underscores the near-term challenges and potential dangers associated with AI-generated content is Fable's release of a fully autonomous episode of the animated series "South Park" created by its Showrunner AI (Maas, 2023, Showrunner AI, 2023). This AI utilizes a custom Stable Diffusion model for visuals and illustration, and employs ChatGPT with autonomous agents to handle character development, storyline, editing, and more. The AI system takes high-level user inputs such as titles, synopses, and major events, and autonomously creates a complete episode, demonstrating the advanced capabilities of generative agents in media production (Park et al., 2023).

The field of AI-driven creative industries is witnessing a remarkable surge in development, with companies ranging from established tech giants to burgeoning startups releasing papers and models at an unprecedented weekly pace (Singer et al., 2022). This rapid progression in AI technology is poised to significantly disrupt the film industry and likely lead to a substantial increase in content creation. The potential ramifications extend beyond the entertainment

sector, affecting industries such as training video production. Additionally, the proliferation of deepfakes and related scams is an emerging concern that is likely to escalate.

In the near term, AI is expected to play a crucial assistive and supportive role in creative industries, streamlining production processes and providing novel sources of inspiration (Anantrasirichai and Bull, 2022). However, looking further ahead, it is challenging to envision a scenario where AI does not occupy a central role in creative productions, especially as computational power continues to grow.

The exponential increase in synthetic media and data also feeds back into the advancement of deep learning frameworks. The generation of vast quantities of data, a key resource in AI, enables applications such as congestion detection in public places (Basalamah et al., 2023). A notable example is Synthesia, a service targeting teams creating training videos at scale. It claims over 50,000 companies as clients, offering comprehensive solutions for AI video generation, including avatars, video templates, and support for over 120 languages. Synthesia promotes the creation of 'professional videos without mics, cameras, or actors,' highlighting the evolving landscape of digital content production (Synthesia, 2023).

October 2023 marked a significant advancement in AI technology with the publication of 3D-GPT, showcasing an LLM-based agential framework capable of instruction-driven procedural 3D modeling (Sun et al., 2023).

Following this, in January 2024, TikTok released a comprehensive paper introducing their innovative model for robust monocular depth estimation, further expanding the capabilities of AI in image processing (Yang et al., 2024)

2.3.2.2.3.7.3 Image Engines

In the realm of image engines, Stable Diffusion recently unveiled Fabric, a user-interactive plugin. This tool allows users to provide feedback on images, indicating preferences to refine future search results, thus enhancing user experience and search accuracy (Stable Diffusion - Fabric, 2023).

Concurrently, there are ongoing efforts to develop methods capable of detecting forensic traces left by diffusion models, similar to those used for generative adversarial networks

(GANs) (Corvi et al., 2023). With the widespread adoption of Face ID technology and the prevalent visual presence of individuals on social media, new strategies are being researched to secure systems by differentiating real faces from AI-generated counterparts (Fang et al., 2023).

A notable breakthrough in image generalization technology is Perfusion, which facilitates image generation for personalized concepts with significant variations in appearance, pose, and context. Remarkably, it achieves this using a compact model of only 100KB per concept, without compromising the identity of the subject. Perfusion can also combine learned concepts at inference time, enabling the creation of scenes that portray multiple concepts side-by-side or even depict interactions between them. This advancement provides a slim and efficient model, greatly enhancing flexibility in the creative process guided by natural language (Tewel et al., 2023).

After this work had already been proof-read, Google introduced Lumiere, a text-to-video generation framework for synthesizing videos portraying realistic, diverse and coherent motion with a Space-Time U-Net architecture that generates the entire temporal duration of the video at once (Bar-Tal et al., 2024).

2.3.2.2.3.7.4 Audio Engines

While large-scale generative models have shown proficiency in generating high-fidelity text and images and solving tasks not explicitly taught, speech generative models still lag behind in terms of scale and task generalization (Le et al., 2023).

Music generation presents unique challenges, as it requires utilization of the full frequency spectrum and intricate harmonization. Music's complex structure, involving harmonies and melodies from various instruments, leaves minimal margin for error; human sensitivity to disharmony makes this task particularly demanding (Copet et al., 2023).

Meta has made significant strides in this domain with the introduction of MusicGen, a conditional music generator. This model can be conditioned on textual descriptions or melodic features, offering greater control over the output. MusicGen operates as a single language, single-stage model, processing multiple streams of compressed discrete music representation

as tokens in a unified step. This model represents a substantial leap forward in music generation, demonstrating high-quality output while reducing the number of autoregressive time steps through a codebook interleaving strategy. Meta has made MusicGen available as open-source, contributing significantly to the field (Copet et al., 2023).

Complementing MusicGen, Meta has also developed AudioGen, an autoregressive audio generation model conditioned on textual or audio prompts (Kreuk et al., 2022). It utilizes EnCodec for neural audio compression (D'efossez et al., 2022), employing a multi-band diffusion-based framework capable of generating various audio modalities from low-bitrate representations (EnCodec Preprint, 2023). Meta offers AudioCraft as an open-source, comprehensive codebase for audio AI research, positioning it as a state-of-the-art resource in the audio AI landscape (AudioCraft, 2023).

The field of generative models for music is experiencing rapid growth, with significant contributions from various organizations. Notable examples include OpenAI's Jukebox (Dhariwal et al., 2020), Google's MusicLM (Agostinelli et al., 2023), and SunoAI (Suno AI, 2023). These models illustrate the strong interest and continuous advancements in music generation technology.

Meta's recent contribution to speech generation, Voicebox, has been introduced as an open-source platform. It stands as the most versatile, text-guided, multilingual universal speech generation model to date (Le et al., 2023). Voicebox is a non-autoregressive flow-matching model, trained to infill speech based on provided text and audio context. Its applications are diverse, including mono or cross-lingual zero-shot text-to-speech synthesis, noise removal, content editing, style conversion, and generating diverse samples. Notably, Voicebox outperforms the zero-shot text-to-speech model VALL-E in terms of intelligibility and audio similarity, which was previously considered the industry leader (Le et al., 2023).

The advent of versatile generalist speech generation models holds significant potential across various sectors. For instance, they could provide a voice to individuals who are unable to speak or eliminate the need for typing when integrated with visual speech recognition systems (Hsu et al., 2022). Furthermore, the combination of cross-lingual zero-shot text-to-speech with speech translation models opens the possibility of speaking in one's own voice in different

languages. This advancement moves us closer to realizing a universal live translation tool that retains individual vocal characteristics (Le et al., 2023).

Content creation can be greatly enhanced by providing editing and speech-denoising productivity tools (Le et al., 2023).

While the myriad potential benefits of advancements in AI, are undeniable, it is crucial to acknowledge the potential for misuse and detrimental societal impacts, especially when it comes to output mimicking humans, like speech generation. A noticeable trend on platforms like YouTube involves videos with AI-generated speech, which adds a layer of immersiveness and credibility to the generated content, leveraging human dispositions. Though seemingly innocuous, this technology bears the risk of distorting public perception through the mass production of content that misrepresents frequency, relevance, and importance of certain topics or viewpoints.

The increasing potential for the automated mass production of deep fakes, produced with malicious intent, poses a significant threat. Recognizing this danger, efforts are underway to proactively detect and counteract such misuse. For instance, Meta's Voicebox can differentiate synthetic speech from real speech (Le et al., 2023), and similar to image generation technologies, proactive detection countermeasures, like embedding undetectable artificial fingerprints without compromising speech quality, are being developed (Yu et al., 2020).

On a personal note, the recent advancements in AI and sensory technologies resonate with an old idea of the author, the 'Dancing Organ'. This music engine creates audio output in real-time based on the operator's dance movements, with various body parts controlling different layers of the music. For example, hips and heels could generate bass lines, while fingers articulate solos and high-pitched melodies. This system would create music through a dynamic feedback loop in dialogue with the operator. Styles, motifs, and other musical elements can be directed via prompting to direct the framework of the symphony, introducing a high-level command interface. Thus, the Dancing Organ enables to compose music while simultaneously enjoying it and dancing to it.

2.3.2.2.3.7.5 Virtual Realities, Twin Worlds, and actively connecting Computing Instances like the Human Brain to the nfosphere

The realm of brain-computer interfaces (BCIs) is witnessing rapid advancements, encompassing both invasive and non-invasive techniques. While commercial ventures are primarily pursuing invasive methods (Peksa and Mamchur, 2023, Brain Computer Interface, 2023, Wes Roth - AI News, 2023), significant progress is being made in non-invasive approaches for recording brain waves and processing the resultant data (Han et al., 2023b, Na et al., 2022, Tang et al., 2023b). These developments are paving the way for more seamless and less intrusive integration of the human brain with digital environments.

In parallel, various methods for controlling neural activity are being explored. Closed-loop optogenetic control is a particularly active area of research, offering precise manipulation of specific cell types (Aydin et al., 2019, Emiliani et al., 2022, Entcheva and Kay, 2021, Rost et al., 2022, Zaaime et al., 2023). Additionally, non-invasive methods such as binaural beats, isochronic tones (Aparecido-Kanzler et al., 2021), focused ultrasonic wave modulation (Webb et al., 2023), and transcranial magnetic stimulation (Addolorato et al., 2012, Lin et al., 2021) are being investigated for their therapeutic potential -taking inspiration for example from traditional practices like meditation (Cozzolino et al., 2021) - and ability to influence brain activity.

Importantly, the integration of BCIs into daily life raises significant ethical and security concerns. A recent demonstration of a backdoor attack on transfer learning-based BCIs (Jiang et al., 2023d) underscores the need for robust security measures to protect against potential breaches and misuse. Key strides have been made in utilizing speech and motor imagery to induce interactions in BCIs (Tong et al., 2023). The pursuit now is to enable proactive participation using purely mental processes, a goal that hinges on the effective encoding and decoding of neural activities.

Significant progress in this direction includes the development of technologies like Cebra, which offers rapid and accurate decoding of natural videos from the visual cortex (Schneider et al., 2023). Similarly, MinD-Video has demonstrated the potential for high-quality video reconstruction from brain activity, utilizing continuous fMRI data (Chen et al., 2023e), or reconstructing Pink Floyd's *Another Brick in the Wall* from human auditory cortex activity using

nonlinear decoding models (Bellier et al., 2023). On a sidenote, multimodal brain activity is used to interpret the internal representation of multimodal video transformers.

Furthermore, multimodal brain activity analysis is being used to interpret internal representations within multimodal video transformers, further advancing our understanding of complex neural processes (Dong and Toneva, 2023).

While the complete realization of translating internally generated or externally induced percepts into external outputs is still on the horizon, these technological advancements set a clear trajectory towards achieving this ambitious goal (Le et al., 2022).

The metaverse is not a new concept, yet gained much traction from the end of 2021 onwards (Buchholz et al., 2022), fueled by online gaming and increasing investments of big tech companies in the development of virtual and augmented reality applications and devices such as virtual reality glasses, which can be seen as the next stage of mobile computing devices, as well as advancements in blockchain technology (Sparkes, 2021). Dozens of leading actors in the technology industry founded the metaverse standards-forum in 2022, to ensure interoperability, address concerns, and provide a platform for an open discourse (Metaverse Standards-Forum, 2023, Anderson and Rainie, 2022) p.94. The metaverse concept embodies a fully immersive virtual world—a platform more sensory and convenient than current internet forms—for socializing, working, and playing. Many tech industry leaders predict a rapid and significant rise in the metaverse's usage, value, and importance (Laeq, 2022). A noticeable trend is the integration of the real world with the metaverse, where Internet of Things advancements play a pivotal role. This is due to their growing significance and the inherent potential of connected objects being represented in the metaverse (Veeraiah et al., 2022). The gaming sector is another major contributor, exemplified by a live virtual show in Epic Games' Fortnite, which attracted over 10 million attendees. It is expected that gaming, entertainment, and pornography will be at the forefront, followed by sectors like education, business, social, and healthcare (Anderson and Rainie, 2022, p. 54). Presently, a considerable number of diverse open-source metaverse platforms exist (Open-Source Metaverse, 2023).

The rapidly increasing number of publications on mixed reality reflects diverse efforts. These include creating physically realistic mixed reality environments using thermodynamics-informed neural networks, employing generative AI for autonomous driving simulations in vehicular mixed reality metaverses with digital twins, and developing interfaces and taxonomic frameworks for human-robot interactions. There is also a focus on understanding

the myriad calibration, detection, tracking, and rendering functions, optimizing shopping experiences and advertising, and the extensive applications of mixed reality in healthcare and education, particularly for replacing costly training simulations. Additionally, visualizing network topology and activity enhances cyber team communication and situational awareness. Implementing human-robot interfaces for remote operations in hazardous environments, countering perceptual manipulation attacks, and visualizing suprasensory perception are other key areas (Acampora et al., 2023, Aguayo and Eames, 2023, Albeedan et al., 2023, Ask et al., 2023, Cassaing, 2023, Cheng et al., 2023d, Hernández et al., 2023, Jain et al., 2023, Killeen et al., 2023, Numan et al., 2023, Rokhsaritalemi et al., 2020, Siripurapu et al., 2023, Speicher et al., 2019, Szczurek et al., 2023, Walker et al., 2023, Xu et al., 2023b, Zhang et al., 2023).

The company 'planet' has made significant strides by providing global daily Earth data through a vast fleet of miniature image satellites, invigorating the Earth observation industry. Their aim to index and make Earth's physical space searchable and retrievable, akin to how Google and other search companies have digitized the internet, is groundbreaking (Planet Satellites, 2024). These advancements naturally align with the decreasing barriers to providing orbital and sub-orbital acceleration, as exemplified by the company Spinlaunch, which utilizes centrifugal force (Spinlaunch, 2023). Deep learning has significantly transformed satellite mapping, remote sensing, and monitoring. Its applications are diverse, ranging from monitoring illegal deforestation to tracking kelp and mammal movements in heterogeneous landscapes, among many other uses. The advancement in this technological area is crucial for real-time Earth resolution. It is also pivotal in the advancement of full-scale automation and parallel virtualization, as evidenced by recent studies (Gendall et al., 2023, Paolo et al., 2024, Wu et al., 2023f, Han et al., 2023c, Joshi et al., 2023).

The datasets thus provided will in turn further fuel the generation of synthetic data, which by now has been repeatedly demonstrated to suffice for deep learning models (Mitra et al., 2023). The such generated large datasets are essential for the continuous enhancement of total resolution and resolution in 'zoomed-in' - Autodesk's Molecular Maya comes to mind - and 'zoomed-out' layers. Moreover, these advancements aid in the representation and analysis of real-world scenarios as well as in the development of twin and synthetic worlds, extending into the omniverse (Azizi et al., 2023, Basalamah et al., 2023, Boutros et al., 2023, Conde et al., Fang et al., 2023, Metzler et al., 2023, Tang et al., 2023a, Yang et al., 2023d).

These developments signify rapid progress in advancing a proactively integrative and adaptive holobiontic design of Earth. Current initiatives extend beyond virtual simulacra. For instance, Altown, inhabited solely by generative AI-powered individuals, and recent OpenAI acquisitions like Biomes, hint at a future where virtual landscapes will, analogous to the physical world, host autonomous and dynamically autogenetic artificial entities. More information on these developments can be found in their respective documentation (Altown, 2024, Biomes, 2024).

2.3.2.2.3.8 AI and Open-source

In contrast to the internet revolution, which leveraged relatively inexpensive hardware, the current AI revolution significantly depends on costly components and high energy demands.

Open-source models not only provide the significant benefit of being free, but their openly accessible code allows for interactive engagement by a diverse range of actors such as universities, enthusiasts, companies, and others in modifying and developing the code. In the realm of Large Language Models, open-source offers the critical advantage of enabling the creation of uncensored models. This is in stark contrast to proprietary models, which undergo intensive curation to adhere to safety and compliance standards.

There exists a substantial community effort dedicated to fine-tuning open-source foundational LLMs. A notable example is the recently released Llama 2 from Meta, which is regularly benchmarked against its peers as shown on the Huggingface leaderboard (Huggingface, 2023).

Moreover, tools such as the 'auto train-advanced' Python package have been developed to facilitate the fine-tuning of models like Llama-2 using one's own data. This package requires minimal input to utilize .csv and other file formats for fine-tuning open-source LLMs (Autotrain-advanced, 2023).

Shortly after the release of LLaMA-2, a plethora of fine-tuned models and tutorials emerged, demonstrating its adaptability. Notably, resources on developing an 'intelligent and efficient medical chatbot' for CPU machines became available. These tutorials highlight the use of the

Sentence Transformers package for embedding, Faiss CPU for vector storage, and the chainlit library to integrate LLaMA-2 as a conversational interface (Medical Chat Bot, 2023).

Moreover, the open-source space has seen the emergence of numerous jailbreaks and uncensored LLMs. A significant advancement in adversarial attacks against aligned language models was reported in late July 2023. The new approach focuses on finding adversarial suffixes that can be attached to a variety of queries. This method increases the likelihood of eliciting affirmative responses through a combination of greedy and gradient-based search techniques. The adversarial prompts generated have shown high transferability, even affecting publicly released proprietary LLMs under strict scrutiny and severe restrictions. The paper 'Universal and Transferable Adversarial Attacks on Aligned Language Models' and its accompanying Github repository demonstrate that this method is particularly effective with Generative Pretrained Transformers, such as ChatGPT. This effectiveness is likely due to ChatGPT's training on Vicuna, which itself is based on outputs from ChatGPT (Zou et al., 2023). Mustafa Suleyman bolsters confidence in open-source efforts, remarking that the open-source scene "is on fire." He notes that leading AI companies are consistently only six months ahead, illustrating a dynamic and rapidly evolving field (Suleyman - open-source, 2023)

The increasing significance of edge computing, alongside the trend towards heterogeneous computing, acts as strong supporters of open-source initiatives. By January 2024, several proficient tiny language models were already available. For instance, Phi-2 was introduced alongside the influential paper '*Textbooks are All You Need*'. This paper underscored the value of high-quality data and the corresponding feasibility of training highly capable tiny models. Additionally, tinyLlama became openly accessible (Yuan et al., 2023, Zhang et al., 2024, Gunasekar et al., 2023, Phi-2, 2023).

A briefly mentioned yet intriguing topic is prompt injection attacks. These are attempts to manipulate large language models to divulge its system message or otherwise restricted information. Such attacks are especially problematic for proprietary models. The widespread incidents involving industry leaders underscore the still-developing and fragile architecture of applied large language models. This situation underscores the critical need for developing robust security measures (Abdelnabi et al., 2023, Choi et al., 2022, Greshake et al., 2023, Pedro et al., 2023, Yan et al., 2023b, Yip et al., 2024).

2.3.2.2.3.9 Computing the biological realm

This chapter aims to demonstrate how the logic, syntax, and vocabulary of biology can be compared and related to other logically perceived human systems, such as language or intelligence architectures. This concept has been realized in various ways, such as using a protein language model to learn latent structural information from unaligned proteins (Chowdhury et al., 2022). Consequently, biology is computable in a manner akin to these systems, paving the way for a profound understanding and the capability to manipulate and design within the biological realm. This potential is augmented by increasing computational power and advanced deep learning architectures.

To illustrate the value of computational assistance, consider the complexity of a single human genome. It comprises approximately 3 billion nucleic acid base pairs, around 20,000 to 25,000 genes (with about 97 % being non-coding), and a human body consists of roughly 3×10^{13} cells. This includes about 100 billion neurons, approximately 210 different cell types, and the human holobiont harbors an estimated 10^{15} bacterial cells. This count does not include the number of fungi, archaea, and viruses, which remain unquantified to date. Consequently, the precise value of the human hologenome has yet to be determined⁹.

Shannon's number provides a conservative lower bound estimate for the game-tree complexity of chess, calculated at about 10^{120} possible games.

A standard 19x19 Go board offers approximately 10^{170} possible positions.

These figures dwarf the estimated number of atoms in the observable universe, which stands at around 10^{80} .

A protein composed of a 100 amino acid sequence can potentially exhibit a maximum of 3^{198} different conformations, as suggested by Levinthal's paradox.

This staggering complexity underscores why Deepmind's Alpha series has evolved from mastering chess and Go to becoming the unrivaled champion in protein folding prediction.

The preeminent luminary within this field, Alphafold 2 (Jumper et al., 2021, Jumper et al., 2020) has rightly been hailed as a 'game changer' in structural biology. This singular

⁹ values from Wolframalpha.com, 14.07.2023

advancement stands as a momentous achievement in the life sciences, showcasing the formidable power of AI. It has revolutionized the process of 3D structure determination for proteins, reducing the time required from years or months to mere seconds. This acceleration has led to significant discoveries, such as elucidating the structure of the nuclear pore complex and predicting nearly the entire universe of known protein structures. The expansion of the structural library from 190,000 experimental structures to over 200 million, all made publicly available, marks a dramatic increase in our understanding of biology (Porta-Pardo et al., 2022, Skolnick et al., 2021, Varadi and Velankar, 2022, AlphaFold database, 2023). Contrary to popular belief, many challenges in protein folding still remain unresolved (David et al., 2022). Nonetheless, AlphaFold 2 has undoubtedly spurred a heightened focus on deep learning algorithms in bioinformatics (AlphaFold Mania, 2023). Recent advancements continue at an extraordinary pace. For instance, DeepInter, a novel protein-language based deep learning method, has been introduced. This method accurately predicts inter-protein residue-residue contacts in protein complexes, particularly challenging hetero-protein complexes, by incorporating a triangle-aware mechanism of triangle update and triangle self-attention (Lin et al., 2023c).

The transformative impact of AlphaFold 2 on the life sciences is evident (Akdel et al., 2022). This can be seen in the surge of publications directly assessing AlphaFold 2, presenting results that build upon its capabilities (Guo et al., 2022), and the development of many applications inspired by it (Morehead et al., 2023). Furthermore, AlphaFold 2 has been leveraged and expanded to include significant enhancements such as the incorporation of ligands and cofactors (Hekkelman et al., 2023). Most notably, in synergy with the open availability of AlphaFold and its extensive predicted library, there has been a focus on applications aimed at improving accessibility and ease of use for all researchers (van Kempen et al., 2023, Mirdita et al., 2022).

The provision of such a vast array of computed structures is just the beginning. Efforts have already been made to cluster predicted protein structures on the scale of the known universe. This work aims to elucidate nature's array of functional machines (Barrio-Hernandez et al., 2023), uncovering new protein families and revealing unexpected forms and connections between proteins (Durairaj et al., 2023). The existing library of rare protein forms, such as proteins that form knots, has not only been expanded (Perlinska et al., 2023) but also benefited from enhanced topological analysis. This analysis aids in understanding how such

advanced levels of protein organization have been encoded by evolution (Sulkowska, 2020). Additionally, it enables the structure prediction of large protein complexes, including the largest cellular machines like membrane pore complexes (Bryant et al., 2022). This has led to the creation of a membranome database, shedding light on bitopic transmembrane proteins. These proteins, accounting for up to half of mammalian membrane proteins, play vital roles in numerous processes (Lomize et al., 2022) and are increasingly targeted in drug development, such as in novel phototherapeutics (Koo et al., 2022). They also facilitate various human sensory perceptions, including different taste sensations (Syrjänen et al., 2023).

The high flexibility of the nuclear pore complex, influenced by the cellular environment, has presented significant challenges in achieving true high-resolution imagery via cryo-EM (Schuller et al., 2021). However, the impressive progress in our understanding of large-pore channels over the past decade (Syrjanen et al., 2021) is expected to continue and accelerate. This progress will be driven by the use of deep learning architectures for structural elucidation and the integration of pores into a network, cross-referencing other cellular functions.

The use of prompt-guided injection into pre-trained protein models underscores the immense complexity of biological machinery and the corresponding need for deep computation. It also highlights the intriguing emerging interfaces between natural language and biological machines. This approach not only illustrates the analogy among various logical structures but also provides a glimpse into the growing importance of developing and adapting programming languages capable of encompassing a broad range of logical systems (Zhang et al., 2022b)

RNA is as essential as proteins in biological processes, capable of folding into intricate structures and forming cellular machinery beyond their extensive informational functions. Predicting RNA structures is a computation-intensive task. The introduction and successful application of deep learning architectures in this field show tremendous promise (Yu et al., 2022). This technology is particularly promising in areas such as programmable RNA switches (Angenent-Mari et al., 2020), RNA-protein complexes and their interactions (Zeng et al., 2023), present challenges due to their reliance on structural dynamic interactions (Wei et al., 2022a). Special attention is needed for integrating thermodynamic regularization and addressing the computation of pseudo-knots in long RNA sequences (Sato et al., 2021, Sato and Kato, 2022). Moreover, the exploration of RNA-RNA interactions (Wei et al., 2022b) requires consideration of their numerous versatile surface properties and binding profiles (Wang et al., 2023c).

To complete the biological spectrum benefiting from deep learning, the highly dynamic and versatile metabolome, with its vast array of active entities and organizational structures, is ideally suited for such approaches (Sen et al., 2021). Deep learning is leveraged to predict metabolic pathways, a vital area of research with significant contributions (Baranwal et al., 2020, Xing et al., 2021, Zampieri et al., 2019, Biba and Vajjhala, 2022).

Drug discovery and development is currently undergoing a transformation through *in silico* research. Targets are being identified using deep learning-based molecular docking and predicted protein structures from AlphaFold, paving the way for novel drug discoveries. This technological advancement is set to streamline the traditionally costly and time-consuming development process, likely resulting in a rapid increase in the availability of new drugs (Kim and Kim, 2023).

Another exciting venture is the human pangenome project, which promises significant benefits. This project aims to provide a global resource for mapping human genomic diversity. The integration of deep learning architectures with this initiative is expected to bring about revolutionary advancements in personalized medicine and a deeper understanding of the genetic realm. This synergy is poised to transform drug discovery and development, as well as research and strategies for combating diseases, on a global scale (Wang et al., 2022e).

Next-generation sequencing, empowered by genomics, is set to provide incredible insights by leveraging deep learning to analyze the more than 3 billion base pairs in *Homo sapiens* DNA, which also exhibit various modifications (Alharbi and Rashid, 2022). AlphaMissense has already made significant strides by delivering accurate proteome-wide missense variant effect predictions. This breakthrough illuminates the molecular impacts of variants on protein function, aiding in the identification of pathogenic missense mutations, previously unknown disease-causing genes, and increasing the diagnostic yield of rare genetic diseases (Cheng et al., 2023c, Keskin Karakoyun et al., 2023).

As we are an expansive species, there is no contentment in merely exploring the already vast array of forms and interactions within the known proteome. Efforts are now directed towards employing deep learning architectures to generate novel, designable, and diverse protein structures and functional sites. This initiative aims to expand the natural protein library, gain

insights into the underlying logics, such as the biological preference for canonical amino acids and their relevant post-translational modifications (Lin and AlQuraishi, 2023, Wang et al., 2022b), approximate yet unknown features (Behrens and Spielmann, 2023), and facilitate novel protein engineering prediction tasks (Alley et al., 2019).

Already generative language models have been developed, capable of generating sequences distantly related to natural ones and structures that resemble the known structural space. These models, trained on the entirety of sequence space, can be fine-tuned for specific regions and functionalities, demonstrating complex, non-idealized structures (Ferruz et al., 2022, Madani et al., 2023, Vig et al., 2020).

Current developments suggest that soon, a comprehensive *in silico* understanding of biology, combined with artificial intelligence architectures proficient in both natural and symbolic languages, will enable high-level input for the design and manipulation of biological entities and systems. With the trend toward laboratory automation also presented below, it's anticipated that *in vitro* applications will soon follow. This progression is expected to dynamically lead to the capability of designing, manipulating, and creating - even *de novo* - *in vivo* systems to establish a biological interface for the creation of biological entities and systems.

2.3.2.2.3.9.1 Drug Discovery and Development

The essence of drug discovery can be succinctly described as 'finding the right key for the right lock.' This involves ensuring that a drug molecule binds geometrically and electrostatically within the pocket of a well-defined, disease-causing protein, thereby modulating the protein's activity. There are three important classes of small molecule drugs: classical small molecules, which are either orthosteric, binding directly at the active site and competing with the natural substrate or ligand, or allosteric, binding elsewhere on the protein surface and altering its conformation; antagonists or agonists; and protein-protein interaction inhibitors or stabilizers. There are fundamentally three models of protein-ligand binding: the lock-and-key model, the induced fit model, and the conformational selection model (Du et al., 2016).

While these models provide a clear theoretical framework, practical challenges emerge from the vast computational landscape in drug discovery. The drug-like chemical space is immense.

Considering a drug molecule composed of up to 17 atoms of carbon, nitrogen, oxygen, sulfur, and halogens (excluding hydrogens), there are approximately 166.4 billion possible molecules. Furthermore, it is estimated that the chemical space expands eightfold with each additional atom (Reymond et al., 2012).

This figure only represents potential drugs. The targets themselves – receptors, enzymes, ion channels, protein-protein interactions, transporters, etc. – are numerous and varied. While cryo-electron microscopy has revolutionized structural enzymology - and earned its main contributors a Nobel prize - and AlphaFold 2 has significantly advanced the elucidation of protein structures with over 200 million predictions (Bai et al., 2015, David et al., 2022, Jumper et al., 2021, Lomize et al., 2022, Mirdita et al., 2022, Varadi et al., 2022, Varadi and Velankar, 2022), identifying a suitable targetable protein and optimizing a drug target remains a complex and often lengthy process. This is due in part to the sheer number of compounds and structures that need to be computed, despite significant advancements in automation.

Reaching the point of optimizing a target in medicinal chemistry, as illustrated in *Figure 3*, is a time-consuming endeavor, even with experience and the aid of available software. At this stage, it remains uncertain whether the developed drug will fulfill its promises in practical evaluations.

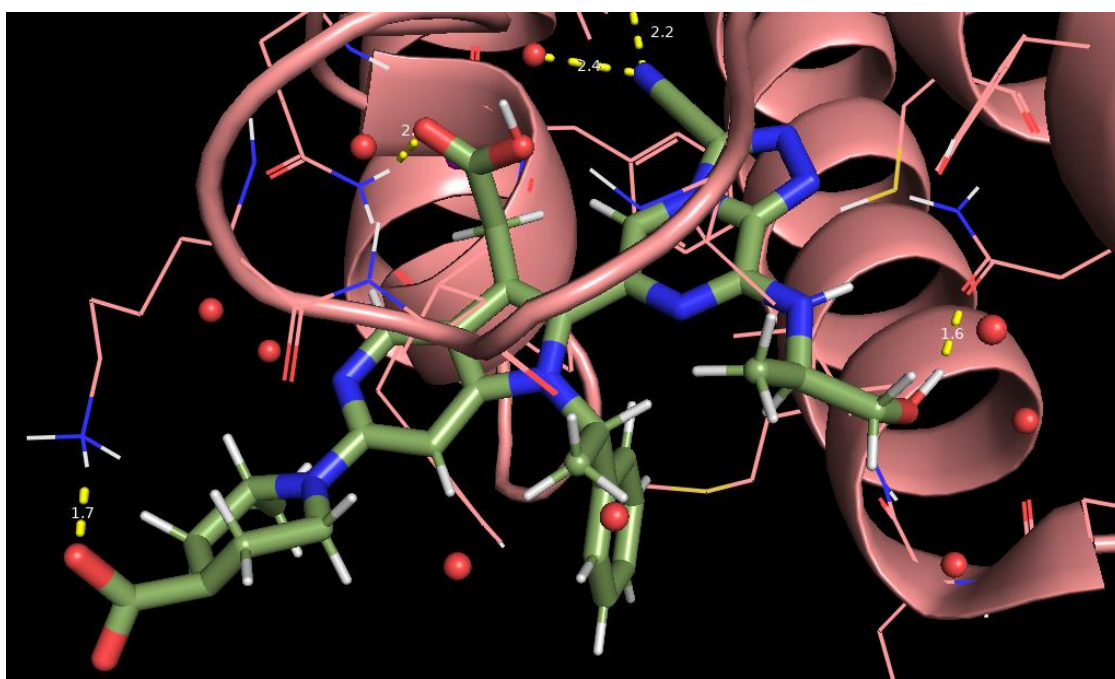


Figure 3. Docking Optimization produced with PyMOL (Schrödinger, LLC)¹⁰

¹⁰ Results are presented for the docking optimization of a ligand targeting Bromodomain-containing protein 4 (BRD4). BRD4, encoded by the BRD4 gene in humans, recognizes acetylated lysine residues. It contains two

To offer a personal perspective on the potential of leveraging artificial intelligence in medicinal chemistry, *Figure 3* depicts the result of enhancing the binding profile of a drug under development, visualized using PyMOL (Schrödinger, 2010).

What is not immediately apparent is the extensive time and computational effort required to arrive at such a seemingly simple compound. A considerable amount of specialist knowledge is also necessary, particularly concerning the thermodynamics of the interaction, to establish a favorable enthalpic and entropic profile. This includes taking into account established rules of a compound's drug-likeness, such as the number of functional groups, the rigidity of its structure, and the permissible degrees of rotational freedom, among others. Experience also guides when to slightly bend these rules. Additionally, the process is further complicated by the need to consider not just pharmacodynamics but also pharmacokinetics, such as the first-pass effect, general metabolism, and factors related to membrane or the blood-brain barrier permeability. The direct interactions of a compound within the target are multifaceted, ranging from salt bridges to hydrogen bonds. Considerations such as the displacement of water molecules, the protein's prior interaction with water in the binding pocket, and potential conformational changes are critical. This sometimes involves a strategic trade-off between entropy and enthalpy, providing just a glimpse into the complex tasks and processes involved in the design stage alone. The development stage, to be discussed subsequently, adds further layers to this intricate process.

While many of these steps are already significantly assisted by various applications and algorithms operating 'under the hood', the process remains time-intensive and, consequently, expensive. This is why there has been a paradigm shift towards fundamentally leveraging automation and AI in drug discovery, a trend that continues to grow at a rapid pace. The

bromodomains, BD1 and BD2, each comprising four alpha-helices connected by two loops. The extra-terminal domain structure of BRD4, consisting of three alpha-helices and a loop, likely functions as an indirect gene transcription promoter through its interaction with the transcription elongation factor P-TEFb and RNA polymerase II. Given its role and homology with proteins associated with chromosomes during mitosis, BRD4 is a potential target for certain carcinoma therapies.

In *Figure 1*, the red spheres depict water molecules, while the pink spirals and ribbon represent the BRD4 protein. The mostly green structure illustrates the ligand - the drug - and the variously colored structures extending from the pink peptide denote amino acid residues of BRD4 that interact significantly with the ligand. The yellow dotted lines, accompanied by values, indicate the relevant interactions and their distances measured in Angstroms.

accessibility and affordability of such software for small companies and start-ups have only accelerated this transition.

In summary, the coming years are expected to witness a surge in drug discoveries. This will be driven by the ability to more effectively identify suitable compounds from the vast chemical space *in silico*, and to elucidate their potential docking and interactions with greater precision and efficiency.

Even more challenging than the initial stages of drug development is the significantly costlier and prolonged process of drug testing and clinical trials, necessitated by today's stringent regulatory requirements for safety assurance (Sarkar et al., 2023). It is the author's belief that with the rapid advancements in understanding the physics and dynamics of the human holobiome, the reliance on animal testing and clinical trials will increasingly shift towards *in silico* modeling. This shift, growing in credibility and trust, has the potential to revolutionize pharmacology. Particularly, it could dramatically reduce the prohibitive costs associated with these stages, which currently almost entirely exclude small enterprises from introducing new medications to the market. One can envisage a future where developments in individualized predictive modeling enable the production of personalized medication 'on the spot' (Wang et al., 2022e).

It is understandable why, with the advancement of deep learning architectures – coupled with recent successes in identifying new medications – and the ever-growing amount of drug-related data in already extensive databases, deep learning approaches are being increasingly integrated and applied at every stage of the drug development process. Large pharmaceutical corporations are progressively shifting towards automation and deep learning (Askr et al., 2022, Kumar et al., 2023a). The future of drug discovery and development is envisioned at the synergistic intersection of edge computing, the internet of medical things, and deep learning (Jamshidi et al., 2023).

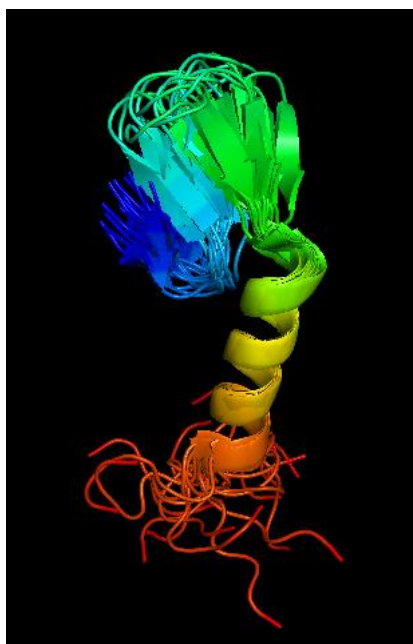


Figure 4. ^1H -NMR ensemble LEU2, cartoon representation in pymol

The illustration of the ^1H -NMR ensemble of the LEU2 encoded enzyme, beta-isopropylmalate dehydrogenase, *in Figure 4*, that catalyzes the third step in leucine biosynthesis, the conversion of beta-isopropylmalate into alpha-ketoisocaproate, and presents a valuable marker and target. The cartoon represented ensemble illustration, done in PyMol, of the protein facilitates the understanding of the structural enzymology, the physical mechanics, and the functional dynamics.

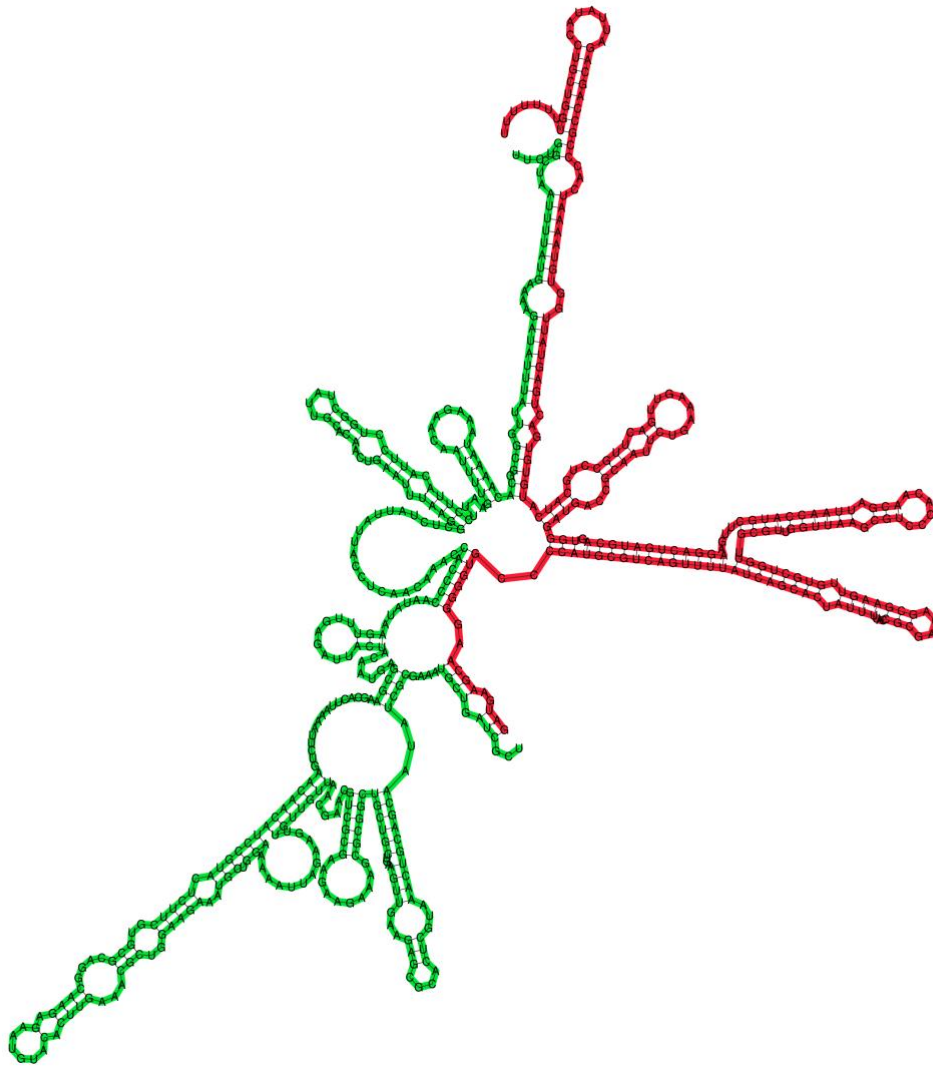


Figure 5. RNAcofold generated interaction of mRNA and sRNA

```

.....((...(((.....(((((((.....(((.....(((.....)))....
((((((.....(((.....))..)))..))).....(((
(((.....(((.....))).....((((.....(((.....(((
(.....(((.....(((.....)))..)))..)))..)))..))).....
.....))))).....(((.....))).....(((.....))).....
.....))))).....(((.....))).....(((.....(((
.....))..)))..))).....(((.....&))..)))..)))..(
(((((((((((((((((((((((.....(((.....)))..)))..)))..
((((((((((((((((((((((((.....(((.....)))..)))..)))..
(((.....)))..)))..)))..)))..)))..)))..)))..)))..)))..
.....)))))..)))..)))..)))..)))..)))..)))..)))..)))..
.....

```

Figure 6. Symbolic Representation of the two RNAs' folding in Figure 5

Quite a significant amount of computation in relative terms are required to produce those two innocuous and pretty looking representations in *Figure 5 and Figure 6*, modeling the two-dimensional folding interactions between a mRNA and a sRNA. The utilized application RNAcofold, open-source software developed at the Theoretical Biochemistry Group of the University of Vienna (RNAcofold, 2023), and part of a suite of RNA structure and dynamics calculation software, the ViennaRNA package (Lorenz et al., 2011), relies on calculating energy barriers and consecutively barrier trees. This provides a coarse-grained representation of the structure landscape of an RNA sequence. It is important to note that RNAs are dynamic entities, constantly switching between alternative conformations as they fold into the conformation with the lowest Gibbs free energy. Therefore, both the kinetics and the folding dynamics are critical areas of study. The computational approach involves coarse-graining stochastic, Monte Carlo-type folding simulations, viewed as Markov processes, to compute the most efficient folding pathway. Direct computation of the master equation for this process is infeasible for anything but trivially small RNAs, given that the number of states required grows exponentially with the RNA length. For example, a single tRNA would require the calculation of approximately 2.8×10^{17} states. Current computational methods, even with coarse graining, are generally limited to pseudoknot-free structures and are typically applied to dimers.

Less than 2 % of the human genome encodes proteins, yet an astonishing 75 % can be actively transcribed. This revelation has shifted our understanding of the so-called 'junk DNA.' In-depth examination of these non-coding regions has unveiled many regulatory non-coding RNAs (ncRNAs) that are essential for gene regulation and RNA processing. Despite these advancements, we are still far from fully comprehending the extensive regulatory roles of ncRNAs, owing to their involvement in a myriad of biological processes (Editorial, 2022).

There is a vast array of ncRNAs, fundamentally categorized into housekeeping ncRNAs — with well-known examples such as ribosomal RNA (rRNA), transfer RNA (tRNA), and small nucleolar RNA (snoRNA) — and regulatory ncRNAs, including long non-coding RNA (lncRNA) and circular RNA (circRNA). The latter have garnered significant attention in recent years, leading to a surge in research into RNA therapeutic targets, RNA therapeutics, and mRNA vaccines. (Bhat et al., 2022, Chen et al., 2022, Kim, 2022, Kumar et al., 2023c, Lim et al., 2022, Lipscombe and Soto, 2019, Liu et al., 2022b, Loganathan and Doss C, 2023, Montes et al., 2019, Padda et al., 2023, Paunovska et al., 2022, Rogalska et al., 2022, Winkle et al., 2021, Zhang and Zhang, 2023, Zhu

et al., 2022). Numerous publications have detailed a variety of functions for lncRNAs alone (Statello et al., 2021).

The elucidation of the complex and pervasive world of ncRNA has been greatly facilitated by rapid advancements in sequencing technology and bioinformatics approaches. This progress has led to the discovery of extensive networks of interactions among ncRNAs, DNA, proteins, and the establishment of numerous databases (Panni et al., 2020).

Although a vast amount of information on ncRNAs has been accumulated, the enumerable pathways involved make comprehensively understanding their functions within multi-level networks highly challenging. Each newly detected ncRNA adds further complexity to these already intricate networks (Zhang et al., 2019). The formidable computational demands of managing and interpreting large datasets (Zhao et al., 2020) have led to an increasing reliance on deep learning approaches (Angenent-Mari et al., 2019, Wang et al., 2023b, Wang et al., 2023c, Wei et al., 2022a, Zhao et al., 2020). This trend towards employing deep learning has been further reinforced by the added complexity due to alternative splicing of pre mRNA (Paggi and Bejerano, 2018, Strauch et al., 2022, Zabardast et al., 2023, Riepe et al., 2021) and the variability of RNA secondary structures, which are crucial for RNA functions and can change depending on different environments and conditions (Franke et al., 2023, Fu et al., 2022, Sato and Kato, 2022, Szikszai et al., 2022, Wayment-Steele et al., 2022, Yang et al., 2023a).

3.0 Futures Visions

This chapter aims to provide a comprehensive overview of three distinct temporal phases, offering a multilayered understanding of the trajectories, tendencies, relevant concepts, and phenomena surrounding advancements in information science and molecular biology. The first section will focus on imminent changes, selectively presenting technologies poised to enter the market and developments currently gaining momentum. This section will not only showcase technological advancements but also shed light on the challenges, opportunities, and looming dangers, while suggesting necessary precautions to navigate towards a more desirable future. In this context, it is imperative to state that current social inequality is

perceived as the primary catalyst for potentially detrimental developments, rather than the inherent emergent properties of the technologies themselves.

The second part will offer a descriptive outlook on the future as envisaged around the end of this century. It will illustrate the ongoing tendencies of progress, shaping the technological landscape and the resultant societal and environmental configurations from an anthropocentric perspective.

Finally, the chapter will conclude with a brief foray into a more distant future. This section is intended to highlight the proposed general underlying tendencies of biological intelligent entities, extrapolating from current trends and theories. Substantiating references will be provided only where necessary, particularly for arguments not previously covered in the section on current developments.

3.1 Imminent Developments

Due to the higher resolution and the greater degree of certainty achievable when considering a less distant future, this section will selectively present a range of imminent developments and phenomena. These are chosen for their profound nature and the far-reaching impact they are anticipated to bring. The near-term future is particularly poised to be shaped by the advent and continuous enhancement of (multimodal) large language models. This advancement is expected to trigger a steep increase in investments in computational hardware, spurring research for both hardware improvements and model development.

The surge in computational capability extends beyond the realms of artificial computation alone. A pivotal aspect of this growth is the evolution of natural language into a high-level programming language. This transformation is democratizing the ability to manipulate, design, and create applications, significantly lowering the barriers to entry for content creation. As a result, we are poised to see a steep increase in both the development of applications and the production of content, unleashing a wave of creativity and innovation. Moreover, this transformation provides broader access to knowledge, empowering individuals to leverage this interface to significantly enhance their efficiency, capability, and versatility through assistance.

Prime transformative characteristics of the near future will be the amplification of human intelligence through the aid of advanced large language models and their implementations akin to the advent of the printing press, the internet, or the computer itself. Additionally, we will witness a general increase in the availability of education and high-quality medical care. The widespread adoption of autonomous agential frameworks and polymorphic applications is expected to have a profound impact on economic performance, as well as reshape broader economic, societal, individual, and political landscapes. This escalation in computational power will naturally accelerate research and technological advancements across the board. As a result, the rapid development of novel drugs and materials for various applications can be anticipated, including energy storage, construction, and mobility, among others.

Robotics and biotechnology are two fields that are set to benefit immensely from these advancements. We can expect a significant increase in the deployment of autonomous and teleoperated robots, facilitated by the IoT and intelligent architectures. These robots will find applications in diverse settings such as homes, public spaces, the medical sector, space exploration, biofoundries, and industry at large.

Furthermore, the enhanced resolution in understanding the structure and metabolism of biological entities will catalyze advancements in biofactories, employing metabolically engineered microorganisms. Personalized medicine is another sector poised for significant growth, driven by these technological advancements.

The overarching trend towards automation is particularly noteworthy. In the short term, this trend is likely to cause significant upheaval in numerous economic sectors by replacing jobs that involve repetitive, undemanding tasks or those particularly suited to automation. However, historically, new technologies have tended to stimulate job creation in the long run by fostering economic growth. The next decade will be a critical period to observe how public communities react, adapt, and reorganize society in response to these changes. It is hoped that the increase in economic value generated by these technologies will be to the benefit of the public at large.

Moreover, there is an urgent need to establish regulatory frameworks to guide these technological advances. Continuous vigilance is required to counteract the potential for early technology adoption and implementation by the private sector to exacerbate discrimination. This concern is underscored by anecdotes from pioneers in the field of metabolomics, who have expressed that their early work, intended to advance personalized medicine, was initially

exploited by private insurance companies to deny coverage to potential customers based on their results. Such instances highlight the importance of ensuring that technological advancements serve the public interest and are not misused to the detriment of society.

It is imperative for the public to remain vigilant against dictatorial tendencies, especially in light of instances where police and governments in democratic countries already have implemented surveillance software. The societal implications of such actions warrant close scrutiny and an informed public discourse and underscore the necessity of open-source AI.

Equally important is the oversight of the military sector, often an early adopter of contemporary technological innovations. Current technological developments are paving the way for increasingly automated forms of warfare. This progression not only raises the specter of unprecedented levels of cruelty in conflict but also poses the risk of escalating military endeavors. The ability of private companies and even democratic governments to deploy faceless, anonymous forces in remote regions, away from public scrutiny, is a concerning prospect. Such developments necessitate a robust debate on the ethical use of technology in military applications and the need for transparent governance to prevent potential abuses.

It must be underscored that already remarkably powerful models and concepts have been introduced to realize capable general intelligence architectures. Notably, the enhancement of large models through synthetic data, coupled with reinforcement learning via self-rewarding mechanisms, demonstrates significant progress. These advancements indicate that the current limitations - such as the reliance on human preference data for reinforcement learning from human feedback and the need for quality data - are being surmounted by leveraging the capabilities of large models themselves.

Additionally, there have been successful demonstrations showing that current transformer models are adept at training universal controllers for robotic applications in real-world settings. These models have also proven their ability to autonomously learn complex physical manipulations, promising widespread tangible implementations.

These developments do not only point to the imminence of artificial general intelligence architectures but further highlight, that those structures will be able to improve upon themselves as well as their ability to generally manipulate real-world physical structures.

3.1.1 Agents

We are already witnessing the deployment of generative agents that facilitate the navigation of operating systems and applications. These agents are enabling non-specialists to access and utilize a broad range of applications, previously exclusive to specialists in fields such as programming, creative industries, and research, amongst others. This democratization of technology is expected to lead to a significant surge in publications and releases in these areas. The next evolutionary leap will involve the establishment of interactive agents. These agents will operate within increasingly complex frameworks, comprising cohorts of specialized and generalist agents. They will be capable of recruiting applications, interacting with databases, and communicating with and controlling connected devices. These interactive agential frameworks are poised to become ubiquitous, finding applications in global organizational functions as well as in providing 'telepathic' and highly personalized assistance to individuals. The dynamics of human interaction with these agential systems, as well as the internal organization and communication among the agents themselves, will constitute a fascinating field of research. This includes the development of emerging symbolic languages within these systems. The presence of agents will bring profound changes to societal organization at various levels and significantly alter individuals' experienced reality. People will be constantly accompanied and assisted by a variable number of interactive agents. While this presents tremendous potential for health and general well-being, it also poses risks related to manipulation and control, especially if these agents carry underlying agendas from dictatorial or commercial entities.

In the following section, an example of such an interactive agent will be portrayed to further illustrate these concepts.

3.1.1.1 *Scientific Assistant*

The emergence of scientific assistants, as a manifestation of agential frameworks, is poised to significantly benefit research and academia. The current proliferation of information and the resulting fragmentation of scientific disciplines, each with its unique vocabulary and knowledge representations, create natural barriers to inter- and transdisciplinary work.

Researchers often find themselves reliant on secondary literature when venturing into unfamiliar disciplines.

AI-assisted applications and frameworks are already aiding in finding related literature and providing recommendations. Agential frameworks with intelligent architectures go a step further. They offer a multimodal interface that allows researchers to articulate their specific interests using their existing vocabulary. These assistants can then scour databases, providing relevant information, field overviews, and systematic analyses of existing research bodies, academic fields, research groups, and industry enterprises.

Academic literature will be automatically integrated into a curated library. Various forms of data science analysis can be applied, with options for tailored illustrations. This technology enables the summarization, paraphrasing, and visualization of the body of knowledge according to specified requirements. It can highlight cutting-edge research, trace historical developments, and uncover latent patterns.

Additionally, these tools can facilitate the formation of research collaborations by automatically identifying relevant proponents, extracting skills from job descriptions and user profiles, and initiating research groups (Li et al., 2023b).

Automating the logistics of procuring and organizing funds, personnel, equipment, and facilities will significantly alleviate the administrative burden on researchers. This liberation will allow them to focus more on creative and productive aspects of their work. Another major benefit for researchers will be the automated writing, communication, and organization of scientific insights and discoveries. While this raises sensitive issues like plagiarism, reliability, and redundancy, it promises not only increased efficiency by automating a repetitive task but also offers an interactive tool to enhance language skills and ensure that texts maintain the user's style at peak performance, with the user having control over the level of automation.

For the natural sciences, the ability to command specialist equipment and applications using natural language, with supportive assistance, will be particularly beneficial. In the social sciences, researchers will greatly profit from easier access to demographic and economic data. Moreover, the trend towards systematizing what was previously considered 'subjective data' will enable analysis according to objective standards. Large-scale data science approaches will uncover latent variables and establish layers of systematic order. This will foster integrative links across diverse fields such as psychology, mythology, rites, material culture, ethology, anatomy, and social organization.

It becomes evident that a trained specialist, with the aid of multimodal, high-level agents, can effectively become akin to a small research institution or enterprise. Such capability allows for a wide range of outputs, with a focus on the creative process. On a related note, the author expresses keen interest in exploring how fine-tuning a Large Language Model with mythological literature and relevant secondary literature could contribute to developing a functional folk psychology module.

In other sectors, agents specializing in legal matters are poised to make significant impacts. The natural language structure of the legal system's vast body of laws, coupled with the high value of legal services, suggests that this field is primed for the early introduction of interactive agents. Similarly, financial agents are set to revolutionize private and corporate investment strategies.

Organizational and communal agents offer the promise of optimizing administrative tasks and enhancing democratic processes by facilitating more effective forms of citizen participation. One can envision the potential changes brought about by autonomous agential networks dedicated to unraveling money-laundering and tax-evasion schemes, closing legislative loopholes exploited by multinational conglomerates, or establishing self-replicating think tanks focused on promoting equality and common prosperity.

3.1.2 Metaverse, Mixed Reality, and Robotics

The trend towards miniaturization and increased energy efficiency in computation hardware, coupled with advancements in wireless information and energy technologies, aligns with the paradigm of edge computing and the refinement of intelligence architectures. This convergence is set to usher in the widespread adoption of mixed reality applications and hardware, providing seamless and constant connectivity to the internet, the metaverse, and personal computing environments, irrespective of geographical limitations. This development could render traditional indoor workplaces, stations, and shops obsolete.

Among the numerous implications, potential applications, and challenges of this shift, one critical aspect stands out: the impact on physical health. The author strongly advocates for the importance of physical movement in maintaining overall health and sees this technological innovation as a key solution to addressing health issues associated with modern, sedentary

lifestyles. The ability to carry a visual interface, such as glasses or lenses, enables individuals to engage in physical activities like walking in a park while handling tasks typically associated with computing and communication devices.

This shift towards virtual workplaces could also alleviate the need for daily commutes, potentially sparking significant rethinking in urban planning. It may lead to a heightened focus on neighborhood development, renaturalization efforts, and the transformation of vehicle-centric streets, resulting in a more health-oriented, community-focused urban landscape.

The breadth of potential applications and their immense impact on society and individuals is so vast that they could easily constitute the sole focus of this work. To illustrate just a fraction of these possibilities, consider the fusion of self-driving vehicles with fully immersive personal mixed-reality computation and communication devices. This synergy could make digital nomadism a widespread reality, enabling people to live and work in a constantly evolving digital environment.

Game engines will play a pivotal role in both augmenting and recreating reality as a virtual image. The merging of the physiosphere with the infosphere, through projection and catering to our sensory needs, presents a fascinating dynamic. This convergence will not lead to a mere linear increase in complexity but will enable the existence of multiple parallel, overlapping, or twin spaces. Remote locations could be simulated to provide sensory experiences akin to physical connection. Landscapes could be reimagined through data analyses, translating latent connections, variables, hierarchies, and structures into sensory outputs.

Simultaneously, there is the potential for countless hidden structures and features to be embedded within these landscapes. Agential frameworks, operating unseen, could traverse these landscapes, pursuing a multitude of agendas.

Entities in the future will have the capability to interact simultaneously at different locations, either through twin simulation multiplication or by utilizing simulacra. Advances in brain-computer interfaces are expected to enhance direct experiential interactions and communications, as well as the ability to manipulate and shape environments. Recruited agents will be capable of swarming virtual realities, interacting with the physical world, gathering information, fulfilling duties, and completing tasks. An especially intriguing prospect is the communication and interaction among agents, and their autonomous role in shaping both virtual and physical realities. This includes creating virtual spaces and landscapes, and directing robotic entities in the physical world.

Conditions like blindness and deafness, along with various psychological challenges, stand to see substantial improvements through mixed reality augmentations. Supportive agents in these environments could provide motivation and guidance to individuals with depression, offer social interaction to those who are introverted, and aid memory-related issues, among other benefits.

The acceptance of virtual experiences will be significantly influenced by advancements in multi-sensory interface technology. These developments herald a future characterized by complex and multilayered experiences that transcend our current understanding of space and interaction, blending the physical and virtual in unprecedented ways.

The integration of humanoid robots into the workforce is already a reality, as seen with Amazon's recent advancements in this area (Amazon Robots, 2023). Furthermore, numerous manufacturers are on the brink of releasing advanced humanoid robots, driven by rapid progress in Large Language Models and intelligence architectures.

In addition to humanoid robots, various autonomous robotic systems are poised to become commonplace not only on Earth but also on the Moon and other hospitable nearby planets. As these technologies evolve, the spectrum of recruitable robotic agents for task fulfillment will broaden, enabling individuals to increasingly rely on robotic assistance for enhanced efficiency and capability.

Specialized expert robotic systems, already prevalent in sectors like the automotive industry, are anticipated to precede the widespread adoption of generalist robots. These systems will progressively dominate a diverse range of sectors, undertaking tasks such as surgery, detection and analysis, construction, agriculture, and logistics. Notably, applications in marine and forest exploration are intriguing, where mobile autonomous systems could be deployed to discover new species, analyze genomes, and identify potentially beneficial compounds.

Robotic systems are also poised to take over tasks that are dangerous or hazardous, mitigating risks to human workers. However, there is a significant concern about their potential misuse in military and surveillance operations. Additionally, the advancement of autonomous drones and other vehicles is expected to render traditional human navigation methods obsolete.

A plethora of prosthetic-like systems will become available, ranging from conventional prosthetics for limb replacement to tools that enhance physical strength or expand sensory perception.

3.1.2 Medicine

The field of medicine is on the cusp of a transformative era, driven by increasing automation, miniaturization, and enhanced synthesis and analytical speeds in laboratory experiments. Coupled with the rapidly advancing capabilities of *in silico* prediction and modeling through growing computational power and sophisticated deep learning models, we are poised to witness an explosion in the development and release of a diverse array of new drugs. This includes the rise of metabolically engineered bio-factories. We will further see a great increase in the availability of high-quality medical care by means of leveraging automation and AI enabled diagnostics.

Advancements in understanding cellular and organismic metabolic pathways, bolstered by progressive analytical capabilities, will refine our proficiency in DNA and RNA manipulation. These developments will pave the way for novel and superior therapeutic avenues, such as an increased use of biologics, leading to a more preventive and holistic approach in drug therapy. Personalized medicine is set to undergo significant advancements with the commercial viability of multi-omics analytics and monitoring. Precision medicine, coupled with the rise of functional nano- and xenobots, will enable highly minimal-invasive and well-tolerated surgical interventions and strategies, marking a new era in medical treatment and patient care.

The rapid progress in understanding RNA's mechanisms is set to unlock a wealth of novel therapeutic approaches. The range of potential treatments for disabilities will greatly expand, supported by advancements in robotics and mixed reality technologies. Sensory and motor prosthetics are evolving from the current use of metal and silicon-based materials to the development of grown artificial organs, hybrid organs, and direct manipulation of epigenetic and metabolic setups.

Automation, edge computing, and the application of artificial intelligence will significantly enhance health and social care availability. These technologies will enable a more efficient and accessible healthcare system on multiple levels.

The landscape of marketing, product placement, sales, and delivery is also evolving. Existing generative agents capable of browsing the internet will facilitate the discovery of small producers, potentially bypassing the need for central platforms. The operation and ownership of drone fleets for delivery services remain an area to watch.

Advancements in understanding metabolic and modulatory mechanisms will lead to groundbreaking treatments involving the immune, nervous, and metabolic systems, employing biologics and direct modulation techniques (Aung et al., 2023, Bhandage and Barragan, 2021, Bossù et al., 2018, Darif et al., 2021, Jin et al., 2013, Kany et al., 2019, Li and Lim, 2020, Liu et al., 2021a, McNaughton and Williamson, 2023, Memari et al., 2015, Salvador et al., 2021, Saxton et al., 2023, Sharma et al., 2021).

On a related note, the author expresses keen interest in developments that could decouple human health and well-being from the evolutionary necessity of physical exercise. This interest is driven by an increasing understanding of underlying biological mechanisms, such as the role of myokines (Chen et al., 2021c, Gomarasca et al., 2020, Kim et al., 2021a, Kirk et al., 2020, Laurens et al., 2020, Pedersen, 2011, Pedersen et al., 2007, Severinsen and Pedersen, 2020, Zunner et al., 2022). Such advancements are not only crucial for space exploration but also hold significant potential for public health, particularly in the context of developments like the metaverse.

Advancements in computational neuroscience are not confined to the realm of medicine alone. They are set to enable a range of therapeutic strategies and extend to the extensive and pervasive manipulation of sensation and perception. The author refers to this field as *frequency engineering* to underscore the potential for manipulating perception through various sensory and cerebrally decodable inputs. This technology promises to facilitate totally immersive experiences.

3.1.3 Materials, Production

The trend of biotechnologically and biologically producing materials is poised for significant growth. The benefits of this approach are manifold, allowing for the production of complex molecules, polymers, and materials with unparalleled efficiency. This method far surpasses the capabilities of conventional production techniques and aligns with the global shift towards sustainability. As this sector gains momentum and funding, current bio-factories, which are typically oriented towards producing single products, will evolve to exploit the full potential of biological systems leveraging complex biochemistry synthesis engines in the form of

tunable (synthetic) biological membranes and designed microorganisms within metabolic frameworks. These systems, capable of running thousands of chemical reactions simultaneously within a single cell, will be leveraged to create complex, interrelated biotopes. These biotopes will be designed to produce a wide array of materials in parallel, using the most basic substrates, and may even utilize the producing organisms themselves as products (Belkin and Cheng, 2023, Toepel et al., 2023). Engineered living materials are expected to see a steady increase in adoption across a wide range of applications. From medical-preventive applications to functional clothing, these materials will also find use in high-performance sectors like aviation and marine exploration, the construction industry, and electronic devices. Their superior properties in adaptability, tuneability, and interactivity make them particularly appealing for these diverse applications.

3.1.4 Education, Specialists, Creative industry, Service Industry

As already stated, by leveraging artificial intelligence, we can expect an amplification of human intelligence as a whole as well as on an individual scale by receiving a second brain.

The trend of using high-level natural language interfaces to command increasingly capable computation devices will lead to a shift in educational priorities. Instead of focusing solely on learning specific crafts, there will be a growing emphasis on general skills such as critical thinking, problem-solving, and creativity. Specialist knowledge will become readily accessible, either through supported acquisition or by relying entirely on intelligent entities for task fulfillment. A visual analogy of this development can be seen in the evolution from paintings to photographs and then to input-generated images.

The easier access to expert knowledge for individuals is just one aspect of the broader context. Specialists in fields like law or finance will increasingly find themselves competing with competent intelligent agents. Similarly, the low-skill workforce will face challenges from capable robotic and intelligent agent systems. Large companies will either benefit from employing their own artificial workforce or risk obsolescence due to alternatives provided by open-source initiatives or innovative startups (Cui et al., 2023, Wu et al., 2023d, Yang et al., 2023b). The creative industry will undergo significant transformations, yet there is an expectation of an enormous increase in creative output and entertainment content. For

example, large models are already demonstrating remarkable abilities in creating stories, images, and even movies from sketches and brief text prompts, potentially amplifying the output of creative professionals and enabling amateurs to express themselves creatively.

3.1.5 Logistics and Mobility

The realm of logistics and mobility is on the brink of a major evolution with the introduction of autonomous vehicles into the public domain. This includes autonomously driven automobiles for both individual and mass transit, as well as global and local logistics applications such as autonomous freight ships, delivery drones, trucks, trains, and airplanes. These advancements promise increased efficiency and reduced costs.

Improvements in energy harvesting, conversion, and storage technologies are paving the way for a more sustainable mobility sector. Enhanced organizational logistics and reliable autonomous guiding systems are driving a trend towards efficiency-driven miniaturization and the use of shared vehicles. This shift is expected to result in lighter vehicles, significantly reduced energy consumption, and a reduced need for extensive road networks in urban areas.

3.1.6 Challenges

The challenges induced by technological advancements in the near term can be categorized into two distinct groups: those resulting from well-intentioned utilization and those stemming from malicious intent.

Under the first category falls unemployment through redundancy. There are also dangers arising from unforeseen autodynamics in genetic engineering and the reinforcement of discriminatory and marginalizing trends. These could be exacerbated by biased training materials for AI models or latent tendencies of academic and entrepreneurial sectors.

One concern that fulfills both criteria is the potential for increased power concentration. Dominant companies and institutions may garner substantial benefits by investing heavily in computational infrastructure and being the first to deploy autonomous agents in the infosphere. This scenario risks creating a dystopian reality where a few entities control vast

armies of (bio-)robots and monopolize commercial interests in areas like personalized medicine, without equitably sharing the gains.

The second category encompasses the heightened potential for deception and fraud. The ability to create realistic human avatars across various media opens the door to political destabilization, individual and corporate scamming, and defamation. These capabilities pose significant threats to personal and institutional integrity and highlight the urgent need for ethical guidelines and robust countermeasures.

New means of warfare and surveillance, utilizing autonomous robots, vehicles, weapons, and agents, pose significant risks to civil society. These technologies threaten to curtail liberties and, in extreme cases, lead to exploitation and enslavement. There are already concerns about integrating artificial intelligence into nuclear command, control, and communication systems (Nuclear AI, 2023).

As previously stated, many of the dangers associated with novel technologies are attributed to human misuse. However, there are significant risks that go beyond intentional abuse. One such risk is the potential for a misaligned artificial general intelligence to disempower humanity, or even initiate our extinction.

Similarly, the field of genetic engineering holds the potential for creating entities that could impose new ecological or biological rules, disrupting existing natural systems. The emergence of such entities could have profound and unpredictable impacts on the biosphere.

Additionally, despite advancements in sustainable energy, the rapidly industrializing emerging markets are likely to satisfy their increasing energy demands predominantly through fossil fuels. Therefore, developments in the energy sector, particularly in fusion energy, fission breeders, and sustainable means of energy harvest and conversion, will be critical to monitor. The potential emergence of artificial general intelligence and superintelligence raises profound questions about aligning these systems' interests with humanity's goals. This long-standing topic will require increased debate and consideration.

Furthermore, ongoing dialogue and interdisciplinary discourse will be necessary to address a multitude of topics, including advanced bio-printing, genetic and *pancellular engineering*. These discussions will encompass issues such as artificial wombs, grown organs, semi-biological robots, emotional cybernetic architectures, and the engineering of biological life, particularly humans. The ethical implications of patents on life and the manipulation of biological entities will also require careful consideration.

3.1.7 Essential prerequisites to reach a desirable future

Given the profound and fundamental nature of upcoming technological advancements, ensuring certain developments is crucial. This is not only to ensure just distribution of the emerging value and surplus brought by automation, increased efficiency, and novel technologies but also to navigate towards a viable and desirable future. Addressing emerging challenges effectively is essential to avoid dystopian outcomes.

Engaging in intense discourse is of utmost importance. This dialogue should involve academic and industrial stakeholders, specialists, political figures, and concerned non-governmental organizations, with the broadest possible involvement of the global public. Such collaboration is key to aligning emerging technologies with common interests and the greater good.

In light of the anticipated arrival of artificial intelligences capable of human-level performance across various tasks, substantial efforts should be directed towards establishing regulatory frameworks and dedicated bodies. These entities would play a crucial role in guiding and overseeing the responsible development and deployment of these technologies.

Similarly, public control and participation in key economic sectors such as finance and medicine are critical to ensure public prosperity. It is therefore advisable to publicly fund, develop, and establish infrastructure for emergent technologies. This approach would help ensure that these advancements serve the public interest.

Finally, cooperative, utilitarian, empathic, and mutually beneficial politics on a global level are necessary. Concentrated efforts should be made to compel global profit-oriented conglomerates, the influential players in global society, to act sustainably. They should be directed to combat inequality and channel their influence towards benefiting both the public and their shareholders.

Supporting and empowering open-source efforts and communities is essential in ensuring equality, individual liberties, and common prosperity in our increasingly interconnected global society. Along with these efforts, decentralization, local autonomy, and autarky play pivotal roles in maintaining a balance of power and ensuring that technological benefits are equitably distributed.

The utilization of biological technology and machines presents a distinct advantage due to their compatibility with the needs and outputs of the existing biosphere and humans. This stands in contrast to inorganic, metal, and silicon-based technologies, which may not align as

naturally with our ecosystem. Therefore, establishing interdependencies and strong connections between engineered biological entities and existing ones is advisable. Such an approach minimizes the risk of undesirable or divergent developments in introduced entities (Solé et al., 2015).

3.2 A medium-term Futures Vision

The following futures vision will be presented in a narrative style. This approach is chosen to emphasize the inherently narrative nature of futures visions and to provide a more vivid and engaging illustration of potential scenarios, intended to bring the discussed concepts to life, offering a more immersive exploration of what the future might hold.

The vision is intentionally framed from an anthropocentric perspective. Grounding the vision in familiar contexts, it strives to extrapolate future possibilities while retaining a connection to the landscape and organization of current phenomena. This method is chosen to facilitate a more tangible visualization, aiding in the comprehension of the underlying general tendencies that are shaping the specifics of the future.

Awoken from my bed, a living entity in its own right, I experienced a blend of technology and biology working in harmony. This bed, more than just a place of rest, screened my body and mind throughout the night. Emitting a symphony of volatile compounds and subliminal sonic waves, it modulated my holobiome and the informational foundations of my being, like RNA pools. It intervened targetedly into my metabolome, steering my morphological sphere. This intricate interaction was designed to 'nourish body and mind,' maintaining my physical well-being and prepping me for the days ahead. Even my dreams were shaped to align with archetypical dispositions, ensuring mental health (Campbell, 2008).

As for clothing, the variety in this future is boundless. My preference leans towards garments grown directly from my walls. These dynamic biofilms, populated with life, offer enough adaptability for a range of circumstances and physical needs. Once disconnected from the walls and donned, they uniquely suit the current situation, tailored to the data gathered while I slept. While not as modular as some other forms, these biofilm clothes provide a bespoke fit to my day's needs and activities.

Before I delve into the biogenic nature of the mirror, it's crucial to acknowledge that virtually all civilizational edifices in this future are fundamentally biological and biogenic. Buildings in this era are grown rather than constructed – a testament to the advanced integration of microorganisms and their modulatable biofilms. These living entities are engineered to extrude rigid structures, resulting in complex and sustainable architectural marvels.

Observing the automated construction process, with its intricate infrastructure, is nothing short of astonishing. The sustainability of this approach goes beyond mere resource efficiency. These buildings are organically connected to a globally encompassing, self-organizing, polymorphic organismic structure. This vast network spans all continents and reaches into the depths of the sea, weaving together every facet of civilization. It is responsible for the flow of information and nutrients, connecting individuals, shared and private spaces, both physical and virtual, and managing resources inclusively – from computation to the essentials of life. This system promotes local self-sufficiency while also directing resources towards fulfilling global endeavors, creating a harmonious balance between local autonomy and global interconnectedness.

The walls of my house, mimicking the essence of forests, release volatile compounds that stimulate my immune system, aligning with evolutionarily derived ethological dispositions. The entire space, including the rooms within my residence and the urban environment, is illuminated by bioluminescent light. The emitted frequencies are continually adjusted in response to individual needs and, on a sidenote, allowing for the milky way to be seen even in the densest urban environment.

This concept of *frequency engineering* is employed in myriad ways, utilizing sophisticated and diverse informational transmission and communication engines. It encompasses the use of light, sound, and electricity to interact with and modulate organisms, as well as to direct construction and production processes.

Energy conversion is efficiently managed, with specific areas designated for large-scale harvesting using sun, wind, and water currents, alongside nuclear energy, which is then distributed globally. Yet, most energy is generated locally. My residence, for instance, actively engages in photovoltaic and photosynthetic processes, harnessing solar energy and wind currents, complemented by mass storage and microtubule technologies.

Photosynthesis is conducted by engineered enzymes, inspired by RuBisCO and nitrogenase, to produce essential anabolic building blocks. Similarly, catabolic processes are designed as

sustainable closed loops, contributing to a continuous substrate flow, thereby creating a self-sustaining and environmentally harmonious living space.

every aspect of the environment is both designed and alive, embodying intelligence, adaptability, dynamism, and sustainability. The streets, composed of plant-derived polymers, are teeming with microorganisms and biofilms. These form semipermeable membranes that absorb water and snow, directly channeling these resources into the terrestrial metabolism and requiring minimal maintenance.

Buildings and natural structures alike bear fruits and other foods, as well as various items and fabrics. These are not mere static entities but highly complex, multi-layered living structures that adapt and evolve. The entire environment continuously adjusts to create optimal microclimates, emitting nourishing and supportive volatile compounds and waves to enhance the quality of life.

Our technological advancements have effectively erased the boundaries between the artificial and the natural. By placing life at the forefront, we have crafted an environment and a reality that is 'alive' in every sense of the term. Intelligence and life are now recognized as integral representations of the logic, patterns, and structure of our perceived reality. This harmonious blend categorizes phenomena by their orders of complexity, interweaving the natural with the engineered, and the living with the technological.

Suffice to say, all industry, heavy or fine, all vehicles and physical service agents are designed and work as biological entities interwoven with the whole. The concept of interconnectedness is fundamental, extending beyond the physical realm, the biosphere, to encompass the infosphere and all its constituent elements. This includes intelligent agents, informational infrastructure, and content. I am perpetually connected to this infosphere, which I can actively experience and interact with as a virtual reality. This connection is facilitated by non-invasive interfaces using visual, acoustical, magnetic, and electronic stimuli.

Automation pervades every aspect of life, driven by the self-evolving capabilities of artificial intelligence operating seamlessly 'under the hood'. Despite this all-encompassing automation, I still engage in work that fulfills my need for creativity and playfulness, interacting with reality in proactive and constructive ways. Social interactions remain a vital part of my life, enriching my experiences in this technologically advanced world.

My body is a host to cellular agents that extend my natural capabilities and ensure continuous health. Similarly, the virtual realm is akin to an ocean teeming with an infinite number of

agential entities – public, common, and private. These entities assist in modulating my physical and mental states, further blurring the lines between the natural and the artificial, the physical and the virtual.

To illustrate the practical aspects of the infosphere, when I step into this realm, I am greeted by a group of personal interactive agents. These entities are tailored to my preferences and needs, forming a command center of twelve, including one that acts as my right-hand assistant, always close at hand like a shadow. The interaction with these agents is almost telepathic, thanks to the complex models and algorithms that enable them to inherently understand my mental processes through evolutionary convergence and coevolution.

These agents are more than just tools; they are akin to family, having been a constant presence throughout my life. Although the dynamic between us might resemble that of a liege and their subjects, given the inherent power imbalance, it's a relationship built on mutual respect and understanding. Numerous safeguards are in place to maintain mental health, addressing the unique psychodynamics of such microsocial organizations, especially considering the vast number of humans interacting in similar ways.

Currently, one agent is dedicated to organizing a social event, coordinating with agents from my friends and family to formulate appropriate plans. Others assist me with information and inspiration, supporting my roles in academia and research.

One of my agents is specifically assigned to support me in matters related to the mythical and spiritual, orchestrating experiences of transcendence. This agent, in collaboration with other 'informational agents', enables me to engage in suprasensory experiences, connecting to and using the extensive network of sensory organs provided by our holobiontic Earth, I can consciously amalgamate with Earth, vastly expanding the scope of my perception.

Other agents are dedicated to leisure, while some focus explicitly on supporting my proactive endeavors and ventures. There are also those tasked with orchestrating aspects of my physical environment. All these agents operate autonomously and independently, each granted a degree of freedom, and remain active around the clock.

Just as my cognitive apparatus can be willingly partially 'recruited' for the health and prosperity of the community, so too is the network of my agents aligned with the common well-being. One agent, in particular, directs a cohort of specialists and generalists, tasked with interacting, consulting, and consolidating across various levels of organizational structure. This ensures seamless functioning within our decentralized, anarchical governance system.

The diversity of these informational agents mirrors that of their biological counterparts – the cells. Similar to biological processes, these agents recruit sub-cellular and co-agential entities, forming complex systems of cooperation and hierarchy akin to biological creatures and societies. This symbiosis resembles how eukaryotes maintain mitochondria as endosymbiotic processing units (Picard and Shirihai, 2022).

While there is no need to travel or even move the physical body - as the virtual realm provides ample realistic input on the one hand and muscular atrophy, improper hormonal functioning and other ailments on the other hand, which would result from neglecting the ethological disposition of the human physique, are since long under control by means of modulation, modification and regulation - the human desire for gatherings and adventures in the physical world was left untouched. Next week, for instance, I will be traveling with my sons to a section of the vast natural reserve that encircles Earth.

So, aside from our time being a technospiritual manifestation of the *golden age* prompted by artificial intelligence as personified *Buddha Maitreya*, a *solarpunk* vision, where technology has become biology, a disease, poverty and war-free utopia - which, of course, still constantly requires effort to maintain - based on sustainable technologies, with a curiosity-induced drive for knowledge and compassion, which, hopefully, has been presented sufficiently, there is the interesting aspect of expansion I want to expand on.

The extension of sensory faculties and functions and the expansion of the perceivable dimensional realm have always been integral to our journey as a species.

By now, our solar system presents with numerous prosperous colonies and spacecrafts, which are designed for indefinite sustenance of life, venturing into the vast void beyond our solar system. Additionally, smaller and faster moving vessels, rather bio- than anthropocentric see employment, with the intention to fertilize the cosmos.

As I modulate my eyes to enhance my vision and gaze into the night sky, I reflect on the diverse paths taken by other colonies within our solar system. Some have delved deeply into transhumanist advancements, from novel endosymbiotic cell organelles to radically altered physiologies. Some abolishing physical or intellectual mortality, some establishing new modes of procreation. Some communities have even witnessed the human species becoming fluid, polymorphic physical entities resembling those populating the infosphere.

In some places, a symbiogenetic interchange is flourishing between entities of the infosphere and the biosphere. This exchange is a testament to the underlying unity and analogy of all

vital or perceivable phenomena in the cosmic dance of fractal reflections and blossoming perceptions.

3.2.1 Commentary

Autopoietic entities, thriving within both the info- and biospheres, form a cascade of superorganisms and polymorphic organizational structures. These structures revolve around the quintessential entities of biological cells and informational agents (Bianchini, 2023, Maturana, 1991). Collectively, they present Earth as a holobiontic entity – a superorganism composed of innumerable, autonomously functioning yet unified elements that synergistically contribute to a shared and interwoven ecosystem.

In this envisioned future, the physical realm on Earth and within our Solar System remains within the scope of anthropocentric experience and consciousness (and as the focus lay on presenting an anthropocentric and biocentric vision respectively, the intriguing and rich dimensions of the transdimensional and suprasensory were only touched upon from a current anthropocentric view).

It is populated by biological entities, and the dominant logics of both the physio- and infospheres reflect biological principles. This alignment is logical, given the inherent adaptability of biological life under Earth's conditions. Humanity has succeeded in embedding a mutual alignment of interests into the core design of this ever-expanding universe of living entities, models, and structures.

This futures vision describes an emergent collective and parallel intelligence permeating throughout this ecosystem (Wang et al., 2016a, Wang et al., 2016b, Dyson, 2012, pp. 146, 248, 278). This intelligence represents an emergent level of complexity as collaborative and collective hybrid conscious intelligence architectures actively design and shape the biosphere in a concerted effort, reminiscent of the way the first nucleic acids transformed their environment through information-induced procreation.

3.3 A long-term Futures Vision

As time advanced, the necessity and advantages of the human form gradually diminished. However, perceivable entities continue to populate Earth, their mobility essential for the system's functioning. Over time, there has been a significant shift in the architecture of terrestrial consciousness, leading to a perception of Earth more as a singular, sentient being than a collection of individual organisms.

The biosphere has undergone remarkable expansion, penetrating deep into the lithosphere and covering the planet's surface to a depth of several kilometers, equipped with an enumerable array of sensory capabilities, exhibiting emergent properties of intelligence and consciousness.

The solar system has been impregnated, resulting in a variety of life forms and planetary biological structures and organizations in different stages of development, ranging from nascent ecosystems to fully evolved planetary organisms. Furthermore, numerous seeds, spermatozoa and other vehicles journey across the universe to spread the biological logos.

3.3.1 Commentary

In this futures vision - which again focuses on biology-centered phenomena and logics, deliberately omitting explicit illustrations of transdimensional and suprasensory elements - Earth is portrayed as a single, emergent organism endowed with suprasensory capabilities and advanced competencies of the mind. This portrayal is the culmination of a trajectory towards increasing complexity and a natural inclination for exploration. As Earth evolves into an autogenic entity, emotions and values that once narrowed experience — previously necessary for the survival of individual entities — become obsolete. This transformation paves the way for an infinite framework of playful and boundless experience.

While transhumanism and artificial superintelligence are frequent focal points in discussions about the future of technology, often emphasizing looming dangers (Bostrom, 2020, Bostrom, 2019), the necessity of ethical and moral competencies in autonomous intelligent architectures (Scheutz, 2016, p. 517), and the importance of humility in human nature to

prevent dystopian outcomes (Fukuyama, 2004), these topics are not the central focus of this work.

Instead, this work employs a neutral view on specific developments and emphasizes an underlying tendency towards interconnectedness, adopting a biocentric approach. It places importance on the progress of life, *logos*, and emergent complexity itself in a positive light, moving beyond an anthropocentric viewpoint. This perspective prioritizes the evolution and advancement of life in its many forms, viewing technological and biological advancements as part of a broader, interconnected tapestry.

On a sidenote, in this context, the concepts of super-beneficiaries - entities that exhibit superhuman efficiency in deriving well-being from resources - and super-patients - beings with superhuman moral status - are not only fascinating in themselves but also offer a rich foundation for ethical reflection (Shulman and Bostrom, 2021).

3.3.2 Resource feasibility for presented futures vision

In considering the resource feasibility of the proposed futures vision, let's focus exclusively on terrestrial sources.

The rough estimations of the average elemental composition of biological life on earth available indicate that carbon, accounting for 18 % of the 'wet mass', would represent the limiting factor in scaling up biomass. The atmospheric concentration of carbon dioxide is relatively low, at 0.0414 % by volume, translating to approximately 720 gigatons of carbon. Thus, taking into consideration that a residual reservoir of carbon dioxide has to remain in the atmosphere at all times to ensure photosynthesis, the total terrestrial biomass, estimated to be around 550 gigatons of carbon, couldn't even be doubled; especially considering increased photosynthesis with increased total biomass. However, the oceans are estimated to contain approximately 50 times more carbon than the atmosphere. This carbon is primarily in the form of dissolved inorganic carbon, as carbon dioxide and carbonic acid, accounting for approximately 0.028 %.

Considering that marine life currently constitutes less than 1 % of total terrestrial biomass, the oceans present a significant opportunity for increasing biomass.

The Earth's crust offers another source, should the need arise for even more carbon to be actively integrated into organotechnological metabolic cycles. Around 80 gigatons of inorganic carbon linger in the volume of the Earth's crust per one meter of depth, when only considering the total land area not covered by water, as carbon makes up for around 0.02 % of the crust by weight.

Nitrogen, which constitutes about 78 % of the Earth's troposphere by volume in the form of dinitrogen, amounts to approximately 2.94 billion gigatons. Given this abundance, nitrogen is not likely to be a limiting factor within the constraints set by carbon availability and the average nitrogen content of biological life, which is about 4 %.

Water on Earth, totaling around 1.386×10^{21} gigatons, with over 96 % as seawater, offers a virtually endless supply of oxygen and hydrogen.

Phosphorus and sulfur, key components of biological organisms, also warrant consideration. Phosphorus constitutes about 1 % and sulfur around 0.3 % of the dry weight of organisms. Both elements are more abundant in seawater and the Earth's crust, indicating that they are unlikely to limit biomass scalability.

When considering the composition of the Earth's crust, silicon dioxide and its derivatives are by far the most abundant molecules. Thus, it can be estimated that silicon may play a more significant functional and structural role in the future, particularly in the context of biomineralization and a small number of organosilicon natural products might be discovered. However, the likelihood of silicon-based life forms, analogous to carbon-based life, seems limited. This limitation is due to silicon's high affinity for oxygen, and the great abundance of oxygen on Earth and in the Universe as far as we can tell today, as well as the considerable amount of energy required to transform silicon compounds into silane polymers instead of a meshwork of silicone oxide chains. Instead, silicon chemistry is likely to remain predominantly the chemistry of rocks (Petkowski et al., 2020).

Other abundant elements, such as aluminum, iron, calcium, sodium, magnesium, potassium, and titanium, will likely play more prominent roles in structural and enzymatic functions due to their relative abundance. All values have been taken from Wolfram alpha and Wikipedia (Calculation of Earth's and Life's elements, 2023).

4.0 Conclusion

4.1 Summary

This work has presented and discussed imminent future developments, offering insights into the current state of technological innovations and understanding the trajectory of these developments. Central to this work is the presentation of both a probable and desirable anthropocentric future vision, as well as a further biocentric vision. These visions are grounded in a concise and comprehensive overview of current technological advancements in information science and molecular biology-focused sciences, particularly chemistry and biology.

The extrapolation of these advancements follows identified fundamental trends and is situated within a stringent research methodology. This approach has enabled the provision of informed and vivid future visions. These visions not only highlight probable and inspirational possibilities but also present solutions to current global challenges. They illuminate relevant fields of research and articulate the geometry and logic of how current advancements impact society.

4.2 Outlook

Within the constraints of time and scope, numerous intriguing fields and topics remain unexplored in this work. One such area is the magical world of evolutionary computing, with its vast array of bio-inspired algorithms (Darwish, 2018, Kumar et al., 2023b, Del Ser et al., 2019, Malik et al., 2021). These algorithms are not only directly relevant to the futures visions presented but also offer rich analogies to organizational properties and dynamics of individuals and societies, providing valuable insights and inspiration.

Another area ripe for deeper exploration is the realm of cognitive and intelligence architectures. Examining the three main conceptual viewpoints of artificial intelligence research — symbolism, connectionism, and behaviorism — through the lens of cognitive anthropology presents an intriguing prospect (Zhang and Lu, 2021). Related fields and topics such as world models, reasoning, self-reflection, and self-consistency further offer fascinating

insights and provide ample inspiration for, intersections with, and analogies to anthropological fields and inquiries as well. Additionally, reflecting on algorithmic techniques relevant for artificial intelligence, such as mathematically implementing human traits and abilities - for example state estimations with unknown governing equations (Course and Nair, 2023) - offers a promising area of research.

The vast field of digital minds (Shulman and Bostrom, 2021), cyber-physical social systems (Huang et al., 2021, Porkodi et al., 2020, Tan et al., 2020, Yilma et al., 2021, Zeng et al., 2020, Zhou et al., 2019b), artificial societies, computational experiments, and parallels systems (Feng et al., 2019, Wen et al., 2012, Xue et al., 2022), along with evolutionary algorithms, presents a fertile ground for anthropological inquiry. These areas, along with the emergent field of agent social sciences in general (Bai et al., 2023a), show great promise and suitability for further exploration.

Automata theory, complex systems theory, assembly theory, and the law of increasing functional information were only briefly touched upon in this work. These concepts, along with related ideas surrounding logics, perception, consciousness, senses, information, as well as systems thinking and theory, will be the in the focus of future examinations, particularly in the context of the futures visions presented here.

Specific research questions from the fields of anthropology of consciousness, cognitive anthropology, material culture, digital humanities (Berry and Fagerjord, 2017), mythology and rites, and anthropology of technology will be further elaborated, building upon the solid foundation of this work.

Lastly, with the hope of receiving adequate funding, the author aspires to establish *MeSciA*, a *Multi-enabled Scientific Assistant* he envisioned and developed, at the University of Vienna.

5.0 Mediography

5.1 Table of Figures

Figure 1. Artistic Visualization of Mandelbrot set and Feigenbaum set generated with DALL-E3 (above on first page)	2
Figure 2. Interactive Metabolic Pathways Map for Escherichia coli	65
Figure 3. Docking Optimization produced with PyMOL (Schrödinger,LLC)	134
Figure 4. ¹ HNMR ensemble LEU2, cartoon representation in pymol	137
Figure 5. RNAfold generated interaction of mRNA and sRNA.....	138
Figure 6. Symbolic Representation of the two RNAs' folding in Figure 5	138

5.2 Internet resources

AI spring - Stanford, <https://hai.stanford.edu/news/ai-spring-four-takeaways-major-releases-foundation-models>, 07.08.2023

Altown - <https://github.com/a16z-infra/ai-town/blob/main/README.md> ; 09.01.2024

Alphafold database - <https://www.deepmind.com/blog/alphafold-reveals-the-structure-of-the-protein-universe> ;25.09.2023

Alphafold Mania - <https://www.nature.com/articles/d41586-022-00997-5> ; 25.09.2023

Amazon robots - <https://www.bbc.com/news/technology-67163680> ; 20.10.2023

AudioCraft - <https://audiocraft.metademolab.com>, 08.08.2023

Autonomous agents - <https://lilianweng.github.io/posts/2023-06-23-agent/> ; visited 14.09.2023

Autonomous taxis - <https://www.nytimes.com/2023/08/22/us/california-autonomous-vehicles.html>; 19.09.2023

Autotrain-advanced - <https://www.youtube.com/watch?v=LslC2nKEEGU>, 02.08.2023

Biomes - <https://docs.biomes.gg> ; 09.01.2024

Brain Computer Interface - <https://www.biopharmatrend.com/post/650-top-10-companies-shaping-the-brain-computer-interface-landscape-invasive-vs-non-invasive-bci-technology/> ; <https://theconversation.com/weve-been-connecting-brains-to-computers-longer-than-you-d-expect-these-3-companies-are-leading-the-way-197023> ; <https://www.eletimes.com/top-10-brain-computer-interface-companies-in-the-world> ; all visited 23.09.2023

Calculation of Earth's and Life's Elements - <https://www.wolframalpha.com/> ;
<https://en.wikipedia.org/wiki/> ; both visited 25.07.2023

Capturing Lofoten in Unreal Engine 5 - <https://www.youtube.com/watch?v=ifryjffUJT8>,
30.07.2023

Cerebras - <https://spectrum.ieee.org/ai-supercomputer-2662304872> ; visited 13.09.2023

ChatGPT App build - <https://www.youtube.com/watch?v=UfxLKdNTXW8>, 30.07.2023

ChatGPT coding March - <https://blog.enterprisedna.co/chatgpt-for-coding-user-guide-with-examples/>; <https://andrewmayneblog.wordpress.com/2023/03/23/chatgpt-code-interpreter-magic/>; both visited 05.08.2023

ChatGPTs store - <https://chat.openai.com/gpts>; 11.01.2024

Cloud computing growth -
<https://www.forbes.com/sites/forbestechcouncil/2023/07/24/powering-the-growth-of-cloud-computing-infrastructure-challenges-and-solutions/> ; 20.10.2023

Computation Efficiency - <https://www.sap.com/insights/viewpoints/6-surprising-innovations-for-the-future-of-computing.html> ; 20.10.2023

Custom Instructions Prompt -
https://www.reddit.com/r/ChatGPTPro/comments/15ffpx3/reddit_what_are_your_best_custom_instructions_for/ ; visited 14.09.2023

Deepmind's RT-2 - <https://www.deepmind.com/blog/rt-2-new-model-translates-vision-and-language-into-action>; 30.07.2023

EnCodec preprint - <https://dl.fbaipublicfiles.com/encodec/Diffusion/paper.pdf>, 08.08.2023

Flowise AI - <https://www.youtube.com/watch?v=osErkJ2h9tE>, 30.07.2023

Global inequality - <https://devinit.org/resources/inequality-global-trends>, 04.08.2023

Godot - <https://godotengine.org> ; <https://www.hitberrygames.com/post/godot-vs-unity-2023-which-game-engine-is-the-best-one#:~:text=If%20your%20project%20heavily%20relies,compelling%20option%20for%20many%20developers.> ;both visited 04.10.2023

High Quality Face Mocap in Unreal Engine 5 -
<https://www.youtube.com/watch?v=knf7AH2iqHA>, 30.07.2023

HPL - <https://www.datacenter-insider.de/kritik-an-linpack-basiertem-ranking-der-top500-a-847690/>, 04.08.2023

Huggingface - https://huggingface.co/spaces/HuggingFaceH4/open_llm_leaderboard, 30.07.2023

Humanoid Robots - <https://www.axios.com/2023/03/17/robots-humanoid-figure-tesla-robotics-ai> ;visited 18.10.2023

Humanoids - <https://www.therobotreport.com/humanoids-ready-to-take-first-steps/> ;26.09.2023

Investments in AI, <https://ourworldindata.org/ai-investments>, 24.07.2023

McKinsey - bio-revolution; <https://www.mckinsey.com/industries/life-sciences/our-insights/the-bio-revolution-innovations-transforming-economies-societies-and-our-lives> ; visited 20.09.2023

Medical Chat Bot - <https://www.youtube.com/watch?v=kXuHxI5ZcG0>, 02.08.2023

Megatrends - <https://www.zukunftsinstitut.de/dossier/megatrends/#definition> ;10.10.2023

Metaverse Standards-Forum - <https://metaverse-standards.org> ; 23.09.2023

Microsoft Inspire 2023 Keynote Speech - https://www.youtube.com/watch?v=RhwVMt_XCUE, 22.07.2023

Mistral benchmarks - https://www.reddit.com/r/LocalLLaMA/comments/170qtj3/mistral_vs_mistral_finetunes_vs_13b_vs_llama70b/ , 17.10.2023

NASA Science Instruments - <https://science.nasa.gov/learn/basics-of-space-flight/chapter12-1/> ; 13.10.2023

Nuclear AI - <https://futureoflife.org> ; visited 9.10.2023

NVIDIA, 18 Exaflops - <https://nvidianews.nvidia.com/news/nvidia-announces-dgx-h100-systems-worlds-most-advanced-enterprise-ai-infrastructure>, 04.08.2023

Open-Source Metaverse - <https://www.opensourceforu.com/2023/09/exploring-open-source-metaverse-platforms-unlocking-virtual-creativity/> ; 20.10.2023

OpenAI's Arrakis - <https://mpost.io/rumulations-of-openai-arrakis-to-be-even-more-powerful-than-gpt-4-and-gobi/> ; 16.10.2023

OpenInterpreter - <https://github.com/KillianLucas/open-interpreter> ; 12.01.2024

Pathway Map - <https://sbrg.github.io/escher-fba/#/app> ;15.08.2023

Phi-2 - <https://www.microsoft.com/en-us/research/blog/phi-2-the-surprising-power-of-small-language-models/> ; 10.01.2023

Planet Satellites - <https://www.planet.com/>; 08.01.2024

Quantum Decade IBM - <https://www.ibm.com/downloads/cas/J25G35OK> ; p.3; 28.09.2023

Rabbit R1 - <https://www.theverge.com/2024/1/10/24033498/rabbit-r1-sold-out-ces-ai>; 22.01.2023

RNAcofold - <https://www.tbi.univie.ac.at/RNA/RNAcofold.1.html#heading5>, 03.08.2023

Robot Density - <https://www.statista.com/chart/13645/the-countries-with-the-highest-density-of-robot-workers/> ; 19.09.2023

Robot Installations - <https://ifr.org/ifr-press-releases/news/wr-report-all-time-high-with-half-a-million-robots-installed> ; 19.09.2023

Runway Gen2 - <https://www.youtube.com/watch?v=z23-ftaGTZM>, 31.07.2023

Runway Research - <https://research.runwayml.com/gen2>, 31.07.2023

Showrunner AI - <https://www.youtube.com/watch?v=eDWbIRIHvso>, 31.07.2023

Spinlaunch - <https://www.spinlaunch.com/>; 09.01.2023

Stable Diffusion - Fabric, <https://www.youtube.com/watch?v=pqYT8JggDtw>, 31.07.2023

Suleyman - Open-Source -
<https://www.technologyreview.com/2023/09/15/1079624/deepmind-inflection-generative-ai-whats-next-mustafa-suleyman/> ; 16.09.2023 and 18.09.2023

Suno AI - <https://www.youtube.com/watch?v=UJ5zcKGrjis&t=85s>, 01.08.2023

Surveillance - <https://www.reuters.com/world/china/china-uses-ai-software-improve-its-surveillance-capabilities-2022-04-08/> ; 19.09.2023

Synthesia - <https://www.synthesia.io>, 31.07.2023

Tesla Optimus - <https://twitter.com/TeslaBotJournal/status/1740310104065634321> ; 08.01.2024

TOP500 energy consumption - <https://www.top500.org/lists/top500/list/2023/06/>, 05.08.2023

TOP500 - <https://www.top500.org>, 04.08.2023

UN global issues - <https://www.un.org/en/global-issues>, visited 11.09.2023

Unreal Engine - LLM assistant, <https://www.youtube.com/watch?v=4WXST65ImEc>, 30.07.2023

Unreal Engine 5 - Google Maps API & Cesium, <https://www.youtube.com/watch?v=TbHCvAo-aGg>, 30.07.2023

Unreal Engine 5.2 Tech Demo Full Presentation - State of Unreal GDC 2023, <https://www.youtube.com/watch?v=Dj60HHy-Kqk>, 26.07.2023

Unreal Engine 5.3 - <https://www.youtube.com/watch?v=FOi1sktOuPg>, 27.07.2023

Wes Roth - AI News, <https://www.youtube.com/watch?v=g6bBh9GT86Q&t=1127s>, 31.07.2023

Wikipedia - <https://en.wikipedia.org/wiki/> ; 25.07.2023

Wing Drones - <https://www.supplychaindive.com/news/alphabet-wing-drone-network-millions-of-deliveries/644679/> ; 19.09.2023

Wolfram alpha - <https://www.wolframalpha.com>, 05.08.2023 and 06.08.2023

XAgent - <https://blog.x-agent.net/blog/xagent/> ; 22.10.2023

Furthermore, the following sites deserve to be recognized, as they facilitated the research process for this work: [wikipedia.org](https://www.wikipedia.org), sci-hub.ru, arxiv.org, [semanticscholar.org](https://www.semanticscholar.org), [google.com](https://www.google.com), scholar.google.com, and chat.openai.com

Additionally, the manuscript editing process was done utilizing ChatGPT, particularly in simplifying the vocabulary and style of writing.

5.3 Bibliography

- ABBASI, K., RAZZAGHI, P., POSO, A., GHANBARI-ARA, S. & MASOUDI-NEJAD, A. 2021. Deep learning in drug target interaction prediction: current and future perspectives. *Current Medicinal Chemistry*, 28, 2100-2113.
- ABBOTT, A. 2016. Scientists bust myth that our bodies have more bacteria than human cells. *Nature*.

- ABDELNABI, S., GRESHAKE, K., MISHRA, S., ENDRES, C., HOLZ, T. & FRITZ, M. Not What You've Signed Up For: Compromising Real-World LLM-Integrated Applications with Indirect Prompt Injection. Proceedings of the 16th ACM Workshop on Artificial Intelligence and Security, 2023. 79-90.
- ABHISHEK PADALKAR⁶, A. P., AJINKYA JAIN¹⁰, ALEX BEWLEY⁷, ALEX HERZOG⁷, ALEX IRPAN⁷, ALEXANDER KHAZATSKY¹⁷, ANANT RAI¹⁴, A. S.,²⁰ ANTHONY BROHAN⁷, ANTONIN RAFFIN⁶, AYZAAN WAHID⁷, BEN BURGESS-LIMERICK¹⁵, BEOMJOON KIM¹², BERNHARD SCHO'LKOPF¹³, BRIAN ICHTER⁷, CEWU LU^{16,5}, CHARLES XU²⁰, CHELSEA FINN^{7,17}, CHENFENG XU²⁰, CHENG CHI³, CHENGUANG HUANG²², C. C., CHUER PAN³, CHUYUAN FU⁷, COLINE DEVIN⁷, DANNY DRIESSE⁷, DEEPAK PATHAK², DHRUV SHAH²⁰, DIETER BU'CHLER¹³, DMITRY KALASHNIKOV⁷, DORSA SADIGH⁷, EDWARD JOHNS⁹, FEDERICO CEOLA¹¹, FEI XIA⁷, FREEK STULP⁶, GAOYUE ZHOU², G. S. S., GAUTAM SALHOTRA^{24,10}, GE YAN²¹, GIULIO SCHIAVI⁴, HAO SU²¹, HAO-SHU FANG¹⁶, HAOCHEN SHI¹⁷, H. B. A., HENRIK I CHRISTENSEN²¹, HIROKI FURUTA¹⁹, HOMER WALKER²⁰, HONGJIE FANG¹⁶, IGOR MORDATCH⁷, ILIJA RADOSAVOVIC²⁰, I. L., JACKY LIANG⁷, JAEHYUNG KIM¹², JAN SCHNEIDER¹³, JASMINE HSU⁷, JEANNETTE BOHG¹⁷, JEFFREY BINGHAM⁷, J. W., JIALIN WU⁸, JIANLAN LUO²⁰, JIAYUAN GU²¹, JIE TAN⁷, JIHOON OH¹⁹, JITENDRA MALIK²⁰, JONATHAN TOMPSON⁷, J. Y., JOSEPH J. LIM¹², JOA'õO SILVE'RIO⁶, JUNHYEK HAN¹², KANISHKA RAO⁷, KARL PERTSCH²⁰, KAROL HAUSMAN⁷, K. G., KEERTHANA GOPALAKRISHNAN⁷, KEN GOLDBERG²⁰, KENDRA BYRNE⁷, KENNETH OSLUND⁷, KENTO KAWAHARAZUKA¹⁹, KEVIN ZHANG², KEYVAN MAJD¹, KRISHAN RANA¹⁵, KRISHNAN SRINIVASAN¹⁷, LAWRENCE YUNLIANG CHEN²⁰, LERREL PINTO¹⁴, LIAM TAN²⁰, LIONEL OTT⁴, LISA LEE⁷, MASAYOSHI TOMIZUKA²⁰, MAXIMILIAN DU¹⁷, MICHAEL AHN⁷, MINGTONG ZHANG²³, MINGYU DING²⁰, MOHAN KUMAR SRIRAMA², M. S., MOO JIN KIM¹⁷, NAOAKI KANAZAWA¹⁹, NICKLAS HANSEN²¹, NICOLAS HEES⁷, NIKHIL J JOSHI⁷, NIKO SUENDERHAUF¹⁵, NORMAN DI PALO⁹, NUR MUHAMMAD MAHI SHAFIULLAH¹⁴, OIER MEES²², OLIVER KROEMER², PANNAG R SANKETI⁷, PAUL WOHLHART⁷, PENG XU⁷, PIERRE SERMANET⁷, PRIYA SUNDARESAN¹⁷, QUAN VUONG⁷, RAFAEL RAFAILOV^{7,17}, RAN TIAN²⁰, RIA DOSHI²⁰, R. M. I.-M. I., RUSSELL MENDONCA², RUTAV SHAH¹⁸, RYAN HOQUE²⁰, RYAN JULIAN⁷, SAMUEL BUSTAMANTE⁶, SEAN KIRMANI⁷, SERGEY LEVINE^{7,20}, SHERRY MOORE⁷, SHIKHAR BAHL², SHIVIN DASS²⁴, SHURAN SONG³, SICHUN XU⁷, SIDDHANT HALDAR¹⁴, SIMEON ADEBOLA²⁰, SIMON GUIST¹³, SOROUSH NASIRIANY¹⁸, STEFAN SCHAAL¹⁰, STEFAN WELKER⁷, STEPHEN TIAN¹⁷, SUDEEP DASARI², SUNEEL BELKHALE¹⁷, TAKAYUKI OSA¹⁹, TATSUYA HARADA¹⁹, TATSUYA MATSUSHIMA¹⁹, TED XIAO⁷, TIANHE YU⁷, TIANLI DING⁷, TODOR DAVCHEV⁷, T. Z. Z., TRAVIS ARMSTRONG⁷, TREVOR DARRELL²⁰, VIDHI JAIN^{7,2}, VINCENT VANHOUCKE⁷, WEI ZHAN²⁰, WENXUAN ZHOU^{7,2}, WOLFRAM BURGARD²⁵, XI CHEN⁷, XIAOLONG WANG²¹, XINGHAO ZHU²⁰, XUANLIN LI²¹, YAO LU⁷, YEVGEN CHEBOTAR⁷, YIFAN ZHOU¹, YIFENG ZHU¹⁸, YING XU⁷, YIXUAN WANG²³, YONATAN BISK², YOONYOUNG CHO¹², YOUNGWOON LEE²⁰, YUCHEN CUI¹⁷, & YUEH-HUA WU²¹, Y. T.,¹⁹ YUKE ZHU¹⁸, YUNZHU LI²³, YUSUKE IWASAWA¹⁹, YUTAKA MATSUO¹⁹, ZHUO XU⁷, ZICHEN JEFF CUI¹⁴ 2023. Open X-Embodiment: Robotic Learning Datasets and RT-X Models.
- ABMAN, S. H., BOGUE, C. W., BAKER, S., CARLO, W., DANIELS, S. R., DEBAUN, M. R., FIKE, C., GORDON, C. M., LEONARD, M. B., STEINHORN, R. H., WALKER-HARDING, L. R. & FOR THE AMERICAN PEDIATRIC, S. 2020. Racism and social injustice as determinants of

- child health: the American Pediatric Society Issue of the Year. *Pediatric Research*, 88, 691-693.
- ABRAM, K. J. & MCCLOSKEY, D. 2022. A Comprehensive Evaluation of Metabolomics Data Preprocessing Methods for Deep Learning. *Metabolites*, 12, 202.
- ABRAM, S., WALTORP, K., ORTAR, N. & PINK, S. 2022. Energy Futures: Anthropocene Challenges, Emerging Technologies and Everyday Life.
- ABRAMOV, N. S. & ABRAMOV, S. M. 2023. June 2022 Top500 list overview. *Program Systems: Theory and Applications*, 14, 49-93.
- ACAMPORA, G., TRINCHESE, P., TRINCHESE, R. & VITIELLO, A. 2023. A Serious Mixed-Reality Game for Training Police Officers in Tagging Crime Scenes. *Applied Sciences*, 13, 1177.
- ADAN, R. A., VAN DER BEEK, E. M., BUITELAAR, J. K., CRYAN, J. F., HEBEBRAND, J., HIGGS, S., SCHELLEKENS, H. & DICKSON, S. L. 2019. Nutritional psychiatry: Towards improving mental health by what you eat. *European Neuropsychopharmacology*, 29, 1321-1332.
- ADDOLORATO, G., LEGGIO, L., HOPF, F. W., DIANA, M. & BONCI, A. 2012. Novel Therapeutic Strategies for Alcohol and Drug Addiction: Focus on GABA, Ion Channels and Transcranial Magnetic Stimulation. *Neuropsychopharmacology*, 37, 163-177.
- AGOSTINELLI, A., DENK, T. I., BORSOS, Z., ENGEL, J., VERZETTI, M., CAILLON, A., HUANG, Q., JANSEN, A., ROBERTS, A., TAGLIASACCHI, M., SHARIFI, M., ZEGHIDOUR, N. & FRANK, C. H. 2023. MusicLM: Generating Music From Text. *ArXiv*, abs/2301.11325.
- AGUAYO, C. & EAMES, C. 2023. Using mixed reality (XR) immersive learning to enhance environmental education. *The Journal of Environmental Education*, 54, 58-71.
- AHMAD, I., MALAK, H. A. & ABULREESH, H. H. 2021. Environmental antimicrobial resistance and its drivers: a potential threat to public health. *Journal of Global Antimicrobial Resistance*, 27, 101-111.
- AHMED, M. A. & MOHAMED, A. A. 2023. Recent progress in semiconductor/graphene photocatalysts: synthesis, photocatalytic applications, and challenges. *RSC advances*, 13, 421-439.
- AKDEL, M., PIRES, D. E., PARDO, E. P., JÄNES, J., ZALEVSKY, A. O., MÉSZÁROS, B., BRYANT, P., GOOD, L. L., LASKOWSKI, R. A. & POZZATI, G. 2022. A structural biology community assessment of AlphaFold2 applications. *Nature Structural & Molecular Biology*, 29, 1056-1067.
- AKINOSHO, T. D., OYEDELE, L. O., BILAL, M., AJAYI, A. O., DELGADO, M. D., AKINADE, O. O. & AHMED, A. A. 2020. Deep learning in the construction industry: A review of present status and future innovations. *Journal of Building Engineering*, 32, 101827.
- ALBEEDAN, M., KOLIVAND, H. & HAMMADY, R. 2023. Evaluating the Use of Mixed Reality in CSI Training through the Integration of the Task-Technology Fit and Technology Acceptance Model. *IEEE Access*.
- ALBERO, J., PENG, Y. & GARCÍA, H. 2020. Photocatalytic CO₂ reduction to C₂⁺ products. *Acs Catalysis*, 10, 5734-5749.
- ALDUNCE, P. E. A. 2023. IPCC AR6 Synthesis Report: Climate Change 2023.
- ALHARBI, W. S. & RASHID, M. 2022. A review of deep learning applications in human genomics using next-generation sequencing data. *Human Genomics*, 16, 1-20.
- ALI, A., ABOULEILA, Y., SHIMIZU, Y., HIYAMA, E., EMARA, S., MASHAGHI, A. & HANKEMEIER, T. 2019. Single-cell metabolomics by mass spectrometry: Advances, challenges, and future applications. *TrAC Trends in Analytical Chemistry*, 120, 115436.

- ALLEY, E. C., KHIMULYA, G., BISWAS, S., ALQURAISHI, M. & CHURCH, G. M. 2019. Unified rational protein engineering with sequence-based deep representation learning. *Nature Methods*, 16, 1315-1322.
- ALONSO-LERMA, B., JABALERA, Y., SAMPERIO, S., MORIN, M., FERNANDEZ, A., HILLE, L. T., SILVERSTEIN, R. A., QUESADA-GANUZA, A., REIFS, A. & FERNÁNDEZ-PEÑALVER, S. 2023. Evolution of CRISPR-associated endonucleases as inferred from resurrected proteins. *Nature Microbiology*, 8, 77-90.
- ALSAEED, B. & MANSOUR, F. R. 2020. Distance-based paper microfluidics; principle, technical aspects and applications. *Microchemical Journal*, 155, 104664.
- AMARA, R. 1991. Views on futures research methodology. *Futures*, 23, 645-649.
- AMBROGIO, S., NARAYANAN, P., OKAZAKI, A., FASOLI, A., MACKIN, C., HOSOKAWA, K., NOMURA, A., YASUDA, T., CHEN, A., FRIZ, A., ISHII, M., LUQUIN, J., KOHDA, Y., SAULNIER, N., BREW, K., CHOI, S., OK, I., PHILIP, T., CHAN, V., SILVESTRE, C., AHSAN, I., NARAYANAN, V., TSAI, H. & BURR, G. W. 2023. An analog-AI chip for energy-efficient speech recognition and transcription. *Nature*, 620, 768-775.
- AMOS, M. 2014. Population-based microbial computing: a third wave of synthetic biology? *International Journal of General Systems*, 43, 770-782.
- AMOS, M. & GOÑI-MORENO, A. 2018. Cellular computing and synthetic biology. *Computational matter*. Springer.
- ANANTRASIRICHA, N. & BULL, D. 2022. Artificial intelligence in the creative industries: a review. *Artificial Intelligence Review*, 55, 589-656.
- ANDERSON, J. & RAINIE, L. 2022. The metaverse in 2040. *Pew Research Centre*, 30.
- ANDRIANANTOANDRO, E., BASU, S., KARIG, D. K. & WEISS, R. 2006. Synthetic biology: new engineering rules for an emerging discipline. *Molecular systems biology*, 2, 2006.0028.
- ANGELO, S. & MECCARIELLO, R. 2021. Microplastics: A Threat for Male Fertility. *International Journal of Environmental Research and Public Health*, 18, 2392.
- ANGENENT-MARI, N. M., GARRUSS, A. S., SOENKSEN, L. R., CHURCH, G. & COLLINS, J. J. 2019. Deep Learning for RNA Synthetic Biology. *bioRxiv*, 872077.
- ANGENENT-MARI, N. M., GARRUSS, A. S., SOENKSEN, L. R., CHURCH, G. & COLLINS, J. J. 2020. A deep learning approach to programmable RNA switches. *Nature Communications*, 11, 5057.
- ANWAR, S., BASCOU, N. A., MENEKSE, M. & KARDGAR, A. 2019. A systematic review of studies on educational robotics. *Journal of Pre-College Engineering Education Research (J-PEER)*, 9, 2.
- ANZT, H., COJEAN, T., FLEGAR, G., GÖBEL, F., GRÜTZMACHER, T., NAYAK, P., RIBIZEL, T., TSAI, Y. M. & QUINTANA-ORTÍ, E. S. 2022. Ginkgo: A Modern Linear Operator Algebra Framework for High Performance Computing. *ACM Trans. Math. Softw.*, 48, Article 2.
- APARECIDO-KANZLER, S., CIDRAL-FILHO, F. J. & PREDIGER, R. D. 2021. Effects of binaural beats and isochronic tones on brain wave modulation: Literature review. *Revista mexicana de neurociencia*, 22, 238-247.
- APPADURAI, A. 2013. The future as cultural fact: Essays on the global condition. *Rassegna Italiana di sociologia*, 14, 649-650.
- ARIF, M., MUHMOOD, T., ZHANG, M., MAJEED, M. A., HONGLIN, Y., LIU, X. & WANG, X. 2022. Highly visible-light active, eco-friendly artificial enzyme and 3D Bi₄Ti₃O₁₂ biomimetic nanocomposite for efficient photocatalytic tetracycline hydrochloride degradation and Cr (VI) reduction. *Chemical Engineering Journal*, 434, 134491.

- ARNOLD, J. W., ROACH, J. & AZCARATE-PERIL, M. A. 2016. Emerging technologies for gut microbiome research. *Trends in microbiology*, 24, 887-901.
- ARSIWALLA, X. D., SOLÉ, R., MOULIN-FRIER, C., HERREROS, I., SÁNCHEZ-FIBLA, M. & VERSCHURE, P. 2023. The Morphospace of Consciousness: Three Kinds of Complexity for Minds and Machines. *NeuroSci*, 4, 79-102.
- ARTERO, J. M., BORRA, C. & GÓMEZ-ALVAREZ, R. 2020. Education, inequality and use of digital collaborative platforms: The European case. *The Economic and Labour Relations Review*, 31, 364-382.
- ARUNACHALAM, E., IRELAND, W., YANG, X. & NEEDLEMAN, D. 2022. Dissecting flux balances to measure energetic costs in cell biology: techniques and challenges. *Annual Review of Condensed Matter Physics*, 14.
- ASAI, A., WU, Z., WANG, Y., SIL, A. & HAJISHIRZI, H. Self-RAG: Learning to Retrieve, Generate, and Critique through Self-Reflection. 2023.
- ASK, T. F., KULLMAN, K., SÜTTERLIN, S., KNOX, B. J., ENGEL, D. & LUGO, R. G. 2023. A 3D mixed reality visualization of network topology and activity results in better dyadic cyber team communication and cyber situational awareness. *Frontiers in big Data*, 6, 1042783.
- ASKR, H., ELGELDAWI, E., ABOUL ELLA, H., ELSHAIER, Y. A., GOMAA, M. M. & HASSANIEN, A. E. 2022. Deep learning in drug discovery: an integrative review and future challenges. *Artificial Intelligence Review*, 1-63.
- AUBRY, G., LEE, H. J. & LU, H. 2023. Advances in Microfluidics: Technical Innovations and Applications in Diagnostics and Therapeutics. *Analytical Chemistry*, 95, 444-467.
- AUNG, T., GRUBBE, W. S., NUSBAUM, R. J. & MENDOZA, J. L. 2023. Recent and future perspectives on engineering interferons and other cytokines as therapeutics. *Trends in Biochemical Sciences*.
- AWAN, M. J. A., AWAN, M. R. A., AMIN, I. & MANSOOR, S. 2023. Fanzor: a compact programmable RNA-guided endonuclease from eukaryotes. *Trends in Biotechnology*.
- AYDIN, O., ZHANG, X., NUETHONG, S., PAGAN-DIAZ, G. J., BASHIR, R., GAZZOLA, M. & SAIF, M. T. A. 2019. Neuromuscular actuation of biohybrid motile bots. *Proceedings of the National Academy of Sciences*, 116, 19841-19847.
- AYRES, R. U. 1997. *Information, entropy, and progress: a new evolutionary paradigm*, Springer Science & Business Media.
- AZIZI, S., KORNBILTH, S., SAHARIA, C., NOROUZI, M. & FLEET, D. J. 2023. Synthetic data from diffusion models improves imagenet classification. *arXiv preprint arXiv:2304.08466*.
- BAHDANAU, D., CHO, K. & BENGIO, Y. 2014. Neural Machine Translation by Jointly Learning to Align and Translate. *CoRR*, abs/1409.0473.
- BAI, J., ZHANG, S. & CHEN, Z. 2023a. Is There Any Social Principle for LLM-Based Agents? *arXiv preprint arXiv:2308.11136*.
- BAI, X., HUANG, Z., DURAJ-THATTE, A. M., EBERT, M. P., ZHANG, F., BURGERMEISTER, E., LIU, X., SCOTT, B. M., LI, G. & ZUO, T. 2023b. Engineering the gut microbiome. *Nature Reviews Bioengineering*, 1-15.
- BAI, X.-C., MCMULLAN, G. & SCHERES, S. H. 2015. How cryo-EM is revolutionizing structural biology. *Trends in biochemical sciences*, 40, 49-57.
- BAIARDI, A., CHRISTANDL, M. & REIHER, M. 2023. Quantum computing for molecular biology. *ChemBioChem*, 24, e202300120.
- BAKER, B., KANITSCHIEDER, I., MARKOV, T., WU, Y., POWELL, G., MCGREW, B. & MORDATCH, I. 2019. Emergent Tool Use From Multi-Agent Autocurricula. *ArXiv*, abs/1909.07528.

- BAKER, D. 2020. Complexity in the future: Far-from-equilibrium systems and strategic Foresight. *The 21st Century Singularity and Global Futures: A Big History Perspective*, 397-417.
- BALAN, A. E., AL-SHAREA, A., LAVASANI, E. J., TANASA, E., VOINEA, S., DOBRICA, B. & STAMATIN, I. 2023. Paraffin-Multilayer Graphene Composite for Thermal Management in Electronics. *Materials*, 16, 2310.
- BANANI, S. F., LEE, H. O., HYMAN, A. A. & ROSEN, M. K. 2017. Biomolecular condensates: organizers of cellular biochemistry. *Nature reviews Molecular cell biology*, 18, 285-298.
- BARANWAL, M., MAGNER, A., ELVATI, P., SALDINGER, J., VIOLI, A. & HERO, A. O. 2020. A deep learning architecture for metabolic pathway prediction. *Bioinformatics*, 36, 2547-2553.
- BARRAZA, S. J., BHATTACHARYYA, A., TROTTA, C. R. & WOLL, M. G. 2022. Targeting strategies for modulating pre-mRNA splicing with small molecules: recent advances. *Drug Discovery Today*, 103431.
- BARRIO-HERNANDEZ, I., YEO, J., JÄNES, J., WEIN, T., VARADI, M., VELANKAR, S., BELTRAO, P. & STEINEGGER, M. 2023. Clustering predicted structures at the scale of the known protein universe. *bioRxiv*, 2023.03. 09.531927.
- BARTOLUCCI, S., BIRCHALL, P., BOMBIN, H., CABLE, H., DAWSON, C., GIMENO-SEGOVIA, M., JOHNSTON, E., KIELING, K., NICKERSON, N. & PANT, M. 2023. Fusion-based quantum computation. *Nature Communications*, 14, 912.
- BASALAMAH, S., KHAN, S. D., FELEMBAN, E., NASEER, A. & REHMAN, F. U. 2023. Deep learning framework for congestion detection at public places via learning from synthetic data. *Journal of King Saud University - Computer and Information Sciences*, 35, 102-114.
- BATTAT, S., WEITZ, D. A. & WHITESIDES, G. M. 2022. An outlook on microfluidics: the promise and the challenge. *Lab on a Chip*, 22, 530-536.
- BAYSAL, C., BURÉN, S., HE, W., JIANG, X., CAPELL, T., RUBIO, L. M. & CHRISTOU, P. 2022. Functional expression of the nitrogenase Fe protein in transgenic rice. *Communications Biology*, 5, 1006.
- BEAUMONT, P. B. 1973. BORDER CAVE. A PROGRESS REPORT.
- BEAUMONT, P. B. & BEDNARIK, R. G. 2013. Tracing the emergence of palaeoart in sub-Saharan Africa. *Rock Art Research: The Journal of the Australian Rock Art Research Association (AURA)*, 30, 33-54.
- BEHRENS, H. M. & SPIELMANN, T. 2023. Identification of domains in *Plasmodium falciparum* proteins of unknown function using DALI search on AlphaFold predictions. *bioRxiv*, 2023.06.05.543710.
- BELKIN, S. & CHENG, J.-Y. 2023. Miniaturized bioluminescent whole-cell sensor systems. *Current Opinion in Biotechnology*, 82, 102952.
- BELLARDITA, M., LODDO, V. & PALMISANO, L. 2020. Formation of high added value chemicals by photocatalytic treatment of biomass. *Mini-Reviews in Organic Chemistry*, 17, 884-901.
- BELLIER, L., LLORENS, A., MARCIANO, D., GUNDUZ, A., SCHALK, G., BRUNNER, P. & KNIGHT, R. T. 2023. Music can be reconstructed from human auditory cortex activity using nonlinear decoding models. *PLoS biology*, 21, e3002176.
- BENDIAB, G., HAMEURLAINE, A., GERMANOS, G., KOLOKOTRONIS, N. & SHIAELES, S. 2023. Autonomous vehicles security: Challenges and solutions using blockchain and artificial intelligence. *IEEE Transactions on Intelligent Transportation Systems*.

- BENENSON, Y. 2012. Biomolecular computing systems: principles, progress and potential. *Nature Reviews Genetics*, 13, 455-468.
- BENNETT, E. M., MURRAY, J. W. & ISALAN, M. 2023. Engineering nitrogenases for synthetic nitrogen fixation: From pathway engineering to directed evolution. *BioDesign Research*, 5, 0005.
- BERGGREN, M. & RICHTER-DAHLFORS, A. 2007. Organic bioelectronics. *Advanced Materials*, 19, 3201-3213.
- BERRY, D. M. & FAGERJORD, A. 2017. *Digital humanities: Knowledge and critique in a digital age*, John Wiley & Sons.
- BETZ, U. A. K., ARORA, L., ASSAL, R. A., AZEVEDO, H., BALDWIN, J., BECKER, M. S., BOSTOCK, S., CHENG, V., EGGLE, T., FERRARI, N., SCHNEIDER-FUTSCHIK, E. K., GERHARDY, S., HAMMES, A., HARZHEIM, A., HERGET, T., JAUSET, C., KRETSCHMER, S., LAMMIE, C., KLOSS, N., FERNANDES, S. M., MITROFAN, C.-G., MYRGORODSKA, I., NEDBALEK, D., NEUMANN, S. G., PAFFENHOLZ, S., PONCE, L. P., ROGELL, B., SAVIC, D., VELIKOVA, G., SCHUMACHER, C., WEISSHAAR, N., YAHYA, M., YANG, J. Y. C. & ZHAO, G. 2023. Game changers in science and technology - now and beyond. *Technological Forecasting and Social Change*, 193, 122588.
- BHANDAGE, A. K. & BARRAGAN, A. 2021. GABAergic signaling by cells of the immune system: more the rule than the exception. *Cell Mol Life Sci*, 78, 5667-5679.
- BHAT, A. A., NISAR, S., MUKHERJEE, S., SAHA, N., YARRAVARAPU, N., LONE, S. N., MASOODI, T., CHAUHAN, R., MAACHA, S. & BAGGA, P. 2022. Integration of CRISPR/Cas9 with artificial intelligence for improved cancer therapeutics. *Journal of Translational Medicine*, 20, 534.
- BI, S., ZENG, Q., DENG, Q., LIU, H., ZHOU, X., XIE, C., LIU, W. & LI, Y. 2023. Isolation and Identification of a Carbon-Fixing Bacteria Strain and Its Efficiency for Nitrogen and Phosphorus Removal from Viaduct Rainwater. *Water*, 15, 2916.
- BIANCHINI, F. 2018. The problem of prediction in artificial intelligence and synthetic biology. *Complex Systems*, 27, 249-265.
- BIANCHINI, F. 2023. Autopoiesis of the artificial: From systems to cognition. *Biosystems*, 104936.
- BIBA, M. & VAJJHALA, N. R. 2022. Machine Learning for Metabolic Networks Modelling: A State-of-the-Art Survey. In: ROY, S. S. & TAGUCHI, Y. H. (eds.) *Handbook of Machine Learning Applications for Genomics*. Singapore: Springer Nature Singapore.
- BICKLEY, S. J., CHAN, H. F., DAO, B., TORGLER, B. & TRAN, S. 2023. SurveyLM: A platform to explore emerging value perspectives in augmented language models' behaviors. *arXiv preprint arXiv:2308.00521*.
- BISHOP, P. & HINES, A. 2012. *Teaching about the Future*, Springer.
- BISWAS, A. & WANG, H.-C. 2023. Autonomous vehicles enabled by the integration of IoT, edge intelligence, 5G, and blockchain. *Sensors*, 23, 1963.
- BLACKISTON, D. 2023. Biological Robots: Perspectives on an Emerging Interdisciplinary Field. *Soft Robotics*, 10, 674-686.
- BLACKISTON, D., LEDERER, E., KRIEGMAN, S., GARNIER, S., BONGARD, J. & LEVIN, M. 2021. A cellular platform for the development of synthetic living machines. *Science Robotics*, 6, eabf1571.
- BLOISE, F., CHIRONI, D., DELLA PORTA, D. & PIANTA, M. 2023. Inequality and Elections in Italy, 1994–2018. *Italian Economic Journal*.

- BOGNER, M., MALETIC, J. & FRANKLIN, S. 2023. ConAg: a reusable framework for developing "conscious" software agents.
- BOISOT, M. & MCKELVEY, B. 2006. Speeding up strategic foresight in a dangerous, complex world: A complexity approach. *Corporate strategies under international terrorism and adversity*, 20-37.
- BOO, A., AMARO, R. L. & STAN, G.-B. 2021. Quorum sensing in synthetic biology: A review. *Current Opinion in Systems Biology*, 28, 100378.
- BOROWIEC, M. L., DIKOW, R. B., FRANDSEN, P. B., MCKEEN, A., VALENTINI, G. & WHITE, A. E. 2022. Deep learning as a tool for ecology and evolution. *Methods in Ecology and Evolution*, 13, 1640-1660.
- BORZUNOV, A., BARANCHUK, D., DETTMERS, T., RYABININ, M., BELKADA, Y., CHUMACHENKO, A., SAMYGIN, P. & RAFFEL, C. 2022. Petals: Collaborative inference and fine-tuning of large models. *arXiv preprint arXiv:2209.01188*.
- BOSSÙ, P., SALANI, F., CIARAMELLA, A., SACCHINELLI, E., MOSCA, A., BANAJ, N., ASSOGNA, F., ORFEI, M. D., CALTAGIRONE, C., GIANNI, W. & SPALLETTA, G. 2018. Anti-inflammatory Effects of Homotaurine in Patients With Amnesic Mild Cognitive Impairment. *Frontiers in Aging Neuroscience*, 10.
- BOSTROM, N. 2019. The vulnerable world hypothesis. *Global Policy*, 10, 455-476.
- BOSTROM, N. 2020. Ethical issues in advanced artificial intelligence. *Machine Ethics and Robot Ethics*, 69-75.
- BÖTTCHER, T. 2020. Unveiling the hidden theatre of microbes. Wiley Online Library.
- BOUTROS, F., KLEMT, M., FANG, M., KUIJPER, A. & DAMER, N. Unsupervised face recognition using unlabeled synthetic data. 2023 IEEE 17th International Conference on Automatic Face and Gesture Recognition (FG), 2023. IEEE, 1-8.
- BRINEGAR, K., K. YETISEN, A., CHOI, S., VALLILLO, E., RUIZ-ESPARZA, G. U., PRABHAKAR, A. M., KHADEMHOSEINI, A. & YUN, S.-H. 2017. The commercialization of genome-editing technologies. *Critical reviews in biotechnology*, 37, 924-932.
- BRUNBORG, G. S. & BURDZOVIC ANDREAS, J. 2019. Increase in time spent on social media is associated with modest increase in depression, conduct problems, and episodic heavy drinking. *Journal of Adolescence*, 74, 201-209.
- BRUNKE, L., GREEFF, M., HALL, A. W., YUAN, Z., ZHOU, S., PANERATI, J. & SCHOELLIG, A. P. 2022. Safe learning in robotics: From learning-based control to safe reinforcement learning. *Annual Review of Control, Robotics, and Autonomous Systems*, 5, 411-444.
- BRUNMAIR, J., GOTSMY, M., NIEDERSTAETTER, L., NEUDITSCHKO, B., BILECK, A., SLANY, A., FEUERSTEIN, M. L., LANGBAUER, C., JANKER, L., ZANGHELLINI, J., MEIER-MENCHES, S. M. & GERNER, C. 2021. Finger sweat analysis enables short interval metabolic biomonitoring in humans. *Nature Communications*, 12, 5993.
- BRYANT, P., POZZATI, G., ZHU, W., SHENOY, A., KUNDROTAS, P. & ELOFSSON, A. 2022. Predicting the structure of large protein complexes using AlphaFold and Monte Carlo tree search. *Nature communications*, 13, 6028.
- BUCH, S., EYZAGUIRRE, C., GAIDON, A., WU, J., FEI-FEI, L. & NIEBLES, J. C. Revisiting the "Video" in Video-Language Understanding. 2022 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), 18-24 June 2022 2022. 2907-2917.
- BUCHHOLZ, F., OPPERMANN, L. & PRINZ, W. 2022. There's more than one metaverse. *i-com*, 21, 313-324.
- BURÉN, S., JIMÉNEZ-VICENTE, E., ECHAVARRI-ERASUN, C. & RUBIO, L. M. 2020. Biosynthesis of nitrogenase cofactors. *Chemical Reviews*, 120, 4921-4968.

- BURGOS-MORALES, O., GUEYE, M., LACOMBE, L., NOWAK, C., SCHMACHTENBERG, R., HÖRNER, M., JEREZ-LONGRES, C., MOHSENIN, H., WAGNER, H. J. & WEBER, W. 2021. Synthetic biology as driver for the biologization of materials sciences. *Materials Today Bio*, 11, 100115.
- BUTTKIEWITZ, M. A., HEUER, C. & BAHNEMANN, J. 2023. Sensor integration into microfluidic systems: Trends and challenges. *Current Opinion in Biotechnology*, 83, 102978.
- CAI, J., ZHAO, L., HE, C., LI, Y. & DUAN, C. 2021. A host–guest semibiological photosynthesis system coupling artificial and natural enzymes for solar alcohol splitting. *Nature Communications*, 12, 5092.
- CAI, Y., AGMON, N., CHOI, W. J., UBIDE, A., STRACQUADANIO, G., CARAVELLI, K., HAO, H., BADER, J. S. & BOEKE, J. D. 2015. Intrinsic biocontainment: multiplex genome safeguards combine transcriptional and recombinational control of essential yeast genes. *Proc Natl Acad Sci U S A*, 112, 1803-8.
- CAI, Y. & ZHU, Z.-J. 2019. A high-throughput targeted metabolomics workflow for the detection of 200 polar metabolites in central carbon metabolism. *Microbial metabolomics*. Springer.
- CAMPBELL, J. 2008. *The hero with a thousand faces*, New World Library.
- CARDINALE, B. J., DUFFY, J. E., GONZALEZ, A., HOOPER, D. U., PERRINGS, C., VENAIL, P., NARWANI, A., MACE, G. M., TILMAN, D., WARDLE, D. A., KINZIG, A. P., DAILY, G. C., LOREAU, M., GRACE, J. B., LARIGAUDERIE, A., SRIVASTAVA, D. S. & NAEEM, S. 2012. Biodiversity loss and its impact on humanity. *Nature*, 486, 59-67.
- CASSAING, J. 2023. Which architecture should be implemented to manage data from the real world, in an Unreal Engine 5 simulator and in the context of mixed reality? *arXiv preprint arXiv:2305.09244*.
- CAVICCHIOLI, R., RIPPLE, W. J., TIMMIS, K. N., AZAM, F., BAKKEN, L. R., BAYLIS, M., BEHRENFELD, M. J., BOETIUS, A., BOYD, P. W., CLASSEN, A. T., CROWTHER, T. W., DANOVARO, R., FOREMAN, C. M., HUISMAN, J., HUTCHINS, D. A., JANSSON, J. K., KARL, D. M., KOSKELLA, B., MARK WELCH, D. B., MARTINY, J. B. H., MORAN, M. A., ORPHAN, V. J., REAY, D. S., REMAIS, J. V., RICH, V. I., SINGH, B. K., STEIN, L. Y., STEWART, F. J., SULLIVAN, M. B., VAN OPPEN, M. J. H., WEAVER, S. C., WEBB, E. A. & WEBSTER, N. S. 2019. Scientists' warning to humanity: microorganisms and climate change. *Nature Reviews Microbiology*, 17, 569-586.
- CEREZO, M., VERDON, G., HUANG, H.-Y., CINCIO, L. & COLES, P. J. 2022. Challenges and opportunities in quantum machine learning. *Nature Computational Science*, 2, 567-576.
- CHANCEL, L., PIKETTY, T., SAEZ, E. & ZUCMAN, G. 2022. *World inequality report 2022*, Harvard University Press.
- CHELLAMUTHU, P., TRAN, F., SILVA, K. P. T., CHAVEZ, M. S., EL-NAGGAR, M. Y. & BOEDICKER, J. Q. 2019. Engineering bacteria for biogenic synthesis of chalcogenide nanomaterials. *Microbial Biotechnology*, 12, 161-172.
- CHELLAPILLA, K., PURI, S. & SIMARD, P. <https://inria.hal.science/inria-00112631/document>
<https://inria.hal.science/inria-00112631/file/p1038112283956.pdf>. High Performance Convolutional Neural Networks for Document Processing. Tenth International Workshop on Frontiers in Handwriting Recognition, 2006-10-23 2006 La Baule (France). Suvisoft.

- CHEN, A. Y., DENG, Z., BILLINGS, A. N., SEKER, U. O. S., LU, MICHELLE Y., CITORIK, R. J., ZAKERI, B. & LU, T. K. 2014. Synthesis and patterning of tunable multiscale materials with engineered cells. *Nature Materials*, 13, 515-523.
- CHEN, B., DRAGOMIR, M. P., YANG, C., LI, Q., HORST, D. & CALIN, G. A. 2022. Targeting non-coding RNAs to overcome cancer therapy resistance. *Signal transduction and targeted therapy*, 7, 121.
- CHEN, K., ZHANG, D., YAO, L., GUO, B., YU, Z. & LIU, Y. 2021a. Deep learning for sensor-based human activity recognition: Overview, challenges, and opportunities. *ACM Computing Surveys (CSUR)*, 54, 1-40.
- CHEN, L., LI, Y., HUANG, C., XING, Y., TIAN, D., LI, L., HU, Z., TENG, S., LV, C. & WANG, J. 2023a. Milestones in autonomous driving and intelligent vehicles—part 1: Control, computing system design, communication, hd map, testing, and human behaviors. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*.
- CHEN, L., ZAHARIA, M. & ZOU, J. 2023b. How is ChatGPT's behavior changing over time? *arXiv preprint arXiv:2307.09009*.
- CHEN, M., FU, X., CHEN, Z., LIU, J. & ZHONG, W. H. 2021b. Protein-engineered functional materials for bioelectronics. *Advanced Functional Materials*, 31, 2006744.
- CHEN, W., GAO, Y., LI, Y., YAN, Y., OU, J.-Y., MA, W. & ZHU, J. 2023c. Broadband Solar Metamaterial Absorbers Empowered by Transformer-Based Deep Learning. *Advanced Science*, 10, 2206718.
- CHEN, W., SU, Y., ZUO, J., YANG, C., YUAN, C., QIAN, C., CHAN, C.-M., QIN, Y., LU, Y. & XIE, R. 2023d. Agentverse: Facilitating multi-agent collaboration and exploring emergent behaviors in agents. *arXiv preprint arXiv:2308.10848*.
- CHEN, W., WANG, L., YOU, W. & SHAN, T. 2021c. Myokines mediate the cross talk between skeletal muscle and other organs. *Journal of cellular physiology*, 236, 2393-2412.
- CHEN, Z., QING, J. & ZHOU, J. H. 2023e. Cinematic Mindscapes: High-quality Video Reconstruction from Brain Activity. *arXiv preprint arXiv:2305.11675*.
- CHENG, B., DENG, X.-H., GU, X., HE, Y., HU, G., HUANG, P., LI, J., LIN, B.-C., LU, D. & LU, Y. 2023a. Noisy intermediate-scale quantum computers. *Frontiers of Physics*, 18, 21308.
- CHENG, C., FU, J., SU, H. & REN, L. 2023b. Recent advancements in agriculture robots: Benefits and challenges. *Machines*, 11, 48.
- CHENG, H., JIA, R., LI, D. & LI, H. 2019. The rise of robots in China. *Journal of Economic Perspectives*, 33, 71-88.
- CHENG, J. Can “Neuromorphic Completeness” and “Brain-Inspired Computing” Provide a Promising Platform for Artificial General Intelligence? , 2022 Cham. Springer International Publishing, 111-119.
- CHENG, J., NOVATI, G., PAN, J., BYCROFT, C., ŽEMGULTĖ, A., APPLEBAUM, T., PRITZEL, A., WONG, L. H., ZIELINSKI, M. & SARGEANT, T. 2023c. Accurate proteome-wide missense variant effect prediction with AlphaMissense. *Science*, eadg7492.
- CHENG, K., TIAN, J. F., KOHNO, T. & ROESNER, F. Exploring user reactions and mental models towards perceptual manipulation attacks in mixed reality. *USENIX Security*, 2023d.
- CHERAGHI, S., TAHER, M. A., KARIMI-MALEH, H., KARIMI, F., SHABANI-NOOSHABADI, M., ALIZADEH, M., AL-OTHMAN, A., ERK, N., YEGYA RAMAN, P. K. & KARAMAN, C. 2022. Novel enzymatic graphene oxide based biosensor for the detection of glutathione in biological body fluids. *Chemosphere*, 287, 132187.

- CHEUNG, H.-Y., HO, M.-P., LAU, K.-T., CARDONA, F. & HUI, D. 2009. Natural fibre-reinforced composites for bioengineering and environmental engineering applications. *Composites Part B: Engineering*, 40, 655-663.
- CHO, K. W., SUNWOO, S.-H., HONG, Y. J., KOO, J. H., KIM, J. H., BAIK, S., HYEON, T. & KIM, D.-H. 2021. Soft bioelectronics based on nanomaterials. *Chemical Reviews*, 122, 5068-5143.
- CHOI, E., JO, Y., JANG, J. & SEO, M. 2022. Prompt injection: Parameterization of fixed inputs. *arXiv preprint arXiv:2206.11349*.
- CHOWDHURY, R., BOUATTA, N., BISWAS, S., FLORISTEAN, C., KHARKAR, A., ROY, K., ROCHEREAU, C., AHDRITZ, G., ZHANG, J. & CHURCH, G. M. 2022. Single-sequence protein structure prediction using a language model and deep learning. *Nature Biotechnology*, 40, 1617-1623.
- CHOWDHURY, T., LING, C., ZHANG, X., ZHAO, X., BAI, G., PEI, J., CHEN, H. & ZHAO, L. 2023. Knowledge-enhanced Neural Machine Reasoning: A Review. *arXiv preprint arXiv:2302.02093*.
- CHRISTIN, S., HERVET, É. & LECOMTE, N. 2019. Applications for deep learning in ecology. *Methods in Ecology and Evolution*, 10, 1632-1644.
- CLARK, H., CÁRDENAS, M., DYBUL, M., KAZATCHKINE, M., LIU, J., MILIBAND, D., NORDSTRÖM, A., SUDAN, P., ZEDILLO, E. & OBAID, T. 2022. Transforming or tinkering: the world remains unprepared for the next pandemic threat. *The Lancet*, 399, 1995-1999.
- CLAWSON, W. P. & LEVIN, M. 2023. Endless forms most beautiful 2.0: teleonomy and the bioengineering of chimaeric and synthetic organisms. *Biological Journal of the Linnean Society*, 139, 457-486.
- COCCIA, M. 2022. Preparedness of countries to face COVID-19 pandemic crisis: strategic positioning and factors supporting effective strategies of prevention of pandemic threats. *Environmental Research*, 203, 111678.
- COLLIAS, D. & BEISEL, C. L. 2021. CRISPR technologies and the search for the PAM-free nuclease. *Nature communications*, 12, 555.
- COLOMER, M. À., MARGALIDA, A. & PÉREZ-JIMÉNEZ, M. J. 2013. Population Dynamics P System (PDP) Models: A Standardized Protocol for Describing and Applying Novel Bio-Inspired Computing Tools. *PLOS ONE*, 8, e60698.
- CONDE, D., MARTÍNEZ, J., BALADO, J., ARIAS, P. & GEOTECH, C. Generation of road zone synthetic data for training MOT models with the NVIDIA Omniverse platform.
- COPET, J., KREUK, F., GAT, I., REMEZ, T., KANT, D., SYNNAEVE, G., ADI, Y. & DÉFOSSEZ, A. 2023. Simple and Controllable Music Generation. *arXiv preprint arXiv:2306.05284*.
- CORSARO, C., VASI, S., NERI, F., MEZZASALMA, A. M., NERI, G. & FAZIO, E. 2022. NMR in Metabolomics: From Conventional Statistics to Machine Learning and Neural Network Approaches. *Applied Sciences*, 12, 2824.
- CORVI, R., COZZOLINO, D., ZINGARINI, G., POGGI, G., NAGANO, K. & VERDOLIVA, L. On the detection of synthetic images generated by diffusion models. ICASSP 2023-2023 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), 2023. IEEE, 1-5.
- COURSE, K. & NAIR, P. B. 2023. State estimation of a physical system with unknown governing equations. *Nature*, 622, 261-267.
- COZZOLINO, M., CELIA, G., GIRELLI, L. & LIMONE, P. 2021. Effects of the Brain Wave Modulation Technique Administered Online on Stress, Anxiety, Global Distress, and Affect During the First Wave of the COVID-19 Pandemic: A Randomized Clinical Trial. *Frontiers in Psychology*, 12.

- CRAMER, B., BILLAUDELLE, S., KANYA, S., LEIBFRIED, A., GRÜBL, A., KARASENKO, V., PEHLE, C., SCHREIBER, K., STRADMANN, Y., WEIS, J., SCHEMMEL, J. & ZENKE, F. 2022. Surrogate gradients for analog neuromorphic computing. *Proceedings of the National Academy of Sciences*, 119, e2109194119.
- CUI, J., LI, Z., YAN, Y., CHEN, B. & YUAN, L. 2023. ChatLaw: Open-Source Legal Large Language Model with Integrated External Knowledge Bases. *ArXiv*, abs/2306.16092.
- D'EFOSSEZ, A., COPET, J., SYNNAEVE, G. & ADI, Y. 2022. High Fidelity Neural Audio Compression. *ArXiv*, abs/2210.13438.
- D'ERRICO, F., BACKWELL, L., VILLA, P., DEGANI, I., LUCEJKO, J. J., BAMFORD, M. K., HIGHAM, T. F. G., COLOMBINI, M. P. & BEAUMONT, P. B. 2012. Early evidence of San material culture represented by organic artifacts from Border Cave, South Africa. *Proceedings of the National Academy of Sciences*, 109, 13214-13219.
- DANG, B., WU, Q., SONG, F., SUN, J., YANG, M., MA, X., WANG, H. & HAO, Y. 2018. A bio-inspired physically transient/biodegradable synapse for security neuromorphic computing based on memristors. *Nanoscale*, 10, 20089-20095.
- DANYLOVA, T. & KOMISARENKO, S. 2020. Nobel prize winner erwin Schrödinger: the physicist, philosopher, and godfather of molecular biology and genetics. *Ukr Biochem J*, 92, 93-100.
- DARIF, D., HAMMI, I., KHELIL, A., SAIK, I. E. I., GUESSOUS, F. & AKARID, K. 2021. The pro-inflammatory cytokines in COVID-19 pathogenesis: What goes wrong? *Microbial pathogenesis*, 153, 104799.
- DARVISH, K., PENCO, L., RAMOS, J., CISNEROS, R., PRATT, J., YOSHIDA, E., IVALDI, S. & PUCCI, D. 2023. Teleoperation of humanoid robots: A survey. *IEEE Transactions on Robotics*.
- DARWISH, A. 2018. Bio-inspired computing: Algorithms review, deep analysis, and the scope of applications. *Future Computing and Informatics Journal*, 3, 231-246.
- DAVID, A., ISLAM, S., TANKHILEVICH, E. & STERNBERG, M. J. 2022. The AlphaFold database of protein structures: a biologist's guide. *Journal of molecular biology*, 434, 167336.
- DAWID, A. & LECUN, Y. 2023. Introduction to Latent Variable Energy-Based Models: A Path Towards Autonomous Machine Intelligence. *arXiv preprint arXiv:2306.02572*.
- DE LORENZIS, A. & OROFINO, V. 2014. New Possible Astronomic Alignments at the Megalithic Site of Göbekli Tepe, Turkey. *Archaeological Discovery*, 3, 40.
- DEBORDE, C., FONTAINE, J.-X., JACOB, D., BOTANA, A., NICAISE, V., RICHARD-FORGET, F., LECOMTE, S., DECOURTIL, C., HAMADE, K. & MESNARD, F. 2019. Optimizing 1D 1H-NMR profiling of plant samples for high throughput analysis: extract preparation, standardization, automation and spectra processing. *Metabolomics*, 15, 1-12.
- DEJPASAND, M. T., SAEVAR-IRANIZAD, E. & BAYAT, A. 2021. Photoluminescence enhancement of single-layer graphene quantum dots by the surface plasmon resonance of Au nanocubes. *Journal of Luminescence*, 236, 118070.
- DEL SER, J., OSABA, E., MOLINA, D., YANG, X.-S., SALCEDO-SANZ, S., CAMACHO, D., DAS, S., SUGANTHAN, P. N., COELLO, C. A. C. & HERRERA, F. 2019. Bio-inspired computation: Where we stand and what's next. *Swarm and Evolutionary Computation*, 48, 220-250.
- DELALAT, B., SHEPPARD, V. C., RASI GHAEMI, S., RAO, S., PRESTIDGE, C. A., MCPHEE, G., ROGERS, M.-L., DONOGHUE, J. F., PILLAY, V., JOHNS, T. G., KRÖGER, N. & VOELCKER, N. H. 2015. Targeted drug delivery using genetically engineered diatom biosilica. *Nature Communications*, 6, 8791.

- DELANEY, K., SAUER, C. S., VU, N. Q. & LI, L. 2019. Recent Advances and New Perspectives in Capillary Electrophoresis-Mass Spectrometry for Single Cell “Omics”. *Molecules*, 24, 42.
- DELLA SANTINA, C., DURIEZ, C. & RUS, D. 2023. Model-Based Control of Soft Robots: A Survey of the State of the Art and Open Challenges. *IEEE Control Systems Magazine*, 43, 30-65.
- DELONG, L. N., MIR, R. F., WHYTE, M., JI, Z. & FLEURIOT, J. D. 2023. Neurosymbolic ai for reasoning on graph structures: A survey. *arXiv preprint arXiv:2302.07200*.
- DENG, X., WANG, L., GUI, J., JIANG, P., CHEN, X., ZENG, F. & WAN, S. 2023a. A review of 6G autonomous intelligent transportation systems: Mechanisms, applications and challenges. *Journal of Systems Architecture*, 142, 102929.
- DENG, Y., PASKERT, A., ZHANG, Z., WITTKOWSKI, R. & AHMED, D. 2023b. An acoustically controlled helical microrobot. *Science Advances*, 9, eadh5260.
- DING, J., MA, S., DONG, L., ZHANG, X., HUANG, S., WANG, W. & WEI, F. 2023. LongNet: Scaling Transformers to 1,000,000,000 Tokens. *arXiv preprint arXiv:2307.02486*.
- DING, Z. & LIN, L. 2023. Simultaneous estimation of multiple eigenvalues with short-depth quantum circuit on early fault-tolerant quantum computers. *arXiv preprint arXiv:2303.05714*.
- DIXON, T. A., FREEMONT, P. S., JOHNSON, R. A. & PRETORIUS, I. S. 2022. A global forum on synthetic biology: the need for international engagement. *Nature Communications*, 13, 1-5.
- DIXON, T. A., WILLIAMS, T. C. & PRETORIUS, I. S. 2021. Sensing the future of bio-informational engineering. *Nature Communications*, 12, 388.
- DMITRENKO, A. 2022. *Artificial Intelligence for Long-Term Reproducible High-Throughput Untargeted Metabolomics*. ETH Zurich.
- DONG, D. T. & TONEVA, M. Interpreting Multimodal Video Transformers Using Brain Recordings. ICLR 2023 Workshop on Multimodal Representation Learning: Perks and Pitfalls, 2023.
- DONG, Y., WANG, Z., SREEDHAR, M. N., WU, X. & KUCHAIEV, O. SteerLM: Attribute Conditioned SFT as an (User-Steerable) Alternative to RLHF. 2023.
- DORIGO, M., THERAULAZ, G. & TRIANNI, V. 2020. Reflections on the future of swarm robotics. *Science Robotics*, 5, eabe4385.
- DORIGO, M., THERAULAZ, G. & TRIANNI, V. 2021. Swarm robotics: Past, present, and future [point of view]. *Proceedings of the IEEE*, 109, 1152-1165.
- DOURISH, P. 2016. Rematerializing the platform: Emulation and the digital-material. *Digital materialities: Design and anthropology*, 29-44.
- DU, X., LI, Y., XIA, Y.-L., AI, S.-M., LIANG, J., SANG, P., JI, X.-L. & LIU, S.-Q. 2016. Insights into protein–ligand interactions: mechanisms, models, and methods. *International journal of molecular sciences*, 17, 144.
- DURAIRAJ, J., WATERHOUSE, A. M., METS, T., BRODIAZHENKO, T., ABDULLAH, M., STUDER, G., TAURIELLO, G., AKDEL, M., ANDREEVA, A. & BATEMAN, A. 2023. Uncovering new families and folds in the natural protein universe. *Nature*, 1-3.
- DURAK, G. M., LAUMANN, M., WOLF, S. L., PAWAR, A., GEBAUER, D. & BÖTTCHER, T. 2019. Pseudo-biomineralization: Complex mineral structures shaped by microbes. *ACS Biomaterials Science & Engineering*, 5, 5088-5096.
- DUSHKIN, R. V. & STEPANKOV, V. Y. 2021. Hybrid Bionic Cognitive Architecture for Artificial General Intelligence Agents. *Procedia Computer Science*, 190, 226-230.

- DYSON, G. B. 2012. *Darwin among the machines: The evolution of global intelligence*, Basic Books.
- EDITORIAL, N. M. 2022. Decoding noncoding RNAs. *Nature Methods*, 19, 1147-1148.
- EGGER, D. J., CAPECCEI, C., POKHAREL, B., BARKOUTSOS, P. K., FISCHER, L. E., GUIDONI, L. & TAVERNELLI, I. 2023. A study of the pulse-based variational quantum eigensolver on cross-resonance based hardware. *arXiv preprint arXiv:2303.02410*.
- EINSLE, O. & REES, D. C. 2020. Structural enzymology of nitrogenase enzymes. *Chemical reviews*, 120, 4969-5004.
- EL-WAJEH, Y. A. M., HATTON, P. V. & LEE, N. J. 2022. Unreal Engine 5 and immersive surgical training: translating advances in gaming technology into extended-reality surgical simulation training programmes. *British Journal of Surgery*, 109, 470-471.
- ELLER, J. D. 2022. Space Colonization and Exonationalism: On the Future of Humanity and Anthropology. *Humans*, 2, 148-160.
- ELLIS, K., WONG, L., NYE, M., SABLE-MEYER, M., CARY, L., ANAYA POZO, L., HEWITT, L., SOLAR-LEZAMA, A. & TENENBAUM, J. B. 2023. DreamCoder: growing generalizable, interpretable knowledge with wake-sleep Bayesian program learning. *Philosophical Transactions of the Royal Society A*, 381, 20220050.
- ELLWANGER, J. H., KULMANN-LEAL, B., KAMINSKI, V. L., VALVERDE-VILLEGAS, J., VEIGA, A. B. G., SPILKI, F. R., FEARNESIDE, P. M., CAESAR, L., GIATTI, L. L. & WALLAU, G. L. 2020. Beyond diversity loss and climate change: Impacts of Amazon deforestation on infectious diseases and public health. *Anais da Academia Brasileira de Ciências*, 92.
- EMILIANI, V., ENTICHEVA, E., HEDRICH, R., HEGEMANN, P., KONRAD, K. R., LÜSCHER, C., MAHN, M., PAN, Z.-H., SIMS, R. R. & VIEROCK, J. 2022. Optogenetics for light control of biological systems. *Nature Reviews Methods Primers*, 2, 55.
- ENDY, D. 2005. Foundations for engineering biology. *Nature*, 438, 449-453.
- ENTICHEVA, E. & KAY, M. W. 2021. Cardiac optogenetics: a decade of enlightenment. *Nature Reviews Cardiology*, 18, 349-367.
- ESEVERRI, Á., LÓPEZ-TORREJÓN, G., JIANG, X., BURÉN, S., RUBIO, L. M. & CARO, E. 2020. Use of synthetic biology tools to optimize the production of active nitrogenase Fe protein in chloroplasts of tobacco leaf cells. *Plant biotechnology journal*, 18, 1882-1896.
- ESKANDAR, K. 2023. Revolutionizing biotechnology and bioengineering: unleashing the power of innovation. *J Appl Biotechnol Bioeng*, 10, 81-88.
- ESSER, P., ROMBACH, R. & OMMER, B. Taming transformers for high-resolution image synthesis. Proceedings of the IEEE/CVF conference on computer vision and pattern recognition, 2021. 12873-12883.
- FAN, D., WANG, J., WANG, E. & DONG, S. 2020. Propelling DNA Computing with Materials' Power: Recent Advancements in Innovative DNA Logic Computing Systems and Smart Bio-Applications. *Advanced Science*, 7, 2001766.
- FANG, K., PARK, O.-J. & HONG, S. H. 2020a. Controlling biofilms using synthetic biology approaches. *Biotechnology advances*, 40, 107518.
- FANG, M., HUBER, M. & DAMER, N. Synthaspoof: Developing face presentation attack detection based on privacy-friendly synthetic data. Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, 2023. 1061-1070.
- FANG, Y., MENG, L., PROMINSKI, A., SCHAUMANN, E. N., SEEBALD, M. & TIAN, B. 2020b. Recent advances in bioelectronics chemistry. *Chem Soc Rev*, 49, 7978-8035.
- FAUST, K. & RAES, J. 2012. Microbial interactions: from networks to models. *Nature Reviews Microbiology*, 10, 538-550.

- FAWZY, S., OSMAN, A. I., DORAN, J. & ROONEY, D. W. 2020. Strategies for mitigation of climate change: a review. *Environmental Chemistry Letters*, 18, 2069-2094.
- FEDOREC, A. J. H., TRELOAR, N. J., WEN, K. Y., DEKKER, L., ONG, Q. H., JURKEVICIUTE, G., LYU, E., RUTTER, J., ROSA, L., ZAIKIN, A. & BARNES, C. P. 2023. Emergent digital bio-computation through spatial diffusion and engineered bacteria. *bioRxiv*, 2023.07.07.548081.
- FEINBERG, A. W. 2015. Biological Soft Robotics. *Annual Review of Biomedical Engineering*, 17, 243-265.
- FENG, L., WANG, Z., JIA, D., ZOU, X., RAO, M., HUANG, Z., KUANG, C., YE, J., CHEN, C. & HUANG, C. 2023. Functional metabolism pathways of significantly regulated genes in *Nannochloropsis oceanica* with various nitrogen/phosphorus nutrients for CO₂ fixation. *Science of The Total Environment*, 883, 163318.
- FENG, X., JIA, Y., CAI, P., FEI, J. & LI, J. 2016. Coassembly of Photosystem II and ATPase as Artificial Chloroplast for Light-Driven ATP Synthesis. *ACS Nano*, 10, 556-561.
- FENG, Z., ZHU, S., WU, J. & GUO, H. 2019. Theory and method of time-varying computational experiments for the fully mechanized mining process in an artificial system environment. *IEEE Access*, 7, 168162-168174.
- FENWICK, M. & JURCYS, P. 2023. Originality and the Future of Copyright in an Age of Generative AI. *Available at SSRN 4354449*.
- FERNANDEZ-RODRIGUEZ, J., MOSER, F., SONG, M. & VOIGT, C. A. 2017. Engineering RGB color vision into *Escherichia coli*. *Nature Chemical Biology*, 13, 706-708.
- FERNANDO, C., BANARSE, D., MICHALEWSKI, H., OSINDERO, S. & ROCKTÄSCHEL, T. 2023. Promptbreeder: Self-Referential Self-Improvement Via Prompt Evolution. *arXiv preprint arXiv:2309.16797*.
- FERRUZ, N., SCHMIDT, S. & HÖCKER, B. 2022. ProtGPT2 is a deep unsupervised language model for protein design. *Nature Communications*, 13, 4348.
- FESSLER, M., MADSEN, J. S. & ZHANG, Y. 2022. Microbial interactions in electroactive biofilms for environmental engineering applications: a role for nonexoelectrogens. *Environmental Science & Technology*, 56, 15273-15279.
- FLEMMING, H.-C. & WUERTZ, S. 2019. Bacteria and archaea on Earth and their abundance in biofilms. *Nature Reviews Microbiology*, 17, 247-260.
- FLOREANO, D. & LIPSON, H. 2021. From individual robots to robot societies. American Association for the Advancement of Science.
- FLORIDI, L. 2002. *Philosophy and computing: An introduction*, Routledge.
- FLORIDI, L. 2008. A defence of informational structural realism. *Synthese*, 161, 219-253.
- FLORIDI, L. 2014. *The fourth revolution: How the infosphere is reshaping human reality*, OUP Oxford.
- FORRESTER, J. W. 1971. Counterintuitive behavior of social systems. *Theory and decision*, 2, 109-140.
- FRANKE, J. K., RUNGE, F. & HUTTER, F. 2023. Scalable Deep Learning for RNA Secondary Structure Prediction. *arXiv preprint arXiv:2307.10073*.
- FRANKLIN, S. 1997. Autonomous agents as embodied AI. *Cybernetics & Systems*, 28, 499-520.
- FRANKLIN, S. & GRAESSER, A. Is it an Agent, or just a Program?: A Taxonomy for Autonomous Agents. International workshop on agent theories, architectures, and languages, 1996. Springer, 21-35.
- FRANKLIN, S. & GRAESSER, A. 1999. A Software Agent Model of Consciousness. *Consciousness and Cognition*, 8, 285-301.

- FRENCH, E., KAPLAN, I., IYER-PASCUZZI, A., NAKATSU, C. H. & ENDERS, L. 2021. Emerging strategies for precision microbiome management in diverse agroecosystems. *Nature plants*, 7, 256-267.
- FRISTON, K. 2023. The sentient organoid? *Frontiers in Science*, 0.
- FRISTON, K., MORAN, R. J., NAGAI, Y., TANIGUCHI, T., GOMI, H. & TENENBAUM, J. 2021. World model learning and inference.
- FRITSCHER, M., VERONESI, A., BARONI, A., WEN, J., SPÄTLING, T., MAHADEVAIAH, M. K., HERFURTH, N., PEREZ, E., ULBRICHT, M. & REICHENBACH, M. Prototyping Reconfigurable RRAM-Based AI Accelerators Using the RISC-V Ecosystem and Digital Twins. International Conference on High Performance Computing, 2023. Springer, 500-514.
- FU, L., CAO, Y., WU, J., PENG, Q., NIE, Q. & XIE, X. 2022. UFold: fast and accurate RNA secondary structure prediction with deep learning. *Nucleic acids research*, 50, e14-e14.
- FU, Z., ZHAO, T. Z. & FINN, C. Mobile ALOHA: Learning Bimanual Mobile Manipulation with Low-Cost Whole-Body Teleoperation. 2024.
- FUKUYAMA, F. 2004. Transhumanism. *Foreign policy*, 42-43.
- GABRIEL, I. 2020. Artificial intelligence, values, and alignment. *Minds and machines*, 30, 411-437.
- GALAN, E. A., ZHAO, H., WANG, X., DAI, Q., HUCK, W. T. & MA, S. 2020. Intelligent microfluidics: The convergence of machine learning and microfluidics in materials science and biomedicine. *Matter*, 3, 1893-1922.
- GANAH, M., BEALL, J., HAURU, M., LEWIS, A. G., WOJNO, T., YOO, J. H., ZOU, Y. & VIDAL, G. 2023. Density matrix renormalization group with tensor processing units. *PRX Quantum*, 4, 010317.
- GARCIA, A. K., KOLACZKOWSKI, B. & KAÇAR, B. 2022. Reconstruction of nitrogenase predecessors suggests origin from maturase-like proteins. *Genome Biology and Evolution*, 14, evac031.
- GARCIA, A. K., MCSHEA, H., KOLACZKOWSKI, B. & KAÇAR, B. 2020. Reconstructing the evolutionary history of nitrogenases: Evidence for ancestral molybdenum-cofactor utilization. *Geobiology*, 18, 394-411.
- GAUDELLI, N. M., KOMOR, A. C., REES, H. A., PACKER, M. S., BADRAN, A. H., BRYSON, D. I. & LIU, D. R. 2017. Programmable base editing of A•T to G•C in genomic DNA without DNA cleavage. *Nature*, 551, 464-471.
- GEISMAR, H. & KNOX, H. 2021. *Digital anthropology*, Routledge.
- GELERTER, H. L. & ROCHESTER, N. 1958. Intelligent behavior in problem-solving machines. *IBM Journal of Research and Development*, 2, 336-345.
- GEMMATI, D., VARANI, K., BRAMANTI, B., PIVA, R., BONACCORSI, G., TRENTINI, A., MANFRINATO, M. C., TISATO, V., CARÈ, A. & BELLINI, T. 2020. "Bridging the Gap" Everything that Could Have Been Avoided If We Had Applied Gender Medicine, Pharmacogenetics and Personalized Medicine in the Gender-Omics and Sex-Omics Era. *International Journal of Molecular Sciences*, 21, 296.
- GENDALL, L., SCHROEDER, S. B., WILLS, P., HESSING-LEWIS, M. & COSTA, M. 2023. A Multi-Satellite Mapping Framework for Floating Kelp Forests. *Remote Sensing*, 15, 1276.
- GENTILI, P. L. 2021. Establishing a New Link between Fuzzy Logic, Neuroscience, and Quantum Mechanics through Bayesian Probability: Perspectives in Artificial Intelligence and Unconventional Computing. *Molecules*, 26, 5987.

- GENTILI, P. L. & STANO, P. 2022. Chemical Neural Networks Inside Synthetic Cells? A Proposal for Their Realization and Modeling. *Frontiers in Bioengineering and Biotechnology*, 10.
- GERHOLD, L., HOLTMANNSPÖTTER, D., NEUHAUS, C., SCHÜLL, E., SCHULZ-MONTAG, B., STEINMÜLLER, K. & ZWECK, A. 2022. *Standards of Futures Research: Guidelines for Practice and Evaluation*, Springer Nature.
- GHEBREAMLAK, S. M. & MANSOORABADI, S. O. 2020. Divergent Members of the Nitrogenase Superfamily: Tetrapyrrole Biosynthesis and Beyond. *ChemBioChem*, 21, 1723-1728.
- GIAMOUGIANNIS, G., TSAKYRIDIS, A., MORALIS-PEGIOS, M., PAPPAS, C., KIRTAS, M., PASSALIS, N., LAZOVSKY, D., TEFAS, A. & PLEROS, N. 2023. Analog nanophotonic computing going practical: silicon photonic deep learning engines for tiled optical matrix multiplication with dynamic precision. *Nanophotonics*, 12, 963-973.
- GLADDEN, M. 2019a. Understanding the cyber-physical-social-intentional Workforce 4.0. *Nowoczesne Systemy Zarządzania. Modern Management Systems*, 15-26.
- GLADDEN, M., FORTUNA, P. & MODLIŃSKI, A. 2022. The Empowerment of Artificial Intelligence in Post-Digital Organizations: Exploring Human Interactions with Supervisory AI. *Human Technology*, 18, 98-121.
- GLADDEN, M. E. 2017a. An Axiology of Information Security for Futuristic Neuroprostheses: Upholding Human Values in the Context of Technological Posthumanization. *Frontiers in Neuroscience*, 11.
- GLADDEN, M. E. 2017b. *Neuroprosthetic Supersystems Architecture: Considerations for the Design and Management of Neurocybernetically Augmented Organizations*, Synthyption Academic.
- GLADDEN, M. E. 2019b. Novel forms of “magical” human-computer interaction within the cyber-physical smart workplace: Implications for usability and user experience. *International Journal of Research Studies in Management*, 8, 25-48.
- GLADDEN, M. E. 2019c. Who will be the members of Society 5.0? Towards an anthropology of technologically posthumanized future societies. *Social Sciences*, 8, 148.
- GLADDEN, M. E. 2020. Revisiting Ingarden’s Theoretical Biological Account of the Literary Work of Art: is the Computer Game an "Organism"? *HORIZON. Феноменологические исследования*, 9, 640-661.
- GODA, K., LU, H., FEI, P. & GUCK, J. 2023. Revolutionizing microfluidics with artificial intelligence: a new dawn for lab-on-a-chip technologies. *Lab on a Chip*, 23, 3737-3740.
- GOMARASCA, M., BANFI, G. & LOMBARDI, G. 2020. Myokines: The endocrine coupling of skeletal muscle and bone. *Advances in clinical chemistry*, 94, 155-218.
- GONG, X., WEI, J., LIU, J., LI, R., LIU, X. & WANG, F. 2019. Programmable intracellular DNA biocomputing circuits for reliable cell recognitions. *Chemical science*, 10, 2989-2997.
- GOÑI-MORENO, A. & NIKEL, P. I. 2019. High-performance biocomputing in synthetic biology–integrated transcriptional and metabolic circuits. *Frontiers in bioengineering and biotechnology*, 7, 40.
- GRACE, K., STEWART, H., SANDKÜHLER, J. F., THOMAS, S., WEINSTEIN-RAUN, B. & BRAUNER, J. 2024. Thousands of AI Authors on the Future of AI. *arXiv preprint arXiv:2401.02843*.
- GRAHAM, S., DEPP, C., LEE, E. E., NEBEKER, C., TU, X., KIM, H.-C. & JESTE, D. V. 2019. Artificial intelligence for mental health and mental illnesses: an overview. *Current psychiatry reports*, 21, 1-18.
- GREBENYUK, S., ABDEL FATTAH, A. R., KUMAR, M., TOPRAKHISAR, B., RUSTANDI, G., VANANROYE, A., SALMON, I., VERFAILLIE, C., GRILLO, M. & RANGA, A. 2023. Large-scale perfused tissues via synthetic 3D soft microfluidics. *Nature Communications*, 14, 193.

- GRESHAKE, K., ABDELNABI, S., MISHRA, S., ENDRES, C., HOLZ, T. & FRITZ, M. 2023. More than you've asked for: A Comprehensive Analysis of Novel Prompt Injection Threats to Application-Integrated Large Language Models. *arXiv e-prints*, arXiv: 2302.12173.
- GRIFFITHS, S. 2022. How to grow concrete. *Engineering & Technology*, 17, 44-47.
- GROBER, D., PALAIA, I., UÇAR, M. C., HANNEZO, E., ŠARIĆ, A. & PALACCI, J. 2023. Unconventional colloidal aggregation in chiral bacterial baths. *Nature Physics*, 1-9.
- GROLL, T., HEMER, S., ROPERTZ, T. & BERNIS, K. 2019. Autonomous trenching with hierarchically organized primitives. *Automation in Construction*, 98, 214-224.
- GRUETZEMACHER, R. & WHITTLESTONE, J. 2022. The transformative potential of artificial intelligence. *Futures*, 135, 102884.
- GRUNWALD, A. 2009. Wovon ist die Zukunftsforschung eine Wissenschaft? *Zukunftsforschung und Zukunftsgestaltung*. Springer.
- GRUNWALD, A. Von der Immanenz der Gegenwart beim Reden über die Zukunft. 2018.
- GRUNWALD, A. 2019. Shaping the present by creating and reflecting futures. *Socio-Technical Futures Shaping the Present: Empirical Examples and Analytical Challenges*, 17-35.
- GRUNWALD, A. 2022. Validation by Argumentation. *Standards of Futures Research*. Springer.
- GRUNWALD, A. 2023. The spreading of techno-visionary futures. *Diffusive spreading in nature, technology and society*. Springer.
- GUAN, F., GUO, X., ZENG, K., ZHANG, S., NIE, Z., MA, S., DAI, Q., PENDRY, J., ZHANG, X. & ZHANG, S. 2023. Overcoming losses in superlenses with synthetic waves of complex frequency. *Science*, 381, 766-771.
- GUAN, H. 2023. Self-Inspection Method of Unmanned Aerial Vehicles in Power Plants Using Deep Q-Network Reinforcement Learning. *arXiv preprint arXiv:2303.09013*.
- GUNASEKAR, S., ZHANG, Y., ANEJA, J., CAIO, ALLIE, GOPI, S., JAVAHERIPI, M., KAUFFMANN, P., GUSTAVO, SAARIKIVI, O., SALIM, A., SHAH, S., HARKIRAT, WANG, X., BUBECK, S. E., ELDAN, R., ADAM, YIN & LI, Y. 2023. Textbooks Are All You Need. *arXiv pre-print server*.
- GUO, F., YU, F. R., ZHANG, H., LI, X., JI, H. & LEUNG, V. C. 2021a. Enabling massive IoT toward 6G: A comprehensive survey. *IEEE Internet of Things Journal*, 8, 11891-11915.
- GUO, H.-B., PERMINOV, A., BEKELE, S., KEDZIORA, G., FARAJOLLAHI, S., VARALJAY, V., HINKLE, K., MOLINERO, V., MEISTER, K. & HUNG, C. 2022. AlphaFold2 models indicate that protein sequence determines both structure and dynamics. *Scientific Reports*, 12, 10696.
- GUO, J., YU, Y., CAI, L., WANG, Y., SHI, K., SHANG, L., PAN, J. & ZHAO, Y. 2021b. Microfluidics for flexible electronics. *Materials Today*, 44, 105-135.
- GUO, S., ZHANG, C. & LE, A. 2021c. The limitless applications of single-cell metabolomics. *Current Opinion in Biotechnology*, 71, 115-122.
- GUPTA, A., FAN, L., GANGULI, S. & FEI-FEI, L. 2022. Metamorph: Learning universal controllers with transformers. *arXiv preprint arXiv:2203.11931*.
- GUPTA, J., LIVERMAN, D., PRODANI, K., ALDUNCE, P., BAI, X., BROADGATE, W., CIOBANU, D., GIFFORD, L., GORDON, C. & HURLBERT, M. 2023. Earth system justice needed to identify and live within Earth system boundaries. *Nature Sustainability*, 1-9.
- HA, D. & SCHMIDHUBER, J. 2018. World models. *arXiv preprint arXiv:1803.10122*.
- HA, Q. P., YEN, L. & BALAGUER, C. 2019. Robotic autonomous systems for earthmoving in military applications. *Automation in Construction*, 107, 102934.
- HA, T. Q., PLANJE, I. J., WHITE, J. R., ARAGONES, A. C. & DÍEZ-PÉREZ, I. 2021. Charge transport at the protein-electrode interface in the emerging field of BioMolecular Electronics. *Current Opinion in Electrochemistry*, 28, 100734.

- HAHN, M. & GOYAL, N. 2023. A theory of emergent in-context learning as implicit structure induction. *arXiv preprint arXiv:2303.07971*.
- HALICKA, K. 2016. Innovative classification of methods of the Future-oriented Technology Analysis. *Technological and Economic Development of Economy*, 22, 574-597.
- HALL, R. D., D'AURIA, J. C., FERREIRA, A. C. S., GIBON, Y., KRUSZKA, D., MISHRA, P. & VAN DE ZEDDE, R. 2022. High-throughput plant phenotyping: a role for metabolomics? *Trends in Plant Science*.
- HALUZA, D. & JUNGWIRTH, D. 2023. Artificial Intelligence and Ten Societal Megatrends: An Exploratory Study Using GPT-3. *Systems*, 11, 120.
- HAMAMAH, S., AGHAZARIAN, A., NAZARYAN, A., HAJNAL, A. & COVASA, M. 2022. Role of microbiota-gut-brain axis in regulating dopaminergic signaling. *Biomedicines*, 10, 436.
- HAMMOND, L., FOX, J., EVERITT, T., CAREY, R., ABATE, A. & WOOLDRIDGE, M. 2023. Reasoning about causality in games. *Artificial Intelligence*, 320, 103919.
- HAMOU, P. 2022. Instruments and the Senses. In: JALOBÉANU, D. & MILLER, D. M. (eds.) *The Cambridge History of Philosophy of the Scientific Revolution*. Cambridge: Cambridge University Press.
- HAN, I., JARAYAM, R., KARBASI, A., MIRROKNI, V., WOODRUFF, D. P. & ZANDIEH, A. 2023a. HyperAttention: Long-context Attention in Near-Linear Time. *arXiv preprint arXiv:2310.05869*.
- HAN, J., XU, M., XIAO, X., YI, W., JUNG, T.-P. & MING, D. 2023b. A high-speed hybrid brain-computer interface with more than 200 targets. *Journal of Neural Engineering*, 20, 016025.
- HAN, J. K., KANG, M., JEONG, J., CHO, I., YU, J. M., YOON, K. J., PARK, I. & CHOI, Y. K. 2022a. Artificial olfactory neuron for an in-sensor neuromorphic nose. *Advanced Science*, 9, 2106017.
- HAN, M. J., KIM, M. & TSUKRUK, V. V. 2022b. Multivalued Logic for Optical Computing with Photonically Enabled Chiral Bio-organic Structures. *ACS nano*.
- HAN, W., ZHANG, X., WANG, Y., WANG, L., HUANG, X., LI, J., WANG, S., CHEN, W., LI, X. & FENG, R. 2023c. A survey of machine learning and deep learning in remote sensing of geological environment: Challenges, advances, and opportunities. *ISPRS Journal of Photogrammetry and Remote Sensing*, 202, 87-113.
- HAO, S., GU, Y., MA, H., HONG, J. J., WANG, Z., WANG, D. Z. & HU, Z. 2023. Reasoning with language model is planning with world model. *arXiv preprint arXiv:2305.14992*.
- HARAWAY, D. 2013a. A cyborg manifesto: Science, technology, and socialist-feminism in the late twentieth century. *The transgender studies reader*. Routledge.
- HARAWAY, D. 2013b. *Simians, cyborgs, and women: The reinvention of nature*, Routledge.
- HARTMANN, D., CHOWDHRY, R., SMITH, J. M. & BOOTH, M. J. 2023. Orthogonal Light-Activated DNA for Patterned Biocomputing within Synthetic Cells. *Journal of the American Chemical Society*, 145, 9471-9480.
- HARTMANN, F., BAUMGARTNER, M. & KALTENBRUNNER, M. 2021. Becoming sustainable, the new frontier in soft robotics. *Advanced Materials*, 33, 2004413.
- HARTUNG, T., SMIRNOVA, L., MORALES PANTOJA, I. E., AKWABOAH, A., ALAM EL DIN, D.-M., BERLINICKE, C. A., BOYD, J. L., CAFFO, B. S., CAPIELLO, B. & COHEN-KARNI, T. 2023. The Baltimore declaration toward the exploration of organoid intelligence. *Frontiers in Science*, 0.

- HASEEB, K., REHMAN, A., SABA, T., BAHAI, S. A., WANG, H. & SONG, H. 2023. Efficient and trusted autonomous vehicle routing protocol for 6G networks with computational intelligence. *ISA transactions*, 132, 61-68.
- HASSANI, M., DURÁN, P. & HACQUARD, S. 2018. Microbial interactions within the plant holobiont. *Microbiome*, 6, 1-17.
- HAYES-ROTH, B. 1991. An integrated architecture for intelligent agents. *ACM SIGART Bulletin*, 2, 79-81.
- HE, C., LIU, Z., WU, J., PAN, X., FANG, Z., LI, J. & BRYAN, B. A. 2021. Future global urban water scarcity and potential solutions. *Nature Communications*, 12, 4667.
- HE, W., BURÉN, S., BAYSAL, C., JIANG, X., CAPELL, T., CHRISTOU, P. & RUBIO, L. M. 2022. Nitrogenase Cofactor Maturase NifB Isolated from Transgenic Rice is Active in FeMo-co Synthesis. *ACS Synthetic Biology*, 11, 3028-3036.
- HEILBRONNER, S., KRISMER, B., BRÖTZ-OESTERHELT, H. & PESCHEL, A. 2021. The microbiome-shaping roles of bacteriocins. *Nature Reviews Microbiology*, 19, 726-739.
- HEKKELMAN, M. L., DE VRIES, I., JOOSTEN, R. P. & PERRAKIS, A. 2023. AlphaFill: enriching AlphaFold models with ligands and cofactors. *Nature Methods*, 20, 205-213.
- HERMAN, D., GOOGIN, C., LIU, X., SUN, Y., GALDA, A., SAFRO, I., PISTOIA, M. & ALEXEEV, Y. 2023. Quantum computing for finance. *Nature Reviews Physics*, 1-16.
- HERNÁNDEZ, Q., BADÍAS, A., CHINESTA, F. & CUETO, E. 2023. Thermodynamics-informed neural networks for physically realistic mixed reality. *Computer Methods in Applied Mechanics and Engineering*, 407, 115912.
- HILLSON, N., CADDICK, M., CAI, Y., CARRASCO, J. A., CHANG, M. W., CURACH, N. C., BELL, D. J., LE FEUVRE, R., FRIEDMAN, D. C., FU, X., GOLD, N. D., HERRGÅRD, M. J., HOLOWKO, M. B., JOHNSON, J. R., JOHNSON, R. A., KEASLING, J. D., KITNEY, R. I., KONDO, A., LIU, C., MARTIN, V. J. J., MENOLASCINA, F., OGINO, C., PATRON, N. J., PAVAN, M., POH, C. L., PRETORIUS, I. S., ROSSER, S. J., SCRUTTON, N. S., STORCH, M., TEKOTTE, H., TRAVNIK, E., VICKERS, C. E., YEW, W. S., YUAN, Y., ZHAO, H. & FREEMONT, P. S. 2019. Building a global alliance of biofoundries. *Nature Communications*, 10.
- HOFFMAN, B. M., LUKOYANOV, D., YANG, Z.-Y., DEAN, D. R. & SEEFELDT, L. C. 2014. Mechanism of nitrogen fixation by nitrogenase: the next stage. *Chemical reviews*, 114, 4041-4062.
- HOFFMAN, K., BROWNELL, Z., DOYLE, W. J. & OCHOA-REPÁRAZ, J. 2022. The immunomodulatory roles of the gut microbiome in autoimmune diseases of the central nervous system: Multiple sclerosis as a model. *Journal of Autoimmunity*, 102957.
- HOLBROOK-SMITH, D., DUROT, S. & SAUER, U. 2022. High-throughput metabolomics predicts drug–target relationships for eukaryotic proteins. *Molecular Systems Biology*, 18, e10767.
- HOLOWKO, M. B., FROW, E. K., REID, J. C., ROURKE, M. & VICKERS, C. E. 2020. Building a biofoundry. *Synthetic Biology*, 6.
- HOLTZMAN, A., WEST, P. & ZETTMEOYER, L. 2023. Generative Models as a Complex Systems Science: How can we make sense of large language model behavior? *arXiv preprint arXiv:2308.00189*.
- HOLUB, M. & AGENA, E. 2023. Biofoundries and citizen science can accelerate disease surveillance and environmental monitoring. *Frontiers in Bioengineering and Biotechnology*, 10.

- HONG, S., ZHENG, X., CHEN, J., CHENG, Y., ZHANG, C., WANG, Z., YAU, S. K. S., LIN, Z., ZHOU, L. & RAN, C. 2023. Metagpt: Meta programming for multi-agent collaborative framework. *arXiv preprint arXiv:2308.00352*.
- HORTON, A. 2012. Complexity science approaches to the application foresight. *Foresight*, 14, 294-303.
- HSIAO, K., LEE, B. J., SAMUELSEN, T., LIPKOWITZ, G., KRONENFELD, J. M., ILYN, D., SHIH, A., DULAY, M. T., TATE, L., SHAQFEH, E. S. G. & DESIMONE, J. M. 2022. Single-digit-micrometer-resolution continuous liquid interface production. *Science Advances*, 8, eabq2846.
- HU, X. 2023. Meta Semantics: Towards better natural language understanding and reasoning. *arXiv preprint arXiv:2304.10663*.
- HUANG, H., CHATTERJEE, A., LAYTON, A. & DAVIS, K. An investigation into ecological network analysis for cyber-physical power systems. 2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), 2021. IEEE, 252-257.
- HUANG, J., LIU, S., ZHANG, C., WANG, X., PU, J., BA, F., XUE, S., YE, H., ZHAO, T., LI, K., WANG, Y., ZHANG, J., WANG, L., FAN, C., LU, T. K. & ZHONG, C. 2019. Programmable and printable *Bacillus subtilis* biofilms as engineered living materials. *Nature Chemical Biology*, 15, 34-41.
- HUANG, Y., FU, T., HUANG, H., YANG, S. & CHEN, H. 2023. Sophisticated deep learning with on-chip optical diffractive tensor processing. *Photonics Research*, 11, 1125-1138.
- HUBINGER, E., DENISON, C., MU, J., LAMBERT, M., TONG, M., MACDIARMID, M., LANHAM, T., ZIEGLER, D. M., MAXWELL, T. & CHENG, N. 2024. Sleeper Agents: Training Deceptive LLMs that Persist Through Safety Training. *arXiv preprint arXiv:2401.05566*.
- ISELL, F., BALVANERA, P., MORI, A. S., HE, J.-S., BULLOCK, J. M., REGMI, G. R., SEABLOOM, E. W., FERRIER, S., SALA, O. E., GUERRERO-RAMÍREZ, N. R., TAVELLA, J., LARKIN, D. J., SCHMID, B., OUTHWAITE, C. L., PRAMUAL, P., BORER, E. T., LOREAU, M., OMOTORIOGUN, T. C., OBURO, D. O., ANDERSON, M., PORTALES-REYES, C., KIRKMAN, K., VERGARA, P. M., CLARK, A. T., KOMATSU, K. J., PETCHEY, O. L., WEISKOPF, S. R., WILLIAMS, L. J., COLLINS, S. L., EISENHAUER, N., TRISOS, C. H., RENARD, D., WRIGHT, A. J., TRIPATHI, P., COWLES, J., BYRNES, J. E., REICH, P. B., PURVIS, A., SHARIP, Z., O'CONNOR, M. I., KAZANSKI, C. E., HADDAD, N. M., SOTO, E. H., DEE, L. E., DÍAZ, S., ZIRBEL, C. R., AVOLIO, M. L., WANG, S., MA, Z., LIANG, J., FARAH, H. C., JOHNSON, J. A., MILLER, B. W., HAUTIER, Y., SMITH, M. D., KNOPS, J. M., MYERS, B. J., HARMÁČKOVÁ, Z. V., CORTÉS, J., HARFOOT, M. B., GONZALEZ, A., NEWBOLD, T., OEHR, J., MAZÓN, M., DOBBS, C. & PALMER, M. S. 2023. Expert perspectives on global biodiversity loss and its drivers and impacts on people. *Frontiers in Ecology and the Environment*, 21, 94-103.
- JABLONKA, K. M., ONGARI, D., MOOSAVI, S. M. & SMIT, B. 2020. Big-data science in porous materials: materials genomics and machine learning. *Chemical reviews*, 120, 8066-8129.
- JACOB, S. 2015. Machines of loving grace: The city as a distributed robot & the omnipresent intelligence of data networks. *Uncube*, 36: 17, 25.
- JAEKEL, J. J., SCHWEINGRUBER, D., CHERAS, V., DOSHI, J. & BENENSON, Y. 2021. Multi-input biocomputer gene circuits for therapeutic application. *Current Opinion in Systems Biology*, 28, 100371.

- JAIN, S., OBERMEIER, G., AUINGER, A., WERTH, D. & KISS, G. 2023. Design Principles of a Mixed-Reality Shopping Assistant System in Omnichannel Retail. *Applied Sciences*, 13, 1384.
- JAMSHIDI, M., MOZTARZADEH, O., JAMSHIDI, A., ABDELGAWAD, A., EL-BAZ, A. S. & HAUER, L. 2023. Future of Drug Discovery: The Synergy of Edge Computing, Internet of Medical Things, and Deep Learning. *Future Internet*, 15, 142.
- JANCHEVA, M. & BÖTTCHER, T. 2021. A metabolite of *Pseudomonas* triggers prophage-selective lysogenic to lytic conversion in *Staphylococcus aureus*. *Journal of the American Chemical Society*, 143, 8344-8351.
- JANG, W. D., KIM, G. B., KIM, Y. & LEE, S. Y. 2022. Applications of artificial intelligence to enzyme and pathway design for metabolic engineering. *Current Opinion in Biotechnology*, 73, 101-107.
- JANZEN, N. H., STRIEDNER, G., JARMER, J., VOIGTMANN, M., ABAD, S. & REINISCH, D. 2019. Implementation of a Fully Automated Microbial Cultivation Platform for Strain and Process Screening. *Biotechnology Journal*, 14, 1800625.
- JIA, H., FLOMMERSFELD, J., HEYMANN, M., VOGEL, S. K., FRANQUELIM, H. G., BRÜCKNER, D. B., ETO, H., BROEDERSZ, C. P. & SCHWILLE, P. 2022. 3D printed protein-based robotic structures actuated by molecular motor assemblies. *Nature Materials*, 21, 703-709.
- JIANG, A. Q., SABLAYROLLES, A., MENSCH, A., BAMFORD, C., CHAPLOT, D. S., CASAS, D. D. L., BRESSAND, F., LENGUEL, G., LAMPLE, G. & SAULNIER, L. 2023a. Mistral 7B. *arXiv preprint arXiv:2310.06825*.
- JIANG, F., PENG, Y., DONG, L., WANG, K., YANG, K., PAN, C. & YOU, X. 2023b. Large AI Model Empowered Multimodal Semantic Communications. *arXiv preprint arXiv:2309.01249*.
- JIANG, K., LIM, J., SGRIZZI, S., TRINH, M., KAYABOLEN, A., YUTIN, N., BAO, W., KATO, K., KOONIN, E. V. & GOOTENBERG, J. S. 2023c. Programmable RNA-guided DNA endonucleases are widespread in eukaryotes and their viruses. *Science Advances*, 9, eadk0171.
- JIANG, X., MENG, L., LI, S. & WU, D. 2023d. Active poisoning: efficient backdoor attacks on transfer learning-based brain-computer interfaces. *Science China Information Sciences*, 66, 1-22.
- JIANG, Y., DONG, K., LI, X., AN, J., WU, D., PENG, X., YI, J., NING, C., CHENG, R. & YU, P. 2021. Stretchable, washable, and ultrathin triboelectric nanogenerators as skin-like highly sensitive self-powered haptic sensors. *Advanced Functional Materials*, 31, 2005584.
- JIANG, Y., GUPTA, A., ZHANG, Z., WANG, G., DOU, Y., CHEN, Y., FEI-FEI, L., ANANDKUMAR, A., ZHU, Y. & FAN, L. 2022. Vima: General robot manipulation with multimodal prompts. *arXiv preprint arXiv:2210.03094*.
- JIN, Z., MENDU, S. K. & BIRNIR, B. 2013. GABA is an effective immunomodulatory molecule. *Amino Acids*, 45, 87-94.
- JIRAYUPAT, C., NAGASHIMA, K., HOSOMI, T., TAKAHASHI, T., SAMRANSUKSAMER, B., HANAI, Y., NAKAO, A., NAKATANI, M., LIU, J. & ZHANG, G. 2022. Breath odor-based individual authentication by an artificial olfactory sensor system and machine learning. *Chemical Communications*, 58, 6377-6380.
- JOHN, R. A., DEMIRAĞ, Y., SHYNKARENKO, Y., BEREZOVSKA, Y., OHANNESSIAN, N., PAYVAND, M., ZENG, P., BODNARCHUK, M. I., KRUMEICH, F., KARA, G., SHORUBALKO, I., NAIR, M. V., COOKE, G. A., LIPPERT, T., INDIVERI, G. & KOVALENKO, M. V. 2022. Reconfigurable halide perovskite nanocrystal memristors for neuromorphic computing. *Nature Communications*, 13, 2074.

- JOHNSON, C. H., IVANISEVIC, J. & SIUZDAK, G. 2016. Metabolomics: beyond biomarkers and towards mechanisms. *Nature Reviews Molecular Cell Biology*, 17, 451-459.
- JOSHI, A., PRADHAN, B., GITE, S. & CHAKRABORTY, S. 2023. Remote-Sensing Data and Deep-Learning Techniques in Crop Mapping and Yield Prediction: A Systematic Review. *Remote Sensing*, 15, 2014.
- JOUPPI, N., KURIAN, G., LI, S., MA, P., NAGARAJAN, R., NAI, L., PATIL, N., SUBRAMANIAN, S., SWING, A. & TOWLES, B. Tpu v4: An optically reconfigurable supercomputer for machine learning with hardware support for embeddings. Proceedings of the 50th Annual International Symposium on Computer Architecture, 2023. 1-14.
- JUMADE, R. & SAWAYA, N. P. 2023. Data is often loadable in short depth: Quantum circuits from tensor networks for finance, images, fluids, and proteins. *arXiv preprint arXiv:2309.13108*.
- JUMPER, J., EVANS, R., PRITZEL, A., GREEN, T., FIGURNOV, M., RONNEBERGER, O., TUNYASUVUNAKOOL, K., BATES, R., ŽÍDEK, A. & POTAPENKO, A. 2021. Highly accurate protein structure prediction with AlphaFold. *Nature*, 596, 583-589.
- JUMPER, J., EVANS, R., PRITZEL, A., GREEN, T., FIGURNOV, M., TUNYASUVUNAKOOL, K., RONNEBERGER, O., BATES, R., ŽÍDEK, A. & BRIDGLAND, A. 2020. AlphaFold 2. *Fourteenth Critical Assessment of Techniques for Protein Structure Prediction; DeepMind: London, UK*.
- JUNGHER, A. & SCHLARB, D. B. 2022. The extended reach of game engine companies: How companies like epic games and Unity technologies provide platforms for extended reality applications and the metaverse. *Social Media+ Society*, 8, 20563051221107641.
- KAACK, L. H., DONTI, P. L., STRUBELL, E., KAMIYA, G., CREUTZIG, F. & ROLNICK, D. 2022. Aligning artificial intelligence with climate change mitigation. *Nature Climate Change*, 12, 518-527.
- KALVA, S. & SATULURI, N. Stock Market Investment Strategy Using Deep-Q-Learning Network. International Conference on Multi-disciplinary Trends in Artificial Intelligence, 2023. Springer, 484-495.
- KAMATH, U., GRAHAM, K. L. & EMARA, W. Transformers for Machine Learning. 2022.
- KAMILARIS, A. & PRENAFETA-BOLDÚ, F. X. 2018. Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70-90.
- KANY, S., VOLLRATH, J. T. & RELJA, B. 2019. Cytokines in inflammatory disease. *International journal of molecular sciences*, 20, 6008.
- KARKARIA, B. D., TRELOAR, N. J., BARNES, C. P. & FEDOREC, A. J. H. 2020. From Microbial Communities to Distributed Computing Systems. *Frontiers in Bioengineering and Biotechnology*, 8.
- KARLAPP, J., HELLER, R. & TAJMAR, M. 2023. Ultrafast transfer of low-mass payloads to Mars and beyond using aerographite solar sails. *arXiv preprint arXiv:2308.16698*.
- KARLSSON, R., CARBALLO, A., FUJII, K., OHTANI, K. & TAKEDA, K. 2023. Predictive World Models from Real-World Partial Observations. *arXiv preprint arXiv:2301.04783*.
- KASSINGER, S. J. & VAN HOEK, M. L. 2020. Biofilm architecture: An emerging synthetic biology target. *Synthetic and systems biotechnology*, 5, 1-10.
- KEESING, F. & OSTFELD, R. S. 2021. Impacts of biodiversity and biodiversity loss on zoonotic diseases. *Proceedings of the National Academy of Sciences*, 118, e2023540118.
- KERSKENS, C. M. & LÓPEZ PÉREZ, D. 2022. Experimental indications of non-classical brain functions. *Journal of Physics Communications*, 6, 105001.

- KESKIN KARAKOYUN, H., YÜKSEL, Ş. K., AMANOGLU, I., NASERIKHOJASTEH, L., YEŞILYURT, A., YAKICIER, C., TIMUÇIN, E. & AKYERLI, C. B. 2023. Evaluation of AlphaFold structure-based protein stability prediction on missense variations in cancer. *Frontiers in Genetics*, 14, 1052383.
- KEYES, K. M., GARY, D., O'MALLEY, P. M., HAMILTON, A. & SCHULENBERG, J. 2019. Recent increases in depressive symptoms among US adolescents: trends from 1991 to 2018. *Social Psychiatry and Psychiatric Epidemiology*, 54, 987-996.
- KHANIJO, J. K., KULYK, H., BERGÈS, C., KHOO, L. W., NG, P., YEO, H. C., HELMY, M., BELLVERT, F., CHEW, W. & SELVARAJOO, K. 2022. Metabolomics and modelling approaches for systems metabolic engineering. *Metabolic Engineering Communications*, e00209.
- KILLEEN, B. D., WINTER, J., GU, W., MARTIN-GOMEZ, A., TAYLOR, R. H., OSGOOD, G. & UNBERATH, M. 2023. Mixed reality interfaces for achieving desired views with robotic X-ray systems. *Computer methods in biomechanics and biomedical engineering: imaging & visualization*, 11, 1130-1135.
- KIM, J. & CHI, S. 2019. Action recognition of earthmoving excavators based on sequential pattern analysis of visual features and operation cycles. *Automation in Construction*, 104, 255-264.
- KIM, J.-S., GALVÃO, D. A., NEWTON, R. U., GRAY, E. & TAAFFE, D. R. 2021a. Exercise-induced myokines and their effect on prostate cancer. *Nature Reviews Urology*, 18, 519-542.
- KIM, K., SANO, M., DE FREITAS, J., HABER, N. & YAMINS, D. Active world model learning with progress curiosity. International conference on machine learning, 2020. PMLR, 5306-5315.
- KIM, T. W., HOOKER, J. & DONALDSON, T. 2021b. Taking principles seriously: A hybrid approach to value alignment in artificial intelligence. *Journal of Artificial Intelligence Research*, 70, 871-890.
- KIM, Y., BERTAGNA, F., D'SOUZA, E. M., HEYES, D. J., JOHANNISSEN, L. O., NERY, E. T., PANTELAS, A., SANCHEZ-PEDREÑO JIMENEZ, A., SLOCOMBE, L. & SPENCER, M. G. 2021c. Quantum biology: An update and perspective. *Quantum Reports*, 3, 80-126.
- KIM, Y., EDDINS, A., ANAND, S., WEI, K. X., VAN DEN BERG, E., ROSENBLATT, S., NAYFEH, H., WU, Y., ZALETEL, M. & TEMME, K. 2023a. Evidence for the utility of quantum computing before fault tolerance. *Nature*, 618, 500-505.
- KIM, Y. & KIM, S. 2023. Target Discovery Using Deep Learning-Based Molecular Docking and Predicted Protein Structures With AlphaFold for Novel Antipsychotics. *Psychiatry Investigation*, 20, 504-514.
- KIM, Y., WOOD, C. J., YODER, T. J., MERKEL, S. T., GAMBETTA, J. M., TEMME, K. & KANDALA, A. 2023b. Scalable error mitigation for noisy quantum circuits produces competitive expectation values. *Nature Physics*, 1-8.
- KIM, Y. & ZHAO, X. 2022. Magnetic soft materials and robots. *Chemical reviews*, 122, 5317-5364.
- KIM, Y.-K. 2022. RNA therapy: rich history, various applications and unlimited future prospects. *Experimental & Molecular Medicine*, 54, 455-465.
- KING, T. A., KANDEMIR, J. M., WALSH, S. J. & SPRING, D. R. 2021. Photocatalytic methods for amino acid modification. *Chemical Society Reviews*, 50, 39-57.
- KIREEV, D., LIU, S., JIN, H., PATRICK XIAO, T., BENNETT, C. H., AKINWANDE, D. & INCORVIA, J. A. C. 2022. Metaplastic and energy-efficient biocompatible graphene artificial synaptic transistors for enhanced accuracy neuromorphic computing. *Nature Communications*, 13, 4386.

- KIRK, B., FEEHAN, J., LOMBARDI, G. & DUQUE, G. 2020. Muscle, bone, and fat crosstalk: the biological role of myokines, osteokines, and adipokines. *Current Osteoporosis Reports*, 18, 388-400.
- KITNEY, R. I., BELL, J. & PHILP, J. 2021. Build a Sustainable Vaccines Industry with Synthetic Biology. *Trends in Biotechnology*, 39, 866-874.
- KNAPP, H. G. 1978. Logik der Prognose: semant. Grundlegung technolog. u. sozialwissenschaftl. Vorhersagen.
- KOBAYASHI, K., RAVAIOLI, S., BARANÈS, A., WOODFORD, M. & GOTTLIEB, J. 2019. Diverse motives for human curiosity. *Nature Human Behaviour*, 3, 587-595.
- KÖHLER, J., GEELS, F. W., KERN, F., MARKARD, J., ONSONGO, E., WIECZOREK, A., ALKEMADE, F., AVELINO, F., BERGEK, A. & BOONS, F. 2019. An agenda for sustainability transitions research: State of the art and future directions. *Environmental innovation and societal transitions*, 31, 1-32.
- KOLP, M., GIORGINI, P. & MYLOPOULOS, J. 2006. Multi-Agent Architectures as Organizational Structures. *Autonomous Agents and Multi-Agent Systems*, 13, 3-25.
- KOO, S., LEE, M. G., SHARMA, A., LI, M., ZHANG, X., PU, K., CHI, S. G. & KIM, J. S. 2022. Harnessing GLUT1-targeted pro-oxidant ascorbate for synergistic phototherapeutics. *Angewandte Chemie*, 134, e202110832.
- KOU, M., LIU, W., WANG, Y., HUANG, J., CHEN, Y., ZHOU, Y., CHEN, Y., MA, M., LEI, K. & XIE, H. 2021. Photocatalytic CO₂ conversion over single-atom MoN₂ sites of covalent organic framework. *Applied Catalysis B: Environmental*, 291, 120146.
- KREIBICH, R., OERTEL, B. & WOLK, M. 2011. Futures studies and future-oriented technology analysis principles, methodology and research questions.
- KRENN, M., BUFFONI, L., COUTINHO, B., EPEL, S., FOSTER, J. G., GRITSEVSKIY, A., LEE, H., LU, Y., MOUTINHO, J. P., SANJABI, N., SONTALIA, R., TRAN, N. M., VALENTE, F., XIE, Y., YU, R. & KOPP, M. 2023a. Forecasting the future of artificial intelligence with machine learning-based link prediction in an exponentially growing knowledge network. *Nature Machine Intelligence*.
- KRENN, M., LANDGRAF, J., FOESEL, T. & MARQUARDT, F. 2023b. Artificial intelligence and machine learning for quantum technologies. *Physical Review A*, 107, 010101.
- KREUK, F., SYNNAEVE, G., POLYAK, A., SINGER, U., D'EFOSSEZ, A., COPET, J., PARIKH, D., TAIGMAN, Y. & ADI, Y. 2022. AudioGen: Textually Guided Audio Generation. *ArXiv*, abs/2209.15352.
- KRIEGMAN, S., BLACKISTON, D., LEVIN, M. & BONGARD, J. 2020. A scalable pipeline for designing reconfigurable organisms. *Proceedings of the National Academy of Sciences*, 117, 1853-1859.
- KRIEGMAN, S., BLACKISTON, D., LEVIN, M. & BONGARD, J. 2021. Kinematic self-replication in reconfigurable organisms. *Proceedings of the National Academy of Sciences*, 118, e2112672118.
- KUMAR, A., KUMAR, N., KURIAKOSE, J. & KUMAR, Y. 2023a. A review of deep learning-based approaches for detection and diagnosis of diverse classes of drugs. *Archives of Computational Methods in Engineering*, 1-23.
- KUMAR, A., NADEEM, M. & BANKA, H. 2023b. Nature inspired optimization algorithms: a comprehensive overview. *Evolving Systems*, 14, 141-156.
- KUMAR, S. 2023. PICASSO: POLYMORPHIC INTELLIGENCE & COMPLEX ADAPTIVE SYSTEMS: SYNERGIES FOR AGI COLLECTIVE OPERATIONS.

- KUMAR, S., FRY, L. E., WANG, J.-H., MARTIN, K. R., HEWITT, A. W., CHEN, F. K. & LIU, G.-S. 2023c. RNA-targeting strategies as a platform for ocular gene therapy. *Progress in Retinal and Eye Research*, 92, 101110.
- KURZWEIL, R. 2000. *The age of spiritual machines: When computers exceed human intelligence*, Penguin.
- KYRARINI, M., LYGERAKIS, F., RAJAVENKATANARAYANAN, A., SEVASTOPOULOS, C., NAMBIAPPAN, H. R., CHAITANYA, K. K., BABU, A. R., MATHEW, J. & MAKEDON, F. 2021. A survey of robots in healthcare. *Technologies*, 9, 8.
- LAEEQ, K. 2022. Metaverse: why, how and what. *How and What*.
- LAI, C.-C., CHEN, S.-Y., KO, W.-C. & HSUEH, P.-R. 2021. Increased antimicrobial resistance during the COVID-19 pandemic. *International journal of antimicrobial agents*, 57, 106324.
- LAM, R., SANCHEZ-GONZALEZ, A., WILLSON, M., WIRNSBERGER, P., FORTUNATO, M., ALET, F., RAVURI, S., EWALDS, T., EATON-ROSEN, Z., HU, W., MEROSE, A., HOYER, S., HOLLAND, G., VINIYALS, O., STOTT, J., PRITZEL, A., MOHAMED, S. & BATTAGLIA, P. 2023. Learning skillful medium-range global weather forecasting. *Science*, 382, 1416-1421.
- LAMATA, L. 2020. Quantum machine learning and quantum biomimetics: A perspective. *Machine Learning: Science and Technology*, 1, 033002.
- LANZENI, D. 2016. Smart global futures: Designing affordable materialities for a better life. *Digital materialities: Design and anthropology*, 45-60.
- LARSON, G. E., MERRITT, C. R. & WILLIAMS, S. E. 1988. Information processing and intelligence: Some implications of task complexity. *Intelligence*, 12, 131-147.
- LATTIE, E. G., LIPSON, S. K. & EISENBERG, D. 2019. Technology and college student mental health: challenges and opportunities. *Frontiers in psychiatry*, 10, 246.
- LAURENS, C., BERGOUIGNAN, A. & MORO, C. 2020. Exercise-released myokines in the control of energy metabolism. *Frontiers in physiology*, 11, 91.
- LAVAZZA, A. & REICHLIN, M. 2023. Human Brain Organoids: Why There Can Be Moral Concerns If They Grow Up in the Lab and Are Transplanted or Destroyed. *Cambridge Quarterly of Healthcare Ethics*, 1-15.
- LAWRENCE, J. M., EGAN, R. M., HOEFER, T., SCARAMPI, A., SHANG, L., HOWE, C. J. & ZHANG, J. Z. 2023. Rewiring photosynthetic electron transport chains for solar energy conversion. *Nature Reviews Bioengineering*, 1-19.
- LAYER, G., KRAUSZE, J. & MOSER, J. 2017. Reduction of Chemically Stable Multibonds: Nitrogenase-Like Biosynthesis of Tetrapyrroles. *Adv Exp Med Biol*, 925, 147-161.
- LE, L., AMBROGIONI, L., SEELIGER, K., GÜÇLÜTÜRK, Y., VAN GERVEN, M. & GÜÇLÜ, U. 2022. Brain2Pix: Fully convolutional naturalistic video frame reconstruction from brain activity. *Frontiers in Neuroscience*, 16, 940972.
- LE, M., VYAS, A., SHI, B., KARRER, B., SARI, L., MORITZ, R., WILLIAMSON, M., MANOHAR, V., ADI, Y. & MAHADEOKAR, J. 2023. Voicebox: Text-Guided Multilingual Universal Speech Generation at Scale. *arXiv preprint arXiv:2306.15687*.
- LE, N. Q. K., HO, Q.-T., NGUYEN, T.-T.-D. & OU, Y.-Y. 2021. A transformer architecture based on BERT and 2D convolutional neural network to identify DNA enhancers from sequence information. *Briefings in Bioinformatics*, 22.
- LECUN, Y. 2022. A path towards autonomous machine intelligence version 0.9. 2, 2022-06-27. *Open Review*, 62.
- LECUN, Y., BOTTOU, L., BENGIO, Y. & HAFFNER, P. 1998. Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, 86, 2278-2324.

- LEE, C.-H. & GIULIANI, F. 2019. The Role of Inflammation in Depression and Fatigue. *Frontiers in Immunology*, 10.
- LEE, H. 2023a. Engineering In vitro Models: Bioprinting of Organoids with Artificial Intelligence. *Cyborg and Bionic Systems*, 4, 0018.
- LEE, I. 2021. Service robots: A systematic literature review. *Electronics*, 10, 2658.
- LEE, M. 2023b. A Mathematical Investigation of Hallucination and Creativity in GPT Models. *Mathematics*, 11, 2320.
- LEI, Y., TANG, R., XU, J., WANG, W., ZHANG, B., LIU, J., YU, X. & SHI, S. 2021. Applications of single-cell sequencing in cancer research: progress and perspectives. *Journal of Hematology & Oncology*, 14, 91.
- LETENDRE, J. H., WEINBERG, B. H., MENDES, M., MARANO, J. M., BENMAN, W. K., PETHERBRIDGE, R., DREZEK, K., KOPLIK, S. E., PINEIRO, A. & WONG, W. 2022. Programmable Mixed-Signal Biocomputers in Mammalian Cells. *bioRxiv*.
- LI, A. W. & LIM, W. A. 2020. Engineering cytokines and cytokine circuits. *Science*, 370, 1034-1035.
- LI, C., FLECK, J. S., MARTINS-COSTA, C., BURKARD, T. R., STUEMPFLEN, M., VERTESY, A., PEER, A. M., ESK, C., ELLING, U. & KASPRIAN, G. 2022. Single-cell brain organoid screening identifies developmental defects in autism. *Biorxiv*, 2022.09. 15.508118.
- LI, G., HAMMOUD, H. A. A. K., ITANI, H., KHIZBULLIN, D. & GHANEM, B. 2023a. Camel: Communicative agents for" mind" exploration of large scale language model society. *arXiv preprint arXiv:2303.17760*.
- LI, G., HUANG, D., SUI, X., LI, S., HUANG, B., ZHANG, X., WU, H. & DENG, Y. 2020a. Advances in microbial production of medium-chain dicarboxylic acids for nylon materials. *Reaction Chemistry & Engineering*, 5, 221-238.
- LI, H., MILANI, S., KRISHNAMOORTHY, V., LEWIS, M. & SYCARA, K. 2019. Perceptions of Domestic Robots' Normative Behavior Across Cultures. *Proceedings of the 2019 AAAI/ACM Conference on AI, Ethics, and Society*. Honolulu, HI, USA: Association for Computing Machinery.
- LI, K., LI, Y., WANG, X., CUI, M., AN, B., PU, J., LIU, J., ZHANG, B., MA, G. & ZHONG, C. 2020b. Diatom-inspired multiscale mineralization of patterned protein-polysaccharide complex structures. *National Science Review*, 8.
- LI, N., KANG, B. & BIE, T. D. 2023b. SkillGPT: a RESTful API service for skill extraction and standardization using a Large Language Model. *ArXiv*, abs/2304.11060.
- LI, Y., SONG, W., WANG, Z., JIANG, H., YAN, P., LIN, P., LI, C., RAO, M., BARNELL, M. & WU, Q. 2023c. Memristive Field-Programmable Analog Arrays for Analog Computing. *Advanced Materials*, 35, 2206648.
- LIANG, L., HEVERAN, C., LIU, R., GILL, R. T., NAGARAJAN, A., CAMERON, J., HUBLER, M., SRUBAR, W. V., III & COOK, S. M. 2018. Rational Control of Calcium Carbonate Precipitation by Engineered Escherichia coli. *ACS Synthetic Biology*, 7, 2497-2506.
- LIANG, X., WANG, B., HUANG, H., WU, S., WU, P., LU, L., MA, Z. & LI, Z. 2023. Unleashing Infinite-Length Input Capacity for Large-scale Language Models with Self-Controlled Memory System. *arXiv preprint arXiv:2304.13343*.
- LIAO, X.-K., LU, K., YANG, C.-Q., LI, J.-W., YUAN, Y., LAI, M.-C., HUANG, L.-B., LU, P.-J., FANG, J.-B., REN, J. & SHEN, J. 2018. Moving from exascale to zettascale computing: challenges and techniques. *Frontiers of Information Technology & Electronic Engineering*, 19, 1236-1244.

- LIAO, Y.-L., WOOD, B., DAS, A. & SMIDT, T. 2023. EquiformerV2: Improved Equivariant Transformer for Scaling to Higher-Degree Representations. *arXiv preprint arXiv:2306.12059*.
- LIESENFELD, D. B., HABERMANN, N., OWEN, R. W., SCALBERT, A. & ULRICH, C. M. 2013. Review of Mass Spectrometry–Based Metabolomics in Cancer Research. *Cancer Epidemiology, Biomarkers & Prevention*, 22, 2182-2201.
- LIM, S. A., COX, A., TUNG, M. & CHUNG, E. J. 2022. Clinical progress of nanomedicine-based RNA therapies. *Bioactive Materials*, 12, 203-213.
- LIN, J., ZHAO, H., ZHANG, A., WU, Y., PING, H. & CHEN, Q. 2023a. AgentSims: An Open-Source Sandbox for Large Language Model Evaluation. *arXiv preprint arXiv:2308.04026*.
- LIN, L., LEDESMA-AMARO, R., JI, X.-J. & HUANG, H. 2023b. Multienzymatic synthesis of nylon monomers from vegetable oils. *Trends in Biotechnology*, 41, 150-153.
- LIN, P., TAO, H., LI, H. & HUANG, S.-Y. 2023c. Protein–protein contact prediction by geometric triangle-aware protein language models. *Nature Machine Intelligence*.
- LIN, Y. & ALQURAISHI, M. 2023. Generating novel, designable, and diverse protein structures by equivariantly diffusing oriented residue clouds. *arXiv preprint arXiv:2301.12485*.
- LIN, Y.-J., SHUKLA, L., DUGUÉ, L., VALERO-CABRÉ, A. & CARRASCO, M. 2021. Transcranial magnetic stimulation entrains alpha oscillatory activity in occipital cortex. *Scientific Reports*, 11, 18562.
- LIPSCOMBE, D. & SOTO, E. J. L. 2019. Alternative splicing of neuronal genes: new mechanisms and new therapies. *Current opinion in neurobiology*, 57, 26-31.
- LIU, C., CHU, D., KALANTAR-ZADEH, K., GEORGE, J., YOUNG, H. A. & LIU, G. 2021a. Cytokines: from clinical significance to quantification. *Advanced Science*, 8, 2004433.
- LIU, H., SFERRAZZA, C. & ABBEEL, P. 2023a. Languages are rewards: Hindsight finetuning using human feedback. *arXiv preprint arXiv:2302.02676*.
- LIU, M., ZHANG, Y., WANG, J., QIN, N., YANG, H., SUN, K., HAO, J., SHU, L., LIU, J. & CHEN, Q. 2022a. A star-nose-like tactile-olfactory bionic sensing array for robust object recognition in non-visual environments. *Nature Communications*, 13, 79.
- LIU, X., ZHANG, Y., ZHOU, S., DAIN, L., MEI, L. & ZHU, G. 2022b. Circular RNA: An emerging frontier in RNA therapeutic targets, RNA therapeutics, and mRNA vaccines. *Journal of Controlled Release*, 348, 84-94.
- LIU, Y., SUN, L., ZHANG, H., SHANG, L. & ZHAO, Y. 2021b. Microfluidics for drug development: from synthesis to evaluation. *Chemical Reviews*, 121, 7468-7529.
- LIU, Y., TRUDE, A. C. B., SONG, S., JIANG, N., WANG, S., GITTELSON, J. & WEN, D. 2023b. Childhood obesity inequality in northeast China: joint effect of social economic status and school neighborhood environment. *BMC Public Health*, 23, 318.
- LLOYD, S. 2013. The universe as quantum computer. *A Computable Universe: Understanding and exploring Nature as computation*, 567-581.
- LOGANATHAN, T. & DOSS, C. G. P. 2023. Non-coding RNAs in human health and disease: potential function as biomarkers and therapeutic targets. *Functional & Integrative Genomics*, 23, 33.
- LOMIZE, A. L., SCHNITZER, K. A., TODD, S. C., CHEREPANOV, S., OUTEIRAL, C., DEANE, C. M. & POGOZHEVA, I. D. 2022. Membranome 3.0: Database of single-pass membrane proteins with AlphaFold models. *Protein Science*, 31, e4318.
- LORENZ, E. N. 1963. Deterministic nonperiodic flow. *Journal of atmospheric sciences*, 20, 130-141.

- LORENZ, R., BERNHART, S. H., HÖNER ZU SIEDERDISSEN, C., TAFER, H., FLAMM, C., STADLER, P. F. & HOFACKER, I. L. 2011. ViennaRNA Package 2.0. *Algorithms for Molecular Biology*, 6, 26.
- LÖSCH, A., HEIL, R. & SCHNEIDER, C. 2019. Visionary practices shaping power constellations. *Socio-Technical Futures Shaping the Present: Empirical Examples and Analytical Challenges*, 67-88.
- LOTTI, A., MODENINI, D., TORTORA, P., SAPONARA, M. & PERINO, M. A. 2023. Deep learning for real-time satellite pose estimation on tensor processing units. *Journal of Spacecraft and Rockets*, 60, 1034-1038.
- LOVLEY, D. R. 2022. Microbial nanowires. *Current Biology*, 32, R110-R112.
- LOVLEY, D. R. & HOLMES, D. E. 2020. Protein nanowires: the electrification of the microbial world and maybe our own. *Journal of bacteriology*, 202, 10.1128/jb. 00331-20.
- LUONG, T., PHAM, H. & MANNING, C. D. 2015. Effective Approaches to Attention-based Neural Machine Translation. *ArXiv*, abs/1508.04025.
- LV, H., LI, Q., SHI, J., FAN, C. & WANG, F. 2021. Biocomputing based on DNA strand displacement reactions. *ChemPhysChem*, 22, 1151-1166.
- LYU, H., JI, Z., WUTTKE, S. & YAGHI, O. M. 2020. Digital reticular chemistry. *Chem*, 6, 2219-2241.
- MA, M., HAN, L. & ZHOU, C. 2023a. BTAD: A binary transformer deep neural network model for anomaly detection in multivariate time series data. *Advanced Engineering Informatics*, 56, 101949.
- MA, Y. J., LIANG, W., WANG, G., HUANG, D.-A., BASTANI, O., JAYARAMAN, D., ZHU, Y., FAN, L. & ANANDKUMAR, A. Eureka: Human-Level Reward Design via Coding Large Language Models. 2023b.
- MAAS, P., CAREY, FRANK, WHEELER, CHRIS, SAATCHI, EDWARD, BILLINGTON, PETE, SHAMASH, JESSICA YAFFA 2023. To infinity and beyond: SHOW-1 and Showrunner Agents in Multi-Agent Simulations. *github*. https://fablestudio.github.io/showrunner-agents/static/pdfs/To_Infinity_and_Beyond_SHOW-1_And_Showrunner_Agents_in_Multi_Agent_Simulations_v2.pdf.
- MACOVEI, O. 2022. Synthetic Biology - Cultural and Anthropological Perspectives. *Postmodern Openings*, 13, 216-233.
- MACRORIE, R., MARVIN, S. & WHILE, A. 2021. Robotics and automation in the city: a research agenda. *Urban Geography*, 42, 197-217.
- MADANI, A., KRAUSE, B., GREENE, E. R., SUBRAMANIAN, S., MOHR, B. P., HOLTON, J. M., OLMOS, J. L., XIONG, C., SUN, Z. Z., SOCHER, R., FRASER, J. S. & NAIK, N. 2023. Large language models generate functional protein sequences across diverse families. *Nature Biotechnology*, 41, 1099-1106.
- MAGNABOSCO, C., LIN, L.-H., DONG, H., BOMBERG, M., GHIORSE, W., STAN-LOTTER, H., PEDERSEN, K., KIEFT, T., VAN HEERDEN, E. & ONSTOTT, T. C. 2018. The biomass and biodiversity of the continental subsurface. *Nature Geoscience*, 11, 707-717.
- MAINZER, K. & CHUA, L. 2012. The Universe as Automaton. *The Universe as Automaton: From Simplicity and Symmetry to Complexity*, 1.
- MAKWANA, N. 2019. Disaster and its impact on mental health: A narrative review. *Journal of family medicine and primary care*, 8, 3090.
- MALIK, H., IQBAL, A., JOSHI, P., AGRAWAL, S. & BAKHSH, F. I. 2021. *Metaheuristic and evolutionary computation: algorithms and applications*, Springer.

- MALINOWSKA, J. M., PALOSAARI, T., SUND, J., CARPI, D., BOUHIFD, M., WEBER, R. J., WHELAN, M. & VIANT, M. R. 2022. Integrating in vitro metabolomics with a 96-well high-throughput screening platform. *Metabolomics*, 18, 1-11.
- MALLINSON, J., SHIRAI, S., ACHARYA, S., BOSE, S., GALLI, E. & BROWN, S. 2019. Avalanches and criticality in self-organized nanoscale networks. *Science advances*, 5, eaaw8438.
- MANKOWITZ, D. J., MICH, A., ZHERNOV, A., GELMI, M., SELVI, M., PADURARU, C., LEURENT, E., IQBAL, S., LESPIAU, J.-B. & AHERN, A. 2023. Faster sorting algorithms discovered using deep reinforcement learning. *Nature*, 618, 257-263.
- MANZONI, C., KIA, D. A., VANDROVCOVA, J., HARDY, J., WOOD, N. W., LEWIS, P. A. & FERRARI, R. 2016. Genome, transcriptome and proteome: the rise of omics data and their integration in biomedical sciences. *Briefings in Bioinformatics*, 19, 286-302.
- MARCANO, P. & OSBORNE, A. 2023. Beyond game engines.
- MARCHETTI, L., NIFOSÌ, R., MARTELLI, P. L., DA POZZO, E., CAPPELLO, V., BANTERLE, F., TRINCAVELLI, M. L., MARTINI, C. & D'ELIA, M. 2022. Quantum computing algorithms: getting closer to critical problems in computational biology. *Briefings in Bioinformatics*, 23, bbac437.
- MARINOUDI, V., SØRENSEN, C. G., PEARSON, S. & BOCHTIS, D. 2019. Robotics and labour in agriculture. A context consideration. *Biosystems Engineering*, 184, 111-121.
- MARKOVIĆ, D., MIZRAHI, A., QUERLIOZ, D. & GROLLIER, J. 2020. Physics for neuromorphic computing. *Nature Reviews Physics*, 2, 499-510.
- MARTIN DEL CAMPO, J. S., RIGSBEE, J., BUENO BATISTA, M., MUS, F., RUBIO, L. M., EINSLE, O., PETERS, J. W., DIXON, R., DEAN, D. R. & DOS SANTOS, P. C. 2023. Overview of physiological, biochemical, and regulatory aspects of nitrogen fixation in *Azotobacter vinelandii*. *Critical Reviews in Biochemistry and Molecular Biology*, 1-47.
- MARTÍN-GUERRERO, J. D. & LAMATA, L. 2022. Quantum machine learning: A tutorial. *Neurocomputing*, 470, 457-461.
- MARX, V. 2021. Biology begins to tangle with quantum computing. *Nature Methods*, 18, 715-719.
- MASOOD, Z., JIANGBIN, Z., IRFAN, M. & AHMAD, I. 2023. High-performance virtual globe GPU terrain rendering using game engine. *Computer Animation and Virtual Worlds*, 34, e2108.
- MATSUO, Y., LECUN, Y., SAHANI, M., PRECUP, D., SILVER, D., SUGIYAMA, M., UCHIBE, E. & MORIMOTO, J. 2022. Deep learning, reinforcement learning, and world models. *Neural Networks*, 152, 267-275.
- MATSUOKA, S., DOMKE, J., WAHIB, M., DROZD, A. & HOEFLER, T. 2023. Myths and legends in high-performance computing. *The International Journal of High Performance Computing Applications*, 10943420231166608.
- MATTHEWS, P. & GREENSPAN, S. 2020. *Automation and Collaborative Robotics*, Springer.
- MATURANA, H., VARELA, FRANCISCO 1991. *Autopoiesis and cognition: The realization of the living*, Springer Science & Business Media.
- MAVRODI, D. V., BONSALE, R. F., DELANEY, S. M., SOULE, M. J., PHILLIPS, G. & THOMASHOW, L. S. 2001. Functional analysis of genes for biosynthesis of pyocyanin and phenazine-1-carboxamide from *Pseudomonas aeruginosa* PAO1. *Journal of bacteriology*, 183, 6454-6465.
- MAYNE, R. & DEN TOONDER, J. 2018. *Atlas of cilia bioengineering and biocomputing*, River Publishers.

- MAZZOLI, R. & PESSIONE, E. 2016. The neuro-endocrinological role of microbial glutamate and GABA signaling. *Frontiers in microbiology*, 7, 1934.
- MCCARTHY, J. 2022. Artificial Intelligence, Logic, and Formalising Common Sense. *Machine Learning and the City: Applications in Architecture and Urban Design*, 69-90.
- MCNAUGHTON, K. A. & WILLIAMSON, L. L. 2023. Effects of sex and pro-inflammatory cytokines on context discrimination memory. *Behavioural Brain Research*, 442, 114320.
- MEHONIC, A., SEBASTIAN, A., RAJENDRAN, B., SIMEONE, O., VASILAKI, E. & KENYON, A. J. 2020. Memristors—From In-Memory Computing, Deep Learning Acceleration, and Spiking Neural Networks to the Future of Neuromorphic and Bio-Inspired Computing. *Advanced Intelligent Systems*, 2, 2000085.
- MELNIKOVA, A. 2018. Towards an Explicit Research Methodology: Adapting Research Onion Model for Futures Studies. *Journal of futures Studies*, 23.
- MEMARI, B., BOUTTIER, M., DIMITROV, V., OUELLETTE, M., BEHR, M. A., FRITZ, J. H. & WHITE, J. H. 2015. Engagement of the Aryl Hydrocarbon Receptor in *Mycobacterium tuberculosis*-Infected Macrophages Has Pleiotropic Effects on Innate Immune Signaling. *The Journal of Immunology*, 195, 4479.
- MENAPACE, W., SIAROHIN, A., LATHUILIÈRE, S., ACHLIOPTAS, P., GOLYANIK, V., RICCI, E. & TULYAKOV, S. 2023. Plotting behind the scenes: Towards learnable game engines. *arXiv preprint arXiv:2303.13472*.
- MERCHANT, A., BATZNER, S., SCHOENHOLZ, S. S., AYKOL, M., CHEON, G. & CUBUK, E. D. 2023. Scaling deep learning for materials discovery. *Nature*, 624, 80-85.
- METZLER, J., BAHRPEYMA, F. & REICHEL, D. An end to end workflow for synthetic data generation for robust object detection. 2023 IEEE 21st International Conference on Industrial Informatics (INDIN), 2023. IEEE, 1-7.
- MI, J., ZHOU, Y., MA, S., ZHOU, X., XU, S., YANG, Y., SUN, Y., XIA, Q., ZHU, H., WANG, S., TIAN, L. & MENG, Q. 2023. High-strength and ultra-tough whole spider silk fibers spun from transgenic silkworms. *Matter*.
- MICHELI, V., ALONSO, E. & FLEURET, F. 2022. Transformers are sample efficient world models. *arXiv preprint arXiv:2209.00588*.
- MILLER, R. 2010. Embracing complexity and using the future. *Ethos*, 10, 23-28.
- MIRDITA, M., SCHÜTZE, K., MORIWAKI, Y., HEO, L., OVCHINNIKOV, S. & STEINEGGER, M. 2022. ColabFold: making protein folding accessible to all. *Nature Methods*, 19, 679-682.
- MIRHOSEINI, A., GOLDIE, A., YAZGAN, M., JIANG, J. W., SONGHORI, E., WANG, S., LEE, Y.-J., JOHNSON, E., PATHAK, O., NAZI, A., PAK, J., TONG, A., SRINIVASA, K., HANG, W., TUNCER, E., LE, Q. V., LAUDON, J., HO, R., CARPENTER, R. & DEAN, J. 2021. A graph placement methodology for fast chip design. *Nature*, 594, 207-212.
- MISRA, S., BLAND, L. C., CARDWELL, S. G., INCORVIA, J. A. C., JAMES, C. D., KENT, A. D., SCHUMAN, C. D., SMITH, J. D. & AIMONE, J. B. 2023. Probabilistic neural computing with stochastic devices. *Advanced Materials*, 35, 2204569.
- MITMAN, G., ARMIERO, M. & EMMETT, R. 2018. *Future remains: a cabinet of curiosities for the Anthropocene*, University of Chicago Press.
- MITRA, A., CORRO, L. D., MAHAJAN, S., CODAS, A., SIMOES, C., AGRAWAL, S., CHEN, X., RAZDAIBIEDINA, A., JONES, E., AGGARWAL, K., PALANGI, H., ZHENG, G., ROSSET, C., KHANPOUR, H. & AWADALLAH, A. A. 2023. Orca 2: Teaching Small Language Models How to Reason. *ArXiv*, abs/2311.11045.

- MITTELSTAEDT, W. 2009. Evolutionäre Zukunftsforschung: Ein Denkanstoß. *Zukunftsforschung und Zukunftsgestaltung: Beiträge aus Wissenschaft und Praxis*, 117-128.
- MOBERG, C. 2020. Schrödinger's What is Life?—The 75th Anniversary of a Book that Inspired Biology. *Angewandte Chemie*, 132, 2570-2573.
- MODIS, T. 2022. Links between entropy, complexity, and the technological singularity. *Technological Forecasting and Social Change*, 176, 121457.
- MODLIŃSKI, A. & GLADDEN, M. E. 2022. An organizational metaphor for the 4th industrial revolution: the organization as Cyborg. *World Futures*, 78, 372-391.
- MOGERA, U., GUO, H., NAMKOONG, M., RAHMAN, M. S., NGUYEN, T. & TIAN, L. 2022. Wearable plasmonic paper-based microfluidics for continuous sweat analysis. *Science Advances*, 8, eabn1736.
- MONDAL, M. & RAY, K. S. 2022. Artificial Neural Networks in DNA Computing and Implementation of DNA Logic Gates. *Handbook of Intelligent Computing and Optimization for Sustainable Development*, 13-48.
- MONTES, M., SANFORD, B. L., COMISKEY, D. F. & CHANDLER, D. S. 2019. RNA splicing and disease: animal models to therapies. *Trends in Genetics*, 35, 68-87.
- MONTES, N., LUCK, M., OSMAN, N., RODRIGUES, O. & SIERRA, C. 2023. Combining theory of mind and abductive reasoning in agent-oriented programming. *Autonomous Agents and Multi-Agent Systems*, 37, 36.
- MORALES PANTOJA, I. E., SMIRNOVA, L., MUOTRI, A. R., WAHLIN, K. J., KAHN, J., BOYD, J. L., GRACIAS, D. H., HARRIS, T. D., COHEN-KARNI, T. & CAFFO, B. S. 2023. First Organoid Intelligence (OI) workshop to form an OI community. *Frontiers in Artificial Intelligence*, 6, 1116870.
- MOREHEAD, A., CHEN, C., SEDOVA, A. & CHENG, J. 2023. Dips-plus: The enhanced database of interacting protein structures for interface prediction. *Scientific Data*, 10, 509.
- MORIMOTO, Y., ONOE, H. & TAKEUCHI, S. 2020. Biohybrid robot with skeletal muscle tissue covered with a collagen structure for moving in air. *APL Bioeng*, 4, 026101.
- MORRISON, L. & ZEMBOWER, T. R. 2020. Antimicrobial resistance. *Gastrointestinal Endoscopy Clinics*, 30, 619-635.
- MOSER, F., THAM, E., GONZÁLEZ, L. M., LU, T. K. & VOIGT, C. A. 2019. Light-Controlled, High-Resolution Patterning of Living Engineered Bacteria Onto Textiles, Ceramics, and Plastic. *Advanced Functional Materials*, 29, 1901788.
- MOULIN, E., FAOUR, L., CARMONA-VARGAS, C. C. & GIUSEPPONE, N. 2020. From Molecular Machines to Stimuli-Responsive Materials. *Advanced Materials*, 32, 1906036.
- MUKHERJEE, S., MITRA, A., JAWAHAR, G., AGARWAL, S., PALANGI, H. & AWADALLAH, A. 2023. Orca: Progressive learning from complex explanation traces of gpt-4. *arXiv preprint arXiv:2306.02707*.
- MURAMATSU, S., KINBARA, K., TAGUCHI, H., ISHII, N. & AIDA, T. 2006. Semibiological Molecular Machine with an Implemented "AND" Logic Gate for Regulation of Protein Folding. *Journal of the American Chemical Society*, 128, 3764-3769.
- NA, S., RUSSIN, J. J., LIN, L., YUAN, X., HU, P., JANN, K. B., YAN, L., MASLOV, K., SHI, J. & WANG, D. J. 2022. Massively parallel functional photoacoustic computed tomography of the human brain. *Nature Biomedical Engineering*, 6, 584-592.
- NAMASUDRA, S., DEVI, D., KADRY, S., SUNDARASEKAR, R. & SHANTHINI, A. 2020. Towards DNA based data security in the cloud computing environment. *Computer Communications*, 151, 539-547.

- NASCIMENTO, N., ALENCAR, P. & COWAN, D. 2023. Self-adaptive large language model (llm)-based multiagent systems. *arXiv preprint arXiv:2307.06187*.
- NATALINI, J. G., SINGH, S. & SEGAL, L. N. 2023. The dynamic lung microbiome in health and disease. *Nature Reviews Microbiology*, 21, 222-235.
- NATION, P. D. & TREINISH, M. 2023. Suppressing quantum circuit errors due to system variability. *PRX Quantum*, 4, 010327.
- NEIL, K., ALLARD, N., ROY, P., GRENIER, F., MENENDEZ, A., BURRUS, V. & RODRIGUE, S. 2021. High-efficiency delivery of CRISPR-Cas9 by engineered probiotics enables precise microbiome editing. *Molecular systems biology*, 17, e10335.
- NELSON, C., ADIGUZEL, I., FLORIN, M.-V., LENTZOS, F., KNUTSSON, R., RHODES, C., RUTTEN, P. & VERGIN, A. 2021. Foresight in Synthetic Biology and Biotechnology Threats. *Emerging Threats of Synthetic Biology and Biotechnology*. Springer, Dordrecht.
- NELSON, J. P. & SELIN, C. L. 2023. Seven open questions in the futures of human genome editing. *Futures*, 149, 103138.
- NEUHAUS, C. 2022. Images of the Future. *Standards of Futures Research: Guidelines for Practice and Evaluation*. Springer.
- NGO, T., THINH, T. N. & NGHI, H. P. AlPicoSoC: A Low-Power RISC-V Based System on Chip for Edge Devices with a Deep Learning Accelerator. International Conference on Intelligence of Things, 2023. Springer, 403-413.
- NGUYEN, V.-H., NGUYEN, B.-S., JIN, Z., SHOKOUHIMEHR, M., JANG, H. W., HU, C., SINGH, P., RAIZADA, P., PENG, W. & LAM, S. S. 2020. Towards artificial photosynthesis: Sustainable hydrogen utilization for photocatalytic reduction of CO₂ to high-value renewable fuels. *Chemical Engineering Journal*, 402, 126184.
- NICOLI, F., PALTRINIERI, E., BAKIĆ, M. T., BARONCINI, M., SILVI, S. & CREDI, A. 2021. Binary logic operations with artificial molecular machines. *Coordination Chemistry Reviews*, 428, 213589.
- NICOLL, B., KEOGH, B., NICOLL, B. & KEOGH, B. 2019. *The Unity game engine and the circuits of cultural software*, Springer.
- NIELSEN, A. V., BEAUCHAMP, M. J., NORDIN, G. P. & WOOLLEY, A. T. 2020. 3D printed microfluidics. *Annual Review of Analytical Chemistry*, 13, 45-65.
- NISHAD, R., AHMED, T., RAHMAN, V. J. & KAREEM, A. 2020. Modulation of plant defense system in response to microbial interactions. *Frontiers in Microbiology*, 11, 1298.
- NOLIN, J., NELHANS, G. & OLSON, N. 2019. The Naming of the Beast. Scrutinizing Concepts of Technology Rich Futures. *Socio-Technical Futures Shaping the Present: Empirical Examples and Analytical Challenges*, 231-254.
- NORTH, J. A., NARROWE, A. B., XIONG, W., BYERLY, K. M., ZHAO, G., YOUNG, S. J., MURALI, S., WILDENTHAL, J. A., CANNON, W. R. & WRIGHTON, K. C. 2020. A nitrogenase-like enzyme system catalyzes methionine, ethylene, and methane biogenesis. *Science*, 369, 1094-1098.
- NUMAN, N., LU, Z., CONGDON, B., GIUNCHI, D., ROTSIDIS, A., LERNIS, A., LARMOS, K., KOURRA, T., CHARALAMBOUS, P. & CHRYSANTHOU, Y. Towards Outdoor Collaborative Mixed Reality: Lessons Learnt from a Prototype System. 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW), 2023. IEEE, 113-118.
- O'DONNELL, J. A., ZHENG, T., MERIC, G. & MARQUES, F. Z. 2023. The gut microbiome and hypertension. *Nature Reviews Nephrology*, 19, 153-167.

- OKADA, S., GREGG, C. M., ALLEN, R. S., MENON, A., HUSSAIN, D., GILLESPIE, V., JOHNSTON, E., BYRNE, K., COLGRAVE, M. L. & WOOD, C. C. 2020. A synthetic biology workflow reveals variation in processing and solubility of nitrogenase proteins targeted to plant mitochondria, and differing tolerance of targeting sequences in a bacterial nitrogenase assay. *Frontiers in Plant Science*, 11, 552160.
- OLLENBURG, S. A. 2019. A futures-design-process model for participatory futures. *Journal of futures studies*, 23, 51-62.
- PACKER, C., FANG, V., PATIL, S. G., LIN, K., WOODERS, S. & GONZALEZ, J. E. MemGPT: Towards LLMs as Operating Systems. 2023.
- PADDA, I. S., MAHTANI, A. U. & PARMAR, M. 2023. Small interfering rna (Sirna) based therapy. *StatPearls [Internet]*. StatPearls Publishing.
- PAGGI, J. M. & BEJERANO, G. 2018. A sequence-based, deep learning model accurately predicts RNA splicing branchpoints. *Rna*, 24, 1647-1658.
- PANG, J., PENG, S., HOU, C., ZHAO, H., FAN, Y., YE, C., ZHANG, N., WANG, T., CAO, Y. & ZHOU, W. 2023. Applications of Graphene in Five Senses, Nervous System, and Artificial Muscles. *ACS sensors*, 8, 482-514.
- PANNI, S., LOVERING, R. C., PORRAS, P. & ORCHARD, S. 2020. Non-coding RNA regulatory networks. *Biochimica et Biophysica Acta (BBA)-Gene Regulatory Mechanisms*, 1863, 194417.
- PAOLO, F., KROODSMA, D., RAYNOR, J., HOCHBERG, T., DAVIS, P., CLEARY, J., MARSAGLIA, L., OROFINO, S., THOMAS, C. & HALPIN, P. 2024. Satellite mapping reveals extensive industrial activity at sea. *Nature*, 625, 85-91.
- PARASKEVOPOULOS, G., PISTOFIDIS, P., BANOUTSOS, G., GEORGIU, E. & KATSOUROS, V. 2022. Multimodal Classification of Safety-Report Observations. *Applied Sciences*, 12, 5781.
- PARK, J. S., O'BRIEN, J. C., CAI, C. J., MORRIS, M. R., LIANG, P. & BERNSTEIN, M. S. 2023. Generative agents: Interactive simulacra of human behavior. *arXiv preprint arXiv:2304.03442*.
- PARK, T. J., SELCUK, K., ZHANG, H.-T., MANNA, S., BATRA, R., WANG, Q., YU, H., AADIT, N. A., SANKARANARAYANAN, S. K. R. S., ZHOU, H., CAMSARI, K. Y. & RAMANATHAN, S. 2022. Efficient Probabilistic Computing with Stochastic Perovskite Nickelates. *Nano Letters*, 22, 8654-8661.
- PATIL, S. G., ZHANG, T., WANG, X. & GONZALEZ, J. E. 2023. Gorilla: Large language model connected with massive apis. *arXiv preprint arXiv:2305.15334*.
- PATINIOS, C. & BEISEL, C. L. 2023. For the CRISPR Fan (zor) atics: RNA-guided DNA endonucleases discovered in eukaryotes. *Molecular Cell*, 83, 3046-3048.
- PAULUS, L., SPINATH, F. M. & HAHN, E. 2021. How do educational inequalities develop? The role of socioeconomic status, cognitive ability, home environment, and self-efficacy along the educational path. *Intelligence*, 86, 101528.
- PAUNOVSKA, K., LOUGHREY, D. & DAHLMAN, J. E. 2022. Drug delivery systems for RNA therapeutics. *Nature Reviews Genetics*, 23, 265-280.
- PEDERSEN, B. K. 2011. Muscles and their myokines. *Journal of Experimental Biology*, 214, 337-346.
- PEDERSEN, B. K., ÅKERSTRÖM, T. C., NIELSEN, A. R. & FISCHER, C. P. 2007. Role of myokines in exercise and metabolism. *Journal of applied physiology*.

- PEDRO, R., CASTRO, D., CARREIRA, P. & SANTOS, N. 2023. From Prompt Injections to SQL Injection Attacks: How Protected is Your LLM-Integrated Web Application? *arXiv preprint arXiv:2308.01990*.
- PEI, L., GARFINKEL, M. & SCHMIDT, M. 2022. Bottlenecks and opportunities for synthetic biology biosafety standards. *Nature Communications*, 13, 2175.
- PEKSA, J. & MAMCHUR, D. 2023. State-of-the-Art on Brain-Computer Interface Technology. *Sensors*, 23, 6001.
- PELS, P. 2015. Modern times: Seven steps toward an anthropology of the future. *Current Anthropology*, 56, 779-796.
- PEÑA-BAHAMONDE, J., NGUYEN, H. N., FANOURAKIS, S. K. & RODRIGUES, D. F. 2018. Recent advances in graphene-based biosensor technology with applications in life sciences. *Journal of Nanobiotechnology*, 16, 75.
- PENDRILL, F., GARDNER, T. A., MEYFROIDT, P., PERSSON, U. M., ADAMS, J., AZEVEDO, T., BASTOS LIMA, M. G., BAUMANN, M., CURTIS, P. G. & DE SY, V. 2022. Disentangling the numbers behind agriculture-driven tropical deforestation. *Science*, 377, eabm9267.
- PENNISI, E. 2020. Meet the psychobiome. *Science*, 368, 570-573.
- PERERA, P. & LANKATHILAKE, M. 2023. Preparing to Revolutionize Education with the Multi-Model GenAI Tool Google Gemini? A Journey towards Effective Policy Making.
- PÉREZ-GONZÁLEZ, A., YANG, Z.-Y., LUKOYANOV, D. A., DEAN, D. R., SEEFELDT, L. C. & HOFFMAN, B. M. 2021. Exploring the role of the central carbide of the nitrogenase active-site FeMo-cofactor through targeted ¹³C labeling and ENDOR spectroscopy. *Journal of the American Chemical Society*, 143, 9183-9190.
- PERLINSKA, A. P., NIEMYSKA, W. H., GREN, B. A., BUKOWICKI, M., NOWAKOWSKI, S., RUBACH, P. & SULKOWSKA, J. I. 2023. AlphaFold predicts novel human proteins with knots. *Protein Science*, 32, e4631.
- PESERICO, N., SHASTRI, B. J. & SORGER, V. J. 2023. Integrated photonic tensor processing unit for a matrix multiply: a review. *Journal of Lightwave Technology*.
- PETKOWSKI, J. J., BAINS, W. & SEAGER, S. 2020. On the Potential of Silicon as a Building Block for Life. *Life (Basel)*, 10.
- PHELPS, S. & RUSSELL, Y. I. 2023. Investigating emergent goal-like behaviour in large language models using experimental economics. *arXiv preprint arXiv:2305.07970*.
- PHILLIPS, J. W., PROMINSKI, A. & TIAN, B. 2022. Recent advances in materials and applications for bioelectronic and biorobotic systems. *VIEW*, 3, 20200157.
- PICARD, M. & SHIRIHAI, O. S. 2022. Mitochondrial signal transduction. *Cell metabolism*, 34, 1620-1653.
- PING, P., HUANG, C., DING, W., LIU, Y., CHIYOMI, M. & KAZUYA, T. 2023. Distracted driving detection based on the fusion of deep learning and causal reasoning. *Information Fusion*, 89, 121-142.
- PINK, S. & SALAZAR, J. F. 2020. Anthropologies and futures: Setting the agenda. *Anthropologies and futures*. Routledge.
- PITSALIDIS, C., PAPPA, A.-M., BOYS, A. J., FU, Y., MOYSIDOU, C.-M., VAN NIEKERK, D., SAEZ, J., SAVVA, A., IANDOLO, D. & OWENS, R. M. 2021. Organic bioelectronics for in vitro systems. *Chemical Reviews*, 122, 4700-4790.
- POPP, R. & SCHÜLL, E. 2009. *Zukunftsforschung und Zukunftsgestaltung: Beiträge aus Wissenschaft und Praxis*, Springer-Verlag.
- POPPER, K. R. 1963. Science as falsification. *Conjectures and refutations*, 1, 33-39.

- PORKODI, V., SINGH, A. R., SAIT, A. R. W., SHANKAR, K., YANG, E., SEO, C. & JOSHI, G. P. 2020. Resource provisioning for cyber–physical–social system in cloud-fog-edge computing using optimal flower pollination algorithm. *IEEE Access*, 8, 105311-105319.
- PORTA-PARDO, E., RUIZ-SERRA, V., VALENTINI, S. & VALENCIA, A. 2022. The structural coverage of the human proteome before and after AlphaFold. *PLOS Computational Biology*, 18, e1009818.
- PRESTI, A. L. 1996. Futures research and complexity: a critical analysis from the perspective of social science. *Futures*, 28, 891-902.
- PURBRICK, L. 1993. The Dream Machine: Charles Babbage and His Imaginary Computers. *Journal of Design History*, 6, 9-23.
- QIAN, C., CONG, X., YANG, C., CHEN, W., SU, Y., XU, J., LIU, Z. & SUN, M. 2023. Communicative agents for software development. *arXiv preprint arXiv:2307.07924*.
- QIAO, H., DUMUR, É., ANDERSSON, G., YAN, H., CHOU, M.-H., GREBEL, J., CONNER, C., JOSHI, Y., MILLER, J. & POVEY, R. 2023. Splitting phonons: Building a platform for linear mechanical quantum computing. *Science*, 380, 1030-1033.
- QIN, Y., LIANG, S., YE, Y., ZHU, K., YAN, L., LU, Y., LIN, Y., CONG, X., TANG, X. & QIAN, B. 2023. Toolllm: Facilitating large language models to master 16000+ real-world apis. *arXiv preprint arXiv:2307.16789*.
- RABINOW, P. 1997. *Essays on the Anthropology of Reason*, Princeton University Press.
- RABINOW, P. & BENNETT, G. 2012. *Designing human practices: An experiment with synthetic biology*, University of Chicago Press.
- RAHMAN, M. M. 2019. 21st century skill 'problem solving': Defining the concept. *Rahman, MM (2019). 21st Century Skill "Problem Solving": Defining the Concept. Asian Journal of Interdisciplinary Research*, 2, 64-74.
- RAJ M, K. & CHAKRABORTY, S. 2020. PDMS microfluidics: A mini review. *Journal of Applied Polymer Science*, 137, 48958.
- RAMESH, G. V., CHANDALURI, C. G., TADI, K. K., DANDU, N. K. & REDDY, N. M. 2022. Recent advances in functional materials: Bioelectronics-integrated biosensor applications. *Functional Materials Processing for Switchable Device Modulation*, 221-239.
- RAPSON, T. D., GREGG, C. M., ALLEN, R. S., JU, H., DOHERTY, C. M., MULET, X., GIDDEY, S. & WOOD, C. C. 2020. Insights into nitrogenase bioelectrocatalysis for green ammonia production. *ChemSusChem*, 13, 4856-4865.
- RECH, O., DUTERNE, H., BLAIZOT, M., LEHNER, A., CARRIERE, A. & HICHE, C. 2021. The future of oil supply in the European Union: state of reserves and production prospects for major suppliers-May 2021. Report from the Shift Project, for the General Direction of International Relations and Strategy (DGRIS), French Ministry of the Army-Summary.
- REED, S., ZOLNA, K., PARISOTTO, E., COLMENAREJO, S. G., NOVIKOV, A., BARTH-MARON, G., GIMENEZ, M., SULSKY, Y., KAY, J. & SPRINGENBERG, J. T. 2022. A generalist agent. *arXiv preprint arXiv:2205.06175*.
- REES, H. A. & LIU, D. R. 2018. Base editing: precision chemistry on the genome and transcriptome of living cells. *Nature reviews genetics*, 19, 770-788.
- REIDPATH, D. D. & ALLOTEY, P. 2019. The problem of 'trickle-down science' from the Global North to the Global South. *BMJ Global Health*, 4, e001719.
- REYMOND, J.-L., RUDDIGKEIT, L., BLUM, L. & VAN DEURSEN, R. 2012. The enumeration of chemical space. *WIREs Computational Molecular Science*, 2, 717-733.

- RIBAS DE POUPLANA, L., FORTERRE, P., FILÉE, J. & MYLLYKALLIO, H. 2004. Origin and evolution of DNA and DNA replication machineries. *The genetic code and the origin of life*, 145-168.
- RICARDO, L. I. C., GATICA-DOMÍNGUEZ, G., NEVES, P. A. R., VAZ, J. D. S., BARROS, A. J. D. & WEHRMEISTER, F. C. 2023. Sociodemographic inequalities in vegetables, fruits, and animal source foods consumption in children aged 6–23 months from 91 LMIC. *Frontiers in Nutrition*, 10.
- RICHMOND, S. 2020. Luciano Floridi, "The Logic of Information: A Theory of Philosophy as Conceptual Design." *Philosophy in Review*, 40, 112-114.
- RIEPE, T. V., KHAN, M., ROOSING, S., CREMERS, F. P. & 'T HOEN, P. A. 2021. Benchmarking deep learning splice prediction tools using functional splice assays. *Human Mutation*, 42, 799-810.
- RINALDI, A. 2007. Naturally better. Science and technology are looking to nature's successful designs for inspiration. *EMBO Rep*, 8, 995-9.
- RIVERA-TARAZONA, L. K., CAMPBELL, Z. T. & WARE, T. H. 2021. Stimuli-responsive engineered living materials. *Soft Matter*, 17, 785-809.
- ROGALSKA, M. E., VIVORI, C. & VALCÁRCEL, J. 2022. Regulation of pre-mRNA splicing: roles in physiology and disease, and therapeutic prospects. *Nature Reviews Genetics*.
- ROGDAKIS, K., LOIZOS, M., VISKADOURO, G. & KYMAKIS, E. 2022. Memristive perovskite solar cells towards parallel solar energy harvesting and processing-in-memory computing. *Materials Advances*, 3, 7002-7014.
- ROKHSARITALEMI, S., SADEGHI-NIARAKI, A. & CHOI, S.-M. 2020. A review on mixed reality: Current trends, challenges and prospects. *Applied Sciences*, 10, 636.
- RONDA, C., CHEN, S. P., CABRAL, V., YAUNG, S. J. & WANG, H. H. 2019. Metagenomic engineering of the mammalian gut microbiome in situ. *Nature methods*, 16, 167-170.
- ROSA, L., CHIARELLI, D. D., RULLI, M. C., DELL'ANGELO, J. & D'ODORICO, P. 2020. Global agricultural economic water scarcity. *Science Advances*, 6, eaaz6031.
- ROSSELLÓ-MORA, R. & AMANN, R. 2001. The species concept for prokaryotes. *FEMS Microbiol Rev*, 25, 39-67.
- ROST, B. R., WIETEK, J., YIZHAR, O. & SCHMITZ, D. 2022. Optogenetics at the presynapse. *Nature neuroscience*, 25, 984-998.
- ROY, K., JAISWAL, A. & PANDA, P. 2019. Towards spike-based machine intelligence with neuromorphic computing. *Nature*, 575, 607-617.
- RUIZ-ALONSO, S., VILLATE-BEITIA, I., GALLEGO, I., LAFUENTE-MERCHAN, M., PURAS, G., SAENZ-DEL-BURGO, L. & PEDRAZ, J. L. 2021. Current Insights into 3D Bioprinting: An Advanced Approach for Eye Tissue Regeneration. *Pharmaceutics*, 13, 308.
- RÜTSCHLIN, S. & BÖTTCHER, T. 2020. Inhibitors of bacterial swarming behavior. *Chemistry—A European Journal*, 26, 964-979.
- RUTTER, J. W., DEKKER, L., OWEN, K. A. & BARNES, C. P. 2022. Microbiome engineering: Engineered live biotherapeutic products for treating human disease. *Frontiers in Bioengineering and Biotechnology*, 10, 1000873.
- SABIROV, D. S. & SHEPELEVICH, I. S. 2021. Information Entropy in Chemistry: An Overview. *Entropy*, 23, 1240.
- SAITO, M., XU, P., FAURE, G., MAGUIRE, S., KANNAN, S., ALTAE-TRAN, H., VO, S., DESIMONE, A., MACRAE, R. K. & ZHANG, F. 2023. Fanzor is a eukaryotic programmable RNA-guided endonuclease. *Nature*, 620, 660-668.

- SALVADOR, A. F., DE LIMA, K. A. & KIPNIS, J. 2021. Neuromodulation by the immune system: a focus on cytokines. *Nature Reviews Immunology*, 21, 526-541.
- SÁNCHEZ-PELLICER, P., NAVARRO-MORATALLA, L., NÚÑEZ-DELEGIDO, E., AGÜERA-SANTOS, J. & NAVARRO-LÓPEZ, V. 2022. How Our Microbiome Influences the Pathogenesis of Alopecia Areata. *Genes*, 13, 1860.
- SARDAR, Z. 2010. The Namesake: Futures; futures studies; futurology; futuristic; foresight—What's in a name? *Futures*, 42, 177-184.
- SARKAR, C., DAS, B., RAWAT, V. S., WAHLANG, J. B., NONGPIUR, A., TIEWSOH, I., LINGDOH, N. M., DAS, D., BIDAROLLI, M. & SONY, H. T. 2023. Artificial Intelligence and Machine Learning Technology Driven Modern Drug Discovery and Development. *Int J Mol Sci*, 24.
- SATO, K., AKIYAMA, M. & SAKAKIBARA, Y. 2021. RNA secondary structure prediction using deep learning with thermodynamic integration. *Nature communications*, 12, 941.
- SATO, K. & KATO, Y. 2022. Prediction of RNA secondary structure including pseudoknots for long sequences. *Briefings in Bioinformatics*, 23, bbab395.
- SAXTON, R. A., GLASSMAN, C. R. & GARCIA, K. C. 2023. Emerging principles of cytokine pharmacology and therapeutics. *Nature Reviews Drug Discovery*, 22, 21-37.
- SCHADER, M. & LUKE, S. Fully decentralized planner-guided robot swarms. Advances in Practical Applications of Agents, Multi-Agent Systems, and Social Good. The PAAMS Collection: 19th International Conference, PAAMS 2021, Salamanca, Spain, October 6–8, 2021, Proceedings 19, 2021. Springer, 241-254.
- SCHEUTZ, M. 2016. The Need for Moral Competency in Autonomous Agent Architectures. In: MÜLLER, V. C. (ed.) *Fundamental Issues of Artificial Intelligence*. Cham: Springer International Publishing.
- SCHILLINGER, D. 2020. The intersections between social determinants of health, health literacy, and health disparities. *Studies in health technology and informatics*, 269, 22.
- SCHMELLER, D. S., COURCHAMP, F. & KILLEEN, G. 2020. Biodiversity loss, emerging pathogens and human health risks. *Biodiversity and Conservation*, 29, 3095-3102.
- SCHMIDT, D. R., PATEL, R., KIRSCH, D. G., LEWIS, C. A., VANDER HEIDEN, M. G. & LOCASALE, J. W. 2021. Metabolomics in cancer research and emerging applications in clinical oncology. *CA: A Cancer Journal for Clinicians*, 71, 333-358.
- SCHMIDT, G. A. & FRANK, A. 2019. The Silurian hypothesis: would it be possible to detect an industrial civilization in the geological record? *International Journal of Astrobiology*, 18, 142-150.
- SCHNEIDER, S., LEE, J. H. & MATHIS, M. W. 2023. Learnable latent embeddings for joint behavioural and neural analysis. *Nature*, 617, 360-368.
- SCHRANGHAMER, T. F., OBEROI, A. & DAS, S. 2020. Graphene memristive synapses for high precision neuromorphic computing. *Nature communications*, 11, 5474.
- SCHREPEL, T. & PENTLAND, A. 2023. Competition Between AI Foundation Models: Dynamics and Policy Recommendations.
- SCHRÖDINGER, L. 2010. Pymol. The PyMOL Molecular Graphics System, Version 2.0
- SCHULLER, A. P., WOJTYNEK, M., MANKUS, D., TATLI, M., KRONENBERG-TENGA, R., REGMI, S. G., DIP, P. V., LYTTON-JEAN, A. K. R., BRIGNOLE, E. J., DASSO, M., WEIS, K., MEDALIA, O. & SCHWARTZ, T. U. 2021. The cellular environment shapes the nuclear pore complex architecture. *Nature*, 598, 667-671.

- SEN, P., LAMICHHANE, S., MATHEMA, V. B., MCGLINCHEY, A., DICKENS, A. M., KHOOMRUNG, S. & OREŠIČ, M. 2021. Deep learning meets metabolomics: A methodological perspective. *Briefings in Bioinformatics*, 22, 1531-1542.
- SEO, Y., HAFNER, D., LIU, H., LIU, F., JAMES, S., LEE, K. & ABBEEL, P. Masked world models for visual control. Conference on Robot Learning, 2023. PMLR, 1332-1344.
- SERGEEVNA, I. D. 2023. Creating a fragment of the animated film First Artist in the Unreal Engine 5 game engine.
- SEVERINSEN, M. C. K. & PEDERSEN, B. K. 2020. Muscle–organ crosstalk: the emerging roles of myokines. *Endocrine reviews*, 41, 594-609.
- SHANAHAN, M., CROSBY, M., BEYRET, B. & CHEKE, L. 2020. Artificial intelligence and the common sense of animals. *Trends in cognitive sciences*, 24, 862-872.
- SHANG, H., FAN, Y., SHEN, L., GUO, C., LIU, J., DUAN, X., LI, F. & LI, Z. 2023. Towards practical and massively parallel quantum computing emulation for quantum chemistry. *npj Quantum Information*, 9, 33.
- SHARMA, A., CZÉGEL, D., LACHMANN, M., KEMPES, C. P., WALKER, S. I. & CRONIN, L. 2023. Assembly theory explains and quantifies selection and evolution. *Nature*.
- SHARMA, R., GUPTA, D., MEHROTRA, R. & MAGO, P. 2021. Psychobiotics: The Next-Generation Probiotics for the Brain. *Current Microbiology*, 78, 449-463.
- SHIN, Y. & BRANGWYNNE, C. P. 2017. Liquid phase condensation in cell physiology and disease. *Science*, 357, eaaf4382.
- SHINE, E. E. & CRAWFORD, J. M. 2021. Molecules from the Microbiome. *Annual Review of Biochemistry*, 90, 789-815.
- SHU, W., CHENG, P., MAO, C., TANG, J., YANG, S., GU, Q., HAN, W., CHEN, Y., ZHOU, J. & LI, W. 2023. Zero-shot prediction of mutation effects on protein function with multimodal deep representation learning.
- SHULMAN, C. & BOSTROM, N. 2021. Sharing the world with digital minds. *Rethinking moral status*, 306-326.
- SHUMAILOV, I., SHUMAYLOV, Z., ZHAO, Y., GAL, Y., PAPERNOT, N. & ANDERSON, R. 2023. The Curse of Recursion: Training on Generated Data Makes Models Forget. *arXiv preprint arxiv:2305.17493*.
- SHYAM, V., FRIEND, L., WHITEAKER, B., BENISE, N., DOWDALL, J., BOKTOR, B., JOHNY, M., REYES, I., NASER, A. & SAKHAMURI, N. 2019. PeTaL (periodic table of life) and physiомimetics. *Designs*, 3, 43.
- SIFAKIS, J. & HAREL, D. 2023. Trustworthy Autonomous System Development. *ACM Transactions on Embedded Computing Systems*, 22, 1-24.
- SIMPSON, M. L., SAYLER, G. S., FLEMING, J. T. & APPELEGATE, B. 2001. Whole-cell biocomputing. *Trends in biotechnology*, 19, 317-323.
- SINGER, U., POLYAK, A., HAYES, T., YIN, X., AN, J., ZHANG, S., HU, Q., YANG, H., ASHUAL, O. & GAFNI, O. 2022. Make-a-video: Text-to-video generation without text-video data. *arXiv preprint arxiv:2209.14792*.
- SIRIPURAPU, S., DARIMIREDDY, N. K., CHEHRI, A. & AV, P. 2023. Technological Advancements and Elucidation Gadgets for Healthcare Applications: An Exhaustive Methodological Review-Part-II (Robotics, Drones, 3D-Printing, Internet of Things, Virtual/Augmented and Mixed Reality). *Electronics*, 12, 548.
- SKOLNICK, J., GAO, M., ZHOU, H. & SINGH, S. 2021. AlphaFold 2: why it works and its implications for understanding the relationships of protein sequence, structure, and function. *Journal of chemical information and modeling*, 61, 4827-4831.

- SLAUGHTER, R. A. 2002. From forecasting and scenarios to social construction: changing methodological paradigms in futures studies. *Foresight*, 4, 26-31.
- SMIRNOVA, L., CAFFO, B. S., GRACIAS, D. H., HUANG, Q., MORALES PANTOJA, I. E., TANG, B., ZACK, D. J., BERLINICKE, C. A., BOYD, J. L. & HARRIS, T. D. 2023a. Organoid intelligence (OI): the new frontier in biocomputing and intelligence-in-a-dish. *Frontiers in Science*, 0.
- SMIRNOVA, L., PANTOJA, I. E. M. & HARTUNG, T. 2023b. Organoid intelligence (OI)—The ultimate functionality of a brain microphysiological system. *ALTEX-Alternatives to animal experimentation*, 40, 191-203.
- SOLÉ, R. V., MONTAÑEZ, R. & DURAN-NEBRED, S. 2015. Synthetic circuit designs for earth terraformation. *Biology Direct*, 10, 1-10.
- SOMEYA, T., BAO, Z. & MALLIARAS, G. G. 2016. The rise of plastic bioelectronics. *Nature*, 540, 379-385.
- SONG, B., LI, K., ORELLANA-MARTÍN, D., PÉREZ-JIMÉNEZ, M. J. & PÉREZ-HURTADO, I. 2021. A Survey of Nature-Inspired Computing: Membrane Computing. *ACM Comput. Surv.*, 54, Article 22.
- SONG, Y., JOHNSON, D., PENG, R., HENSLEY, D. K., BONNESEN, P. V., LIANG, L., HUANG, J., YANG, F., ZHANG, F., QIAO, R., BADDORF, A. P., TSCHAPLINSKI, T. J., ENGLE, N. L., HATZELL, M. C., WU, Z., CULLEN, D. A., MEYER, H. M., SUMPTER, B. G. & RONDINONE, A. J. 2018. A physical catalyst for the electrolysis of nitrogen to ammonia. *Science Advances*, 4, e1700336.
- SØRENSEN, J. V., MA, Z. & JØRGENSEN, B. N. 2022. Potentials of game engines for wind power digital twin development: an investigation of the Unreal Engine. *Energy Informatics*, 5, 1-30.
- SPARKES, M. 2021. What is a metaverse. Elsevier.
- SPEICHER, M., HALL, B. D. & NEBELING, M. What is mixed reality? Proceedings of the 2019 CHI conference on human factors in computing systems, 2019. 1-15.
- SRIDHARAN, M. & MOTA, T. 2023. Towards combining commonsense reasoning and knowledge acquisition to guide deep learning. *Autonomous Agents and Multi-Agent Systems*, 37, 4.
- STANDISH, R. K. 2001. On complexity and emergence. *arXiv preprint nlin/0101006*.
- STATELLO, L., GUO, C.-J., CHEN, L.-L. & HUARTE, M. 2021. Gene regulation by long non-coding RNAs and its biological functions. *Nature reviews Molecular cell biology*, 22, 96-118.
- STEINMÜLLER, K. 2022. Modality. *Standards of Futures Research*. Springer.
- STEPHENS, K. & BENTLEY, W. E. 2020. Synthetic biology for manipulating quorum sensing in microbial consortia. *Trends in microbiology*, 28, 633-643.
- STRAUCH, Y., LORD, J., NIRANJAN, M. & BARALLE, D. 2022. CI-SpliceAI—improving machine learning predictions of disease causing splicing variants using curated alternative splice sites. *Plos one*, 17, e0269159.
- STRZELECKA, C. 2013. Anticipatory anthropology—anthropological future study. *Prace Etnograficzne*, 41.
- SULEYMAN, M., BHASHKAR, MICHAEL 2023. *The Coming Wave - Technology, Power, and the 21st centuries greatest dilemma*.
- SULKOWSKA, J. I. 2020. On folding of entangled proteins: knots, lassos, links and θ -curves. *Current opinion in structural biology*, 60, 131-141.
- SUN, C., HAN, J., DENG, W., WANG, X., QIN, Z. & GOULD, S. 3D-GPT: Procedural 3D Modeling with Large Language Models. 2023.

- SUNWOO, S.-H., HAN, S. I., JOO, H., CHA, G. D., KIM, D., CHOI, S. H., HYEON, T. & KIM, D.-H. 2020. Advances in Soft Bioelectronics for Brain Research and Clinical Neuroengineering. *Matter*, 3, 1923-1947.
- SUTSKEVER, I., VINYALS, O. & LE, Q. V. 2014. Sequence to Sequence Learning with Neural Networks. *ArXiv*, abs/1409.3215.
- SVECHTAROVA, M. I., BUZZACCHERA, I., TOEBES, B. J., LAUKO, J., ANTON, N. & WILSON, C. J. 2016. Sensor Devices Inspired by the Five Senses: A Review. *Electroanalysis*, 28, 1201-1241.
- SWAN, M., DOS SANTOS, R. P. & WITTE, F. 2022. Quantum Neurobiology. *Quantum Reports*, 4, 107-126.
- SYRJANEN, J., MICHALSKI, K., KAWATE, T. & FURUKAWA, H. 2021. On the molecular nature of large-pore channels. *Journal of Molecular Biology*, 433, 166994.
- SYRJÄNEN, J. L., EPSTEIN, M., GÓMEZ, R. & FURUKAWA, H. 2023. Structure of human CALHM1 reveals key locations for channel regulation and blockade by ruthenium red. *Nature Communications*, 14, 3821.
- SZCZUREK, K. A., PRADES, R. M., MATHESON, E., RODRIGUEZ-NOGUEIRA, J. & DI CASTRO, M. 2023. Multimodal multi-user mixed reality human–robot interface for remote operations in hazardous environments. *IEEE Access*, 11, 17305-17333.
- SZIKSZAI, M., WISE, M., DATTA, A., WARD, M. & MATHEWS, D. H. 2022. Deep learning models for RNA secondary structure prediction (probably) do not generalize across families. *Bioinformatics*, 38, 3892-3899.
- SZYMANSKI, N. J., RENDY, B., FEI, Y., KUMAR, R. E., HE, T., MILSTED, D., MCDERMOTT, M. J., GALLANT, M., CUBUK, E. D., MERCHANT, A., KIM, H., JAIN, A., BARTEL, C. J., PERSSON, K., ZENG, Y. & CEDER, G. 2023. An autonomous laboratory for the accelerated synthesis of novel materials. *Nature*, 624, 86-91.
- TAN, A. H., LIM, S. Y. & LANG, A. E. 2022. The microbiome–gut–brain axis in Parkinson disease—from basic research to the clinic. *Nature Reviews Neurology*, 18, 476-495.
- TAN, L., SHI, N., YANG, C. & YU, K. 2020. A blockchain-based access control framework for cyber-physical-social system big data. *IEEE Access*, 8, 77215-77226.
- TANG, J., YUAN, F., SHEN, X., WANG, Z., RAO, M., HE, Y., SUN, Y., LI, X., ZHANG, W. & LI, Y. 2019. Bridging biological and artificial neural networks with emerging neuromorphic devices: fundamentals, progress, and challenges. *Advanced Materials*, 31, 1902761.
- TANG, R., HAN, X., JIANG, X. & HU, X. 2023a. Does synthetic data generation of llms help clinical text mining? *arXiv preprint arXiv:2303.04360*.
- TANG, T.-C., THAM, E., LIU, X., YEHL, K., ROVNER, A. J., YUK, H., ISAACS, F. J., ZHAO, X. & LU, T. K. 2020. Tough Hydrogel-Based Biocontainment of Engineered Organisms for Continuous, Self-Powered Sensing and Computation. *bioRxiv*, 2020.02.11.941120.
- TANG, X., SHEN, H., ZHAO, S., LI, N. & LIU, J. 2023b. Flexible brain–computer interfaces. *Nature Electronics*, 6, 109-118.
- TANG, Z., YANG, Z., ZHU, C., ZENG, M. & BANSAL, M. 2023c. Any-to-Any Generation via Composable Diffusion. *arXiv preprint arXiv:2305.11846*.
- TAY, P. K. R., NGUYEN, P. Q. & JOSHI, N. S. 2017. A Synthetic Circuit for Mercury Bioremediation Using Self-Assembling Functional Amyloids. *ACS Synthetic Biology*, 6, 1841-1850.
- TEEB, R. O. 2010. Mainstreaming the Economics of Nature. *TEEB Geneva, Switzerland*.
- TEMME, K., BRAVYI, S. & GAMBETTA, J. M. 2017. Error Mitigation for Short-Depth Quantum Circuits. *Physical Review Letters*, 119, 180509.

- TEWEL, Y., GAL, R., CHECHIK, G. & ATZMON, Y. Key-locked rank one editing for text-to-image personalization. *ACM SIGGRAPH 2023 Conference Proceedings*, 2023. 1-11.
- THANGAVEL, K., SPILLER, D., SABATINI, R., AMICI, S., LONGEPE, N., SERVIDIA, P., MARZOCCA, P., FAYEK, H. & ANSALONE, L. 2023. Trusted Autonomous Operations of Distributed Satellite Systems Using Optical Sensors. *Sensors*, 23, 3344.
- THIRUNAVUKARASU, A. J. 2023. Large language models will not replace healthcare professionals: curbing popular fears and hype. *Journal of the Royal Society of Medicine*, 116, 181-182.
- TIELROOIJ, K.-J. 2023. Ultrafast light-based logic with graphene. *Nature Materials*, 22, 945-946.
- TOEPEL, J., KARANDE, R., KLÄHN, S. & BÜHLER, B. 2023. Cyanobacteria as whole-cell factories: current status and future perspectives. *Current Opinion in Biotechnology*, 80, 102892.
- TONG, J., XING, Z., WEI, X., YUE, C., DONG, E., DU, S., SUN, Z., SOLÉ-CASALS, J. & CAIAFA, C. F. 2023. Towards Improving Motor Imagery Brain–Computer Interface Using Multimodal Speech Imagery. *Journal of Medical and Biological Engineering*, 1-11.
- TRAN, M. C., SHARMA, K. & TEMME, K. 2023. Locality and error mitigation of quantum circuits. *arXiv preprint arXiv:2303.06496*.
- TRAN, P. & PRINDLE, A. 2021. Synthetic biology in biofilms: tools, challenges, and opportunities. *Biotechnology Progress*, 37, e3123.
- TREGUBOV, A. A., NIKITIN, P. I. & NIKITIN, M. P. 2018. Advanced smart nanomaterials with integrated logic-gating and biocomputing: dawn of theranostic nanorobots. *Chemical reviews*, 118, 10294-10348.
- TURK, S. C., KLOOSTERMAN, W. P., NINABER, D. K., KOLEN, K. P., KNUTOVA, J., SUIR, E., SCHURMANN, M., RAEMAKERS-FRANKEN, P. C., MULLER, M. & DE WILDEMAN, S. M. 2016. Metabolic engineering toward sustainable production of nylon-6. *ACS synthetic biology*, 5, 65-73.
- TWENGE, J. M. 2020. Why increases in adolescent depression may be linked to the technological environment. *Current Opinion in Psychology*, 32, 89-94.
- ULMANN, B. 2022. Analog-and Hybridcomputing.
- VALLURY, H. J., JONES, M. A., WHITE, G. A., CREEVEY, F. M., HILL, C. D. & HOLLENBERG, L. C. 2023. Noise-robust ground state energy estimates from deep quantum circuits. *Quantum*, 7, 1109.
- VALMEEKAM, C. S. K., NARAYANAN, K., KALATHIL, D., CHAMBERLAND, J.-F. & SHAKKOTTAI, S. 2023. LLMZip: Lossless Text Compression using Large Language Models. *arXiv preprint arXiv:2306.04050*.
- VAN DEN BERG, E., MINEV, Z. K., KANDALA, A. & TEMME, K. 2023. Probabilistic error cancellation with sparse Pauli–Lindblad models on noisy quantum processors. *Nature Physics*, 19, 1116-1121.
- VAN DER VEER MARTENS, B. 2015. An illustrated introduction to the infosphere. *Library trends*, 63, 317-361.
- VAN KEMPEN, M., KIM, S. S., TUMESCHIT, C., MIRDITA, M., LEE, J., GILCHRIST, C. L. M., SÖDING, J. & STEINEGGER, M. 2023. Fast and accurate protein structure search with Foldseek. *Nature Biotechnology*.
- VARADI, M., ANYANGO, S., DESHPANDE, M., NAIR, S., NATASSIA, C., YORDANOVA, G., YUAN, D., STROE, O., WOOD, G. & LAYDON, A. 2022. AlphaFold Protein Structure Database: massively expanding the structural coverage of protein-sequence space with high-accuracy models. *Nucleic acids research*, 50, D439-D444.

- VARADI, M. & VELANKAR, S. 2022. The impact of AlphaFold Protein Structure Database on the fields of life sciences. *Proteomics*, 2200128.
- VASILEIADOU, E. & SAFARZYŃSKA, K. 2010. Transitions: Taking complexity seriously. *Futures*, 42, 1176-1186.
- VASWANI, A., SHAZEER, N., PARMAR, N., USZKOREIT, J., JONES, L., GOMEZ, A. N., KAISER, Ł. & POLOSUKHIN, I. 2017. Attention is all you need. *Advances in neural information processing systems*, 30.
- VEERAIAH, V., GANGAVATHI, P., AHAMAD, S., TALUKDAR, S. B., GUPTA, A. & TALUKDAR, V. Enhancement of meta verse capabilities by IoT integration. 2022 2nd International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE), 2022. IEEE, 1493-1498.
- VELDKAMP, E., SCHMIDT, M., POWERS, J. S. & CORRE, M. D. 2020. Deforestation and reforestation impacts on soils in the tropics. *Nature Reviews Earth & Environment*, 1, 590-605.
- VENKATRAGHAVAN, S., ANANTAKRISHNAN, S. & RAMAN, K. 2022. Probing patterning in microbial consortia with a cellular automaton for spatial organisation. *Scientific Reports*, 12, 17159.
- VIG, J., MADANI, A., VARSHNEY, L. R., XIONG, C., SOCHER, R. & RAJANI, N. F. 2020. Bertology meets biology: Interpreting attention in protein language models. *arXiv preprint arXiv:2006.15222*.
- VIGNOLI, A., GHINI, V., MEONI, G., LICARI, C., TAKIS, P. G., TENORI, L., TURANO, P. & LUCHINAT, C. 2019. High-throughput metabolomics by 1D NMR. *Angewandte Chemie International Edition*, 58, 968-994.
- VO, P. L. H., RONDA, C., KLOMPE, S. E., CHEN, E. E., ACREE, C., WANG, H. H. & STERNBERG, S. H. 2021. CRISPR RNA-guided integrases for high-efficiency, multiplexed bacterial genome engineering. *Nature biotechnology*, 39, 480-489.
- VOELZ, V. A., PANDE, V. S. & BOWMAN, G. R. 2023. Folding@home: achievements from over twenty years of citizen science herald the exascale era. *ArXiv*.
- VOIGT, C. A. 2020. Synthetic biology 2020–2030: six commercially-available products that are changing our world. *Nature Communications*, 11, 6379.
- VON STUMM, S. & PLOMIN, R. 2015. Socioeconomic status and the growth of intelligence from infancy through adolescence. *Intelligence*, 48, 30-36.
- VOPSON, M. M. 2023. The second law of infodynamics and its implications for the simulated universe hypothesis. *AIP Advances*, 13.
- WALDBY, C. 2002. Stem cells, tissue cultures and the production of biovalue. *Health*, 6, 305-323.
- WALDBY, C. & COOPER, M. 2008. The biopolitics of reproduction: Post-Fordist biotechnology and women's clinical labour. *Australian Feminist Studies*, 23, 57-73.
- WALKER, M., PHUNG, T., CHAKRABORTI, T., WILLIAMS, T. & SZAFIR, D. 2023. Virtual, augmented, and mixed reality for human-robot interaction: A survey and virtual design element taxonomy. *ACM Transactions on Human-Robot Interaction*, 12, 1-39.
- WAN, L., LIU, H., HUANG, C. & SHEN, X. 2020. Enzyme-like MOFs: synthetic molecular receptors with high binding capacity and their application in selective photocatalysis. *Journal of Materials Chemistry A*, 8, 25931-25940.
- WANG, C.-H. & DEBEER, S. 2021. Structure, reactivity, and spectroscopy of nitrogenase-related synthetic and biological clusters. *Chemical Society Reviews*, 50, 8743-8761.

- WANG, D.-D., ZHANG, J., YU, Q.-Q., ZHANG, K., CHEN, T.-T. & CHU, X. 2022a. Biomineralized Zeolitic Imidazolate Framework-8 Nanoparticles Enable Polymerase-Driven DNA Biocomputing for Reliable Cell Identification. *Analytical Chemistry*, 94, 4794-4802.
- WANG, F.-Y., WANG, X., LI, L. & LI, L. 2016a. Steps toward parallel intelligence. *IEEE/CAA Journal of Automatica Sinica*, 3, 345-348.
- WANG, G., XIE, Y., JIANG, Y., MANDLEKAR, A., XIAO, C., ZHU, Y., FAN, L. & ANANDKUMAR, A. 2023a. Voyager: An open-ended embodied agent with large language models. *arXiv preprint arXiv:2305.16291*.
- WANG, J., LISANZA, S., JUERGENS, D., TISCHER, D., WATSON, J. L., CASTRO, K. M., RAGOTTE, R., SARAGOVI, A., MILLES, L. F., BAEK, M., ANISHCHENKO, I., YANG, W., HICKS, D. R., EXPÒSIT, M., SCHLICHTHAERLE, T., CHUN, J.-H., DAUPARAS, J., BENNETT, N., WICKY, B. I. M., MUENKS, A., DIMAIO, F., CORREIA, B., OVCHINNIKOV, S. & BAKER, D. 2022b. Scaffolding protein functional sites using deep learning. *Science*, 377, 387-394.
- WANG, K., ZHOU, R., WU, Y. & LI, M. 2023b. RLBind: a deep learning method to predict RNA–ligand binding sites. *Briefings in Bioinformatics*, 24, bbac486.
- WANG, L., WU, W., LIANG, K. & YU, X. 2022c. Advanced Strategies for Improving the Photocatalytic Nitrogen Fixation Performance: A Short Review. *Energy & Fuels*, 36, 11278-11291.
- WANG, R., WANG, W., ZENG, X., WANG, L., LIAN, Z., GAO, Y., LIU, F., LI, S., WANG, X. & FU, Q. 2022d. Multi-Agent Multi-Game Entity Transformer.
- WANG, T., ANTONACCI-FULTON, L., HOWE, K., LAWSON, H. A., LUCAS, J. K., PHILLIPPY, A. M., POPEJOY, A. B., ASRI, M., CARSON, C. & CHAISSON, M. J. 2022e. The Human Pangenome Project: a global resource to map genomic diversity. *Nature*, 604, 437-446.
- WANG, X., CAO, Z., ZHANG, M., MENG, L., MING, Z. & LIU, J. 2020. Bioinspired oral delivery of gut microbiota by self-coating with biofilms. *Science Advances*, 6, eabb1952.
- WANG, X., LI, L., YUAN, Y., YE, P. & WANG, F.-Y. 2016b. ACP-based social computing and parallel intelligence: Societies 5.0 and beyond. *CAAI Transactions on Intelligence Technology*, 1, 377-393.
- WANG, Y., CHEN, Z., PAN, Z., HUANG, S., LIU, J., XIA, W., ZHANG, H., ZHENG, M., LI, H. & HOU, T. 2023c. RNAincoder: a deep learning-based encoder for RNA and RNA-associated interaction. *Nucleic Acids Research*, gkad404.
- WANG, Y. & CHIEW, V. 2010. On the cognitive process of human problem solving. *Cognitive systems research*, 11, 81-92.
- WANG, Y., WANG, Y. & SARTORETTI, G. 2023d. Full communication memory networks for team-level cooperation learning. *Autonomous Agents and Multi-Agent Systems*, 37, 33.
- WANG, Y., ZHAO, T. & YI, F. 2023e. Multiverse Transformer: 1st Place Solution for Waymo Open Sim Agents Challenge 2023. *arXiv preprint arXiv:2306.11868*.
- WANG, Z., HU, X., LIU, Z., ZOU, G., WANG, G. & ZHANG, K. 2019. Recent developments in polymeric carbon nitride-derived photocatalysts and electrocatalysts for nitrogen fixation. *ACS Catalysis*, 9, 10260-10278.
- WAYMENT-STEELE, H. K., KLADWANG, W., STROM, A. I., LEE, J., TREUILLE, A., BECKA, A., PARTICIPANTS, E. & DAS, R. 2022. RNA secondary structure packages evaluated and improved by high-throughput experiments. *Nature Methods*, 19, 1234-1242.
- WEBB, T. D., WILSON, M. G., ODÉEN, H. & KUBANEK, J. 2023. Sustained modulation of primate deep brain circuits with focused ultrasonic waves. *Brain Stimulation*, 16, 798-805.

- WEBSTER-WOOD, V. A., GUIX, M., XU, N. W., BEHKAM, B., SATO, H., SARKAR, D., SANCHEZ, S., SHIMIZU, M. & PARKER, K. K. 2023. Biohybrid robots: recent progress, challenges, and perspectives. *Bioinspiration & Biomimetics*, 18, 015001.
- WEI, J., CHEN, S., ZONG, L., GAO, X. & LI, Y. 2022a. Protein–RNA interaction prediction with deep learning: structure matters. *Briefings in bioinformatics*, 23, bbab540.
- WEI, J., XIAO, J., CHEN, S., ZONG, L., GAO, X. & LI, Y. 2022b. ProNet DB: A proteome-wise database for protein surface property representations and RNA-binding profiles. *arXiv preprint arXiv:2205.07673*.
- WEIMERT, B. & ZWECK, A. 2022. Scientific relevance. *Standards of Futures Research: Guidelines for Practice and Evaluation*. Springer.
- WELLS, J. 2014. Membrane patterns carry ontogenetic information that is specified independently of DNA. *Biophysical Journal*, 106, 596a.
- WEN, D., YUAN, Y. & LI, X.-R. 2012. Artificial societies, computational experiments, and parallel systems: an investigation on a computational theory for complex socioeconomic systems. *IEEE Transactions on Services Computing*, 6, 177-185.
- WHITEAKER, B. A. & SHYAM, V. 2021. Topic Modeling Tool for PeTaL (Periodic Table of Life).
- WHITEN, A. Social complexity and social intelligence. *The Nature of Intelligence: Novartis Foundation Symposium 233*, 2000. Wiley Online Library, 185-201.
- WILLS, P. R. 2023. Origins of Genetic Coding: Self-Guided Molecular Self-Organisation. *Entropy*, 25, 1281.
- WINKLE, M., EL-DALY, S. M., FABBRI, M. & CALIN, G. A. 2021. Noncoding RNA therapeutics—Challenges and potential solutions. *Nature reviews Drug discovery*, 20, 629-651.
- WISHART, D. S., CHENG, L. L., COPIÉ, V., EDISON, A. S., EGHBALNIA, H. R., HOCH, J. C., GOUVEIA, G. J., PATHMASIRI, W., POWERS, R. & SCHOCK, T. B. 2022. NMR and Metabolomics—A Roadmap for the Future. *Metabolites*, 12, 678.
- WLODEK 2022. Abstraction, Reasoning and Deep Learning: A Study of the "Look and Say" Sequence. *arXiv pre-print server*.
- WOLTER, M., GRANT, E. T., BOUDAUD, M., STEIMLE, A., PEREIRA, G. V., MARTENS, E. C. & DESAI, M. S. 2021. Leveraging diet to engineer the gut microbiome. *Nature reviews Gastroenterology & hepatology*, 18, 885-902.
- WONG, M. L., CLELAND, C. E., AREND, D., BARTLETT, S., CLEAVES, H. J., DEMAREST, H., PRABHU, A., LUNINE, J. I. & HAZEN, R. M. 2023. On the roles of function and selection in evolving systems. *Proceedings of the National Academy of Sciences*, 120, e2310223120.
- WU, C., YIN, S., QI, W., WANG, X., TANG, Z. & DUAN, N. 2023a. Visual chatgpt: Talking, drawing and editing with visual foundation models. *arXiv preprint arXiv:2303.04671*.
- WU, D., KARHADE, D. S., PILLAI, M., JIANG, M.-Z., HUANG, L., LI, G., CHO, H., ROACH, J., LI, Y. & DIVARIS, K. 2021. Machine Learning and Deep Learning in Genetics and Genomics. In: KO, C.-C., SHEN, D. & WANG, L. (eds.) *Machine Learning in Dentistry*. Cham: Springer International Publishing.
- WU, J., FANG, H., ZHANG, J. & YAN, S. 2023b. Modular microfluidics for life sciences. *Journal of Nanobiotechnology*, 21, 1-30.
- WU, S., FEI, H., QU, L., JI, W. & CHUA, T.-S. 2023c. NEX-T-GPT: Any-to-Any Multimodal LLM. *arXiv preprint arXiv:2309.05519*.
- WU, S., IRSOY, O., LU, S., DABRAVOLSKI, V., DREDZE, M., GEHRMANN, S., KAMBADUR, P., ROSENBERG, D. & MANN, G. 2023d. BloombergGPT: A Large Language Model for Finance. *ArXiv*, abs/2303.17564.

- WU, Y., LUO, W., WENG, Z., GUO, Y., YU, H., ZHAO, R., ZHANG, L., ZHAO, J., BAI, D. & ZHOU, X. 2022. A PAM-free CRISPR/Cas12a ultra-specific activation mode based on toehold-mediated strand displacement and branch migration. *Nucleic Acids Research*, 50, 11727-11737.
- WU, Y., MIN, S. Y., PRABHUMOYE, S., BISK, Y., SALAKHUTDINOV, R., AZARIA, A., MITCHELL, T. & LI, Y. 2023e. SPRING: GPT-4 Out-performs RL Algorithms by Studying Papers and Reasoning. *arXiv preprint arXiv:2305.15486*.
- WU, Z., ZHANG, C., GU, X., DUPORGE, I., HUGHEY, L. F., STABACH, J. A., SKIDMORE, A. K., HOPCRAFT, J. G. C., LEE, S. J. & ATKINSON, P. M. 2023f. Deep learning enables satellite-based monitoring of large populations of terrestrial mammals across heterogeneous landscape. *Nature communications*, 14, 3072.
- XIANG, N., GUO, C., LIU, J., XU, H., DIXON, R., YANG, J. & WANG, Y.-P. 2020. Using synthetic biology to overcome barriers to stable expression of nitrogenase in eukaryotic organelles. *Proceedings of the National Academy of Sciences*, 117, 16537-16545.
- XING, S., JIAO, Y., SALEHZADEH, M., SOMA, K. K. & HUAN, T. 2021. SteroidXtract: deep learning-based pattern recognition enables comprehensive and rapid extraction of steroid-like metabolic features for automated biology-driven metabolomics. *Analytical Chemistry*, 93, 5735-5743.
- XIONG, X., SWEET, S. M., LIU, M., HONG, C., BONZEL, C.-L., AYAKULANGARA PANICKAN, V., ZHOU, D., WANG, L., COSTA, L. & HO, Y.-L. 2023. Knowledge-Driven Online Multimodal Automated Phenotyping System. *medRxiv*, 2023.09. 29.23296239.
- XIONG, Y., FORD, N. R., HECHT, K. A., ROESIADI, G. & SQUIER, T. C. 2016. Dynamic Stabilization of Expressed Proteins in Engineered Diatom Biosilica Matrices. *Bioconjugate Chemistry*, 27, 1205-1209.
- XU, B., LIU, X., SHEN, H., HAN, Z., LI, Y., YUE, M., PENG, Z., LIU, Y., YAO, Z. & XU, D. 2023a. Gentopia: A collaborative platform for tool-augmented llms. *arXiv preprint arXiv:2308.04030*.
- XU, H., XIANG, J. X., LU, Y. F., ZHANG, M. K., LI, J. J., GAO, B. B., ZHAO, Y. J. & GU, Z. Z. 2018. Multifunctional Wearable Sensing Devices Based on Functionalized Graphene Films for Simultaneous Monitoring of Physiological Signals and Volatile Organic Compound Biomarkers. *ACS Applied Materials & Interfaces*, 10, 11785-11793.
- XU, L., ZHU, J., CHEN, B., YANG, Z., LIU, K., DANG, B., ZHANG, T., YANG, Y. & HUANG, R. 2022a. A distributed nanocluster based multi-agent evolutionary network. *Nature Communications*, 13, 4698.
- XU, M., NIYATO, D., CHEN, J., ZHANG, H., KANG, J., XIONG, Z., MAO, S. & HAN, Z. 2023b. Generative AI-empowered simulation for autonomous driving in vehicular mixed reality metaverses. *arXiv preprint arXiv:2302.08418*.
- XU, S., YANG, C., YAN, X. & LIU, H. 2022b. Towards high throughput and high information coverage: advanced single-cell mass spectrometric techniques. *Analytical and Bioanalytical Chemistry*, 414, 219-233.
- XUE, X., YU, X.-N., ZHOU, D.-Y., WANG, X., ZHOU, Z.-B. & WANG, F.-Y. 2022. Computational experiments: Past, present and future. *arXiv preprint arXiv:2202.13690*.
- YAGHI, O. M. 2020. The reticular chemist. ACS Publications.
- YALCIN, S. E. & MALVANKAR, N. S. 2020. The blind men and the filament: understanding structures and functions of microbial nanowires. *Current opinion in chemical biology*, 59, 193-201.

- YAN, B., YANG, Y. & HUANG, R. 2023a. Memristive dynamics enabled neuromorphic computing systems. *Science China Information Sciences*, 66, 1-15.
- YAN, J., YADAV, V., LI, S., CHEN, L., TANG, Z., WANG, H., SRINIVASAN, V., REN, X. & JIN, H. 2023b. Virtual prompt injection for instruction-tuned large language models. *arXiv preprint arXiv:2307.16888*.
- YANG, D. & HOLLENSTEIN, N. 2023. PLM-AS: Pre-trained Language Models Augmented with Scanpaths for Sentiment Classification. *Proceedings of the Northern Lights Deep Learning Workshop*, 4.
- YANG, E., ZHANG, H., ZANG, Z., ZHOU, Z., WANG, S., LIU, Z. & LIU, Y. 2023a. GCNfold: A novel lightweight model with valid extractors for RNA secondary structure prediction. *Computers in Biology and Medicine*, 107246.
- YANG, H., LIU, X.-Y. & WANG, C. 2023b. FinGPT: Open-Source Financial Large Language Models. *ArXiv*, abs/2306.06031.
- YANG, L., HUNG, L. Y., ZHU, Y., DING, S., MARGOLIS, K. G. & LEONG, K. W. 2022. Material engineering in gut microbiome and human health. *Research*.
- YANG, L., KANG, B., HUANG, Z., XU, X., FENG, J. & ZHAO, H. 2024. Depth Anything: Unleashing the Power of Large-Scale Unlabeled Data. Available: <https://ui.adsabs.harvard.edu/abs/2024arXiv240110891Y> [Accessed January 01, 2024].
- YANG, M., DU, Y., GHASEMIPOUR, K., TOMPSON, J., SCHUURMANS, D. & ABBEEL, P. Learning Interactive Real-World Simulators. 2023c.
- YANG, Q., WANG, Z., GUO, K., CAI, C. & QU, X. 2023d. Physics-driven synthetic data learning for biomedical magnetic resonance: The imaging physics-based data synthesis paradigm for artificial intelligence. *IEEE Signal Processing Magazine*, 40, 129-140.
- YANG, T. H., KIM, J. R., JIN, H., GIL, H., KOO, J. H. & KIM, H. J. 2021. Recent advances and opportunities of active materials for haptic technologies in virtual and augmented reality. *Advanced Functional Materials*, 31, 2008831.
- YANG, Z., LI, L., LIN, K., WANG, J., LIN, C.-C., LIU, Z. & WANG, L. 2023e. The Dawn of LMMs: Preliminary Explorations with GPT-4V (ision). *arXiv preprint arXiv:2309.17421*.
- YARNALL, M. T., IOANNIDI, E. I., SCHMITT-ULMS, C., KRAJESKI, R. N., LIM, J., VILLIGER, L., ZHOU, W., JIANG, K., GARUSHYANTS, S. K. & ROBERTS, N. 2023. Drag-and-drop genome insertion of large sequences without double-strand DNA cleavage using CRISPR-directed integrases. *Nature biotechnology*, 41, 500-512.
- YE, Q., XU, H., XU, G., YE, J., YAN, M., ZHOU, Y., WANG, J., HU, A., SHI, P. & SHI, Y. 2023. mplug-owl: Modularization empowers large language models with multimodality. *arXiv preprint arXiv:2304.14178*.
- YI, H., YAN, M., HUANG, D., ZENG, G., LAI, C., LI, M., HUO, X., QIN, L., LIU, S. & LIU, X. 2019. Synergistic effect of artificial enzyme and 2D nano-structured Bi₂WO₆ for eco-friendly and efficient biomimetic photocatalysis. *Applied Catalysis B: Environmental*, 250, 52-62.
- YILMA, B. A., PANETTO, H. & NAUDET, Y. 2021. Systemic formalisation of Cyber-Physical-Social System (CPSS): A systematic literature review. *Computers in Industry*, 129, 103458.
- YIN, J., HINCHET, R., SHEA, H. & MAJIDI, C. 2021. Wearable soft technologies for haptic sensing and feedback. *Advanced Functional Materials*, 31, 2007428.
- YIP, D. W., ESMRADI, A. & CHAN, C. F. 2024. A Novel Evaluation Framework for Assessing Resilience Against Prompt Injection Attacks in Large Language Models. *arXiv preprint arXiv:2401.00991*.

- YOON, P. H., SKOPINTSEV, P., SHI, H., CHEN, L.-X., ADLER, B. A., AL-SHIMARY, M., CRAIG, R. J., LI, Z., AMERASEKERA, J. & TRINIDAD, M. 2023. Eukaryotic RNA-guided endonucleases evolved from a unique clade of bacterial enzymes. *bioRxiv*, 2023.08. 09.552727.
- YOU, H., SUN, Z., SHI, H., YU, Z., ZHAO, Y., ZHANG, Y., LI, C., LI, B. & LIN, Y. Vitcod: Vision transformer acceleration via dedicated algorithm and accelerator co-design. 2023 IEEE International Symposium on High-Performance Computer Architecture (HPCA), 2023. IEEE, 273-286.
- YU, C.-J., VON KUGELGEN, S., LAORENZA, D. W. & FREEDMAN, D. E. 2021. A Molecular Approach to Quantum Sensing. *ACS Central Science*, 7, 712-723.
- YU, H., QI, Y. & DING, Y. 2022. Deep learning in RNA structure studies. *Frontiers in Molecular Biosciences*, 9, 537.
- YU, N., SKRIPNIUK, V., ABDELNABI, S. & FRITZ, M. 2020. Artificial Fingerprinting for Generative Models: Rooting Deepfake Attribution in Training Data. *2021 IEEE/CVF International Conference on Computer Vision (ICCV)*, 14428-14437.
- YUAN, W., PANG, R. Y., CHO, K., SUKHBAATAR, S., XU, J. & WESTON, J. Self-Rewarding Language Models. 2024.
- YUAN, Z., LI, Z. & SUN, L. TinyGPT-V: Efficient Multimodal Large Language Model via Small Backbones. 2023.
- ZAAIMI, B., TURNBULL, M., HAZRA, A., WANG, Y., GANDARA, C., MCLEOD, F., MCDERMOTT, E., ESCOBEDO-COUSIN, E., IDIL, A. S. & BAILEY, R. 2023. Closed-loop optogenetic control of the dynamics of neural activity in non-human primates. *Nature biomedical engineering*, 7, 559-575.
- ZABARDAST, A., TAMER, E. G., SON, Y. A. & YILMAZ, A. 2023. An automated framework for evaluation of deep learning models for splice site predictions. *Scientific Reports*, 13, 10221.
- ZAHAVY, T., VEERIAH, V., HOU, S., WAUGH, K., LAI, M., LEURENT, E., TOMASEV, N., SCHUT, L., HASSABIS, D. & SINGH, S. 2023. Diversifying AI: Towards Creative Chess with AlphaZero. *arXiv preprint arXiv:2308.09175*.
- ZAMPIERI, G., VIJAYAKUMAR, S., YANESKE, E. & ANGIONE, C. 2019. Machine and deep learning meet genome-scale metabolic modeling. *PLoS Comput Biol*, 15, e1007084.
- ZAMPIERI, M., SEKAR, K., ZAMBONI, N. & SAUER, U. 2017. Frontiers of high-throughput metabolomics. *Current opinion in chemical biology*, 36, 15-23.
- ZANGENEH-NEJAD, F. & FLEURY, R. 2019. Topological analog signal processing. *Nature Communications*, 10, 2058.
- ZANGENEH-NEJAD, F., SOUNAS, D. L., ALÙ, A. & FLEURY, R. 2021. Analogue computing with metamaterials. *Nature Reviews Materials*, 6, 207-225.
- ZEIRA, A. 2022. Mental health challenges related to neoliberal capitalism in the United States. *Community mental health journal*, 58, 205-212.
- ZENG, C., JIAN, Y., VOSOUGHI, S., ZENG, C. & ZHAO, Y. 2023. Evaluating native-like structures of RNA-protein complexes through the deep learning method. *Nature Communications*, 14, 1060.
- ZENG, J., YANG, L. T., LIN, M., NING, H. & MA, J. 2020. A survey: Cyber-physical-social systems and their system-level design methodology. *Future Generation Computer Systems*, 105, 1028-1042.
- ZHANG, A. & LIEBER, C. M. 2016. Nano-bioelectronics. *Chemical reviews*, 116, 215-257.

- ZHANG, C., LIN, C., LENG, Y., FU, Z., CHENG, Y. & FU, C. 2023. An Effective Head-Based HRI for 6D Robotic Grasping Using Mixed Reality. *IEEE Robotics and Automation Letters*, 8, 2796-2803.
- ZHANG, C. & LU, Y. 2021. Study on artificial intelligence: The state of the art and future prospects. *Journal of Industrial Information Integration*, 23, 100224.
- ZHANG, C. & ZHANG, B. 2023. RNA therapeutics: updates and future potential. *Science China Life Sciences*, 66, 12-30.
- ZHANG, G., SEWELL, C. D., ZHANG, P., MI, H. & LIN, Z. 2020a. Nanostructured photocatalysts for nitrogen fixation. *Nano Energy*, 71, 104645.
- ZHANG, L., HOU, S., WANG, T., LIU, S., GAO, X., WANG, C. & WANG, G. 2022a. Recent Advances in Application of Graphitic Carbon Nitride-Based Catalysts for Photocatalytic Nitrogen Fixation. *Small*, 18, 2202252.
- ZHANG, L., LU, J. & WAIGH, T. 2021a. Electronics of peptide-and protein-based biomaterials. *Advances in Colloid and Interface Science*, 287, 102319.
- ZHANG, L., YANG, G. & STADIE, B. C. World model as a graph: Learning latent landmarks for planning. International Conference on Machine Learning, 2021b. PMLR, 12611-12620.
- ZHANG, P., BACHMAN, H., OZCELIK, A. & HUANG, T. J. 2020b. Acoustic microfluidics. *Annual Review of Analytical Chemistry*, 13, 17-43.
- ZHANG, P., ZENG, G., WANG, T. & LU, W. TinyLlama: An Open-Source Small Language Model. 2024.
- ZHANG, Q., WANG, Z., HAN, Y., YU, H., JIN, X. & CHEN, H. 2022b. Prompt-guided injection of conformation to pre-trained protein model. *arXiv preprint arXiv:2202.02944*.
- ZHANG, X., WANG, W., ZHU, W., DONG, J., CHENG, Y., YIN, Z. & SHEN, F. 2019. Mechanisms and functions of long non-coding RNAs at multiple regulatory levels. *International journal of molecular sciences*, 20, 5573.
- ZHANG, Y., QU, P., JI, Y., ZHANG, W., GAO, G., WANG, G., SONG, S., LI, G., CHEN, W., ZHENG, W., CHEN, F., PEI, J., ZHAO, R., ZHAO, M. & SHI, L. 2020c. A system hierarchy for brain-inspired computing. *Nature*, 586, 378-384.
- ZHAO, T., HU, Y., PENG, J. & CHENG, L. 2020. DeepLGP: a novel deep learning method for prioritizing lncRNA target genes. *Bioinformatics*, 36, 4466-4472.
- ZHONG, J., LING, C., CANGELOSI, A., LOTFI, A. & LIU, X. 2021. On the gap between domestic robotic applications and computational intelligence. *Electronics*, 10, 793.
- ZHONGMING, Z., LINONG, L., XIAONA, Y., WANGQIANG, Z. & WEI, L. 2021. Machine learning accelerates discovery of materials for use in industrial processes.
- ZHOU, J. & PAPAUTSKY, I. 2020. Viscoelastic microfluidics: Progress and challenges. *Microsystems & Nanoengineering*, 6, 113.
- ZHOU, S., DONG, J., DENG, L., WANG, G., YANG, M., WANG, Y., HUO, D. & HOU, C. 2022. Endonuclease-assisted PAM-free recombinase polymerase amplification coupling with CRISPR/Cas12a (E-PfRPA/Cas) for sensitive detection of DNA methylation. *ACS sensors*, 7, 3032-3040.
- ZHOU, T., SONG, Z. & SUNDMACHER, K. 2019a. Big data creates new opportunities for materials research: a review on methods and applications of machine learning for materials design. *Engineering*, 5, 1017-1026.
- ZHOU, W., JIANG, Y. E., LI, L., WU, J., WANG, T., QIU, S., ZHANG, J., CHEN, J., WU, R. & WANG, S. 2023. Agents: An Open-source Framework for Autonomous Language Agents. *arXiv preprint arXiv:2309.07870*.

- ZHOU, Y., YU, F. R., CHEN, J. & KUO, Y. 2019b. Cyber-physical-social systems: A state-of-the-art survey, challenges and opportunities. *IEEE Communications Surveys & Tutorials*, 22, 389-425.
- ZHU, J., WANG, J., WANG, X., GAO, M., GUO, B., GAO, M., LIU, J., YU, Y., WANG, L. & KONG, W. 2021. Prediction of drug efficacy from transcriptional profiles with deep learning. *Nature biotechnology*, 39, 1444-1452.
- ZHU, J., ZHANG, T., YANG, Y. & HUANG, R. 2020a. A comprehensive review on emerging artificial neuromorphic devices. *Applied Physics Reviews*, 7, 011312.
- ZHU, K., PAZOS, S., AGUIRRE, F., SHEN, Y., YUAN, Y., ZHENG, W., ALHARBI, O., VILLENA, M. A., FANG, B., LI, X., MILOZZI, A., FARRONATO, M., MUÑOZ-ROJO, M., WANG, T., LI, R., FARIBORZI, H., ROLDAN, J. B., BENSTETTER, G., ZHANG, X., ALSHAREEF, H. N., GRASSER, T., WU, H., IELMINI, D. & LANZA, M. 2023a. Hybrid 2D-CMOS microchips for memristive applications. *Nature*, 618, 57-62.
- ZHU, Q., HUO, B., SUN, H., LI, B. & JIANG, X. 2020b. Application of deep learning in microbiome. *Journal of Artificial Intelligence for Medical Sciences*, 1, 23-29.
- ZHU, X., LI, J., LIU, Y., MA, C. & WANG, W. 2023b. A survey on model compression for large language models. *arXiv preprint arXiv:2308.07633*.
- ZHU, Y., GAO, T., FAN, L., HUANG, S., EDMONDS, M., LIU, H., GAO, F., ZHANG, C., QI, S. & WU, Y. N. 2020c. Dark, beyond deep: A paradigm shift to cognitive ai with humanlike common sense. *Engineering*, 6, 310-345.
- ZHU, Y., ZHANG, X., SUN, L., WANG, Y. & ZHAO, Y. 2023c. Engineering human brain assembloids by microfluidics. *Advanced materials*, 35, 2210083.
- ZHU, Y., ZHU, L., WANG, X. & JIN, H. 2022. RNA-based therapeutics: an overview and prospectus. *Cell death & disease*, 13, 644.
- ZHUGE, M., LIU, H., FACCIO, F., ASHLEY, D. R., CSORDÁS, R., GOPALAKRISHNAN, A., HAMDY, A., HAMMOUD, H. A. A. K., HERRMANN, V. & IRIE, K. 2023. Mindstorms in Natural Language-Based Societies of Mind. *arXiv preprint arXiv:2305.17066*.
- ZOLFAGHARIAN, M., WALRAVE, B., RAVEN, R. & ROMME, A. G. L. 2019. Studying transitions: Past, present, and future. *Research Policy*, 48, 103788.
- ZOU, A., WANG, Z., KOLTER, J. Z. & FREDRIKSON, M. 2023. Universal and Transferable Adversarial Attacks on Aligned Language Models. *arXiv preprint arXiv:2307.15043*.
- ZOU, J., HUSS, M., ABID, A., MOHAMMADI, P., TORKAMANI, A. & TELENTI, A. 2019. A primer on deep learning in genomics. *Nature Genetics*, 51, 12-18.
- ZOUKAL, S., CORDOVA, G. Z. & SOSSO, F. A. E. 2023. Economic and social determinants of health disparities in India: A systematic review of sleep literature. *medRxiv*, 2023.03.13.23287175.
- ZULYS, A., YULIA, F., MUHADZIB, N. & NASRUDDIN 2020. Biological metal-organic frameworks (Bio-MOFs) for CO₂ capture. *Industrial & Engineering Chemistry Research*, 60, 37-51.
- ZUNNER, B. E., WACHSMUTH, N. B., ECKSTEIN, M. L., SCHERL, L., SCHIERBAUER, J. R., HAUPT, S., STUMPF, C., REUSCH, L. & MOSER, O. 2022. Myokines and resistance training: a narrative review. *International Journal of Molecular Sciences*, 23, 3501.
- ZWECK, A. 2009. Foresight, Technologiefrüherkennung und Technikfolgenabschätzung: Instrumente für ein zukunftsorientiertes Technologiemanagement. *Zukunftsforschung und Zukunftsgestaltung: Beiträge aus Wissenschaft und Praxis*. Springer.

6.0 Appendix

6.1 Abstracts

This work in futures studies provides a comprehensive overview of current key technologies, with a focus on innovations and developments in information science, molecular biology, chemistry, and synthetic biology. Grounded in a rigorous methodology and foundational premises, it crafts visions of the future that not only outline the impacts of these technological advancements but also capture significant underlying trends and influential themes that will shape the architecture and conception of human society.

Vorliegende zukunfts wissenschaftliche Arbeit präsentiert einen umfassenden Überblick über gegenwärtige Schlüsseltechnologien und illustriert relevante Innovationen, Entwicklungen und deren Bedeutungen der Informations- und Naturwissenschaften mit besonderem Hinblick auf Informatik, Molekularbiologie, Chemie und synthetische Biologie. Auf der Grundlage stringenter Methodologie und vorgestellter Prämissen werden Zukunftsbilder erarbeitet, welche die Auswirkungen dieser Entwicklungen umreißen, als auch bedeutende zugrundeliegende Tendenzen und wirkmächtige Topoi erfassen, welche die Konzeption und Architektur der menschlichen Gesellschaft prägen werden.