

Future Directions Workshop on the Synthesis and Evolution of Life-like Artificial Systems

April 29-30, 2026

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Future Directions Workshop series
Workshop sponsored by the Science & Technology Foundations Office, Office of the Undersecretary of War for Research and Engineering

VT-ARC Virginia Tech Applied Research Corporation

CLEARED
For Open Publication
Oct 02, 2026
Department of War
DEFENSE OFFICE OF PREPUBLICATION AND SECURITY REVIEW
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Innovation is the key to the future, but basic research is the key to future innovation.

–Jerome Isaac Friedman,
Nobel Prize Recipient (1990)

Preface

Over the past century, science and technology has brought remarkable new capabilities to all sectors of the economy; from telecommunications, energy, and electronics to medicine, transportation and defense. Technologies that were fantasy decades ago, such as the internet and mobile devices, now inform the way we live, work, and interact with our environment. Key to this technological progress is the capacity of the global basic research community to create new knowledge and to develop new insights in science, technology, and engineering. Understanding the trajectories of this fundamental research, within the context of global challenges, empowers stakeholders to identify and seize potential opportunities.

The Future Directions Workshop series, sponsored by the Science and Technology Foundations Office of the Undersecretary of War for Research and Engineering, seeks to examine emerging research and engineering areas that are most likely to transform future technology capabilities. These workshops gather distinguished academic researchers from around the globe to engage in an interactive dialogue about the promises and challenges of each emerging basic research area and how they could impact future capabilities. Chaired by leaders in the field, these workshops encourage unfettered considerations of the prospects of fundamental science areas from the most talented minds in the research community.

Reports from the Future Direction Workshop series capture these discussions and therefore play a vital role in the discussion of basic research priorities. In each report, participants are challenged to address the following important questions:

- How will the research impact science and technology capabilities of the future?
- What is the trajectory of scientific achievement over the next few decades?
- What are the most fundamental challenges to progress?

This report is the product of a workshop held April 29-30, 2026, in Arlington, Virginia on the future of research on Synthesis and Evolution of Life-like Artificial Systems. It is intended as a resource to the S&T community including the broader federal funding community, federal laboratories, domestic industrial base, and academia.

Executive Summary

Living systems are self-sustaining and possess properties such as robustness (resiliency and self-repair), adaptability, and near-optimal fit to their environment, that are unmatched by anything humans have engineered. These properties are the product of biological evolution acting over billions of years, yet the living world occupies only a negligible fraction of the possible "design space." If artificial biological ("life-like") systems could be created and specifically designed to address humanity's needs, it could revolutionize improvements and solutions in energy, health, materials science, and more. However, the ability to redirect biological evolution to meet humanity's needs is currently impractical because evolution is far too slow. Evolution as we know it utilizes terrestrial genetics that is subject to historical constraints that are impossible to avoid. Yet, decades of research in computational and digital evolution has shown that we can vastly increase evolutionary speed if we instead design the system from the ground up.

Constructing a new starting point, such as an artificial living or life-like system, built on fundamental principles of life rather than inherited from terrestrial ancestry, would allow us to make fundamental changes: revealing what makes life possible, sharpening the search for life elsewhere, allowing evolution to be harnessed for design, and enabling systems tailored to human needs. Given the power such control would confer, this prospect also demands careful attention to safety and oversight at every step.

Creating an artificial living (or life-like) system, be it engineered from biochemistry or within robotics, is not currently feasible because of a number of significant knowledge gaps. For example, engineered systems are not robust, and tend to decay and lose components, because the components are not well adapted to each other. We cannot currently create a minimal system that then could evolve and adapt because we do not know how life (even artificial life) originates. While significant progress on artificial cell-like structures has been made, we are still searching for the optimal "new materials" and building blocks for artificial life. These are just a few of the knowledge gaps that we must fill to make progress in this exciting endeavor.

The Future Directions Workshop on the Synthesis and Evolution of Life-like Artificial Systems (SELAS) convened 21 researchers from chemistry, biology, physics, planetary science, computer science, and ethics to chart the research directions that could make this vision achievable over the next 10–20 years.

The two-day workshop was organized to encourage lively discussion and debate about the future of SELAS. The first day was spent in small group discussions about the fundamental challenges and opportunities for the three subtopics of emergence, evolution, and future of life-like systems. The second day of the workshop was spent as a whole group examining cross-cutting themes and topics not covered on the first day. This report summarizes the findings of the workshop as research challenges and opportunities and the trajectory for SELAS research over the next twenty years.

Emergence

The Emergence topic is the grey area where abiotic chemistry escalates in complexity toward life-like behavior. A central difficulty is that there is no consensus definition of life; and so rather than resolve that debate, the focus of discussions was on the "edge cases" where disagreement is greatest. Because emergence is inseparable from environmental context, distinguishing a genuine biosignature from abiotic or pre-biotic organic complexity—and tracing the largely unknown pathways of inheritance from the prebiotic world to life—remains a defining challenge for both planetary missions and laboratory experiments.

One of the most distinctive research opportunities is "systems geochemistry" that treats planetary environments not as passive backdrops but as sources of disequilibria that drive reactions toward life. Another lies in how self-assembly and compartment formation select molecular "winners" from complex mixtures, and the cultivation of a research cohort at the interface of prebiotic chemistry and ancient biochemistry.

Evolution

The Evolution topic describes the capacity that most distinguishes living systems: the ability to adapt, inherit, and generate novelty over time. Because most current work is built on the specific solutions of terrestrial biology—DNA, RNA, proteins, and lipid membranes—a central question is whether these are unique requirements or merely one possible realization among many. Developing alternative information storage and genotype-phenotype coupling, and understanding how evolution generates genuine novelty rather than merely optimizing known functions, are the key barriers to synthetic systems capable of sustained, open-ended evolution.

The opportunities lie in non-canonical information systems (alternative polymers, dynamic molecular networks, self-assembled structures, and compositional states) that could support inheritance without DNA, RNA, or proteins. Adaptive compartments offer a complementary route, localizing information and establishing the individuality on which selection can act.

Futures

The Futures topic examines why artificial life-like systems are worth pursuing, focusing on applications where biological evolution has provided no solution or where engineered systems are too fragile: biomedicine, hazardous-environment operations, space exploration and terraforming, and the synthesis of novel materials and manufacturing by growth rather than top-down assembly. Discussions centered on two complementary tracks—biochemical artificial life and robotic artificial life—and identified the "inverse mapping" problem of specifying the information that would encode a desired function as the foremost obstacle.

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Near-term opportunities include the intersection of evolution and robotics, along with how artificial cells can serve as drug delivery vehicles and screening platforms. Mid- and far-term opportunities lie in autonomous operation beyond the reach of real-time control, evolvable artificial cells, and (with advances in inverse mapping) the decentralized growth of designed structures.

Although the three subtopics were discussed independently, similar obstacles and opportunities surfaced within each, revealing a coherent set of cross-cutting themes that define the field.

Cross-cutting challenges

Foremost is the challenge of having only a single example of life (known as the "n=1" problem). To date, life on Earth is the only known instance of emergent, evolving matter that led to a biosphere. Therefore, every effort to understand, generalize, or engineer life is shadowed by the difficulty of distinguishing what is universal about life from what is merely an accident of terrestrial history—a constraint that consistently biases research toward recapitulating "life as we know it." A related mapping problem runs throughout the discussion: researchers can readily move from information to function but struggle to invert that relationship. Reinforcing these are the vastness of the chemical and evolutionary search spaces, the difficulty of harnessing energy flow far from equilibrium, and the unresolved question of how to apply AI to problems for which large datasets do not yet exist—compounded by the field's multidisciplinary character and long timescales, which sit poorly with short funding cycles and conventional training.

Cross-cutting opportunities

One of the most pervasive opportunities is the deliberate exploration of "life as we don't know it," pursuing non-canonical components and reaction networks both to widen the possibility space and to clarify which features of life are truly universal. A second opportunity is bridging the bottom-up and top-down approaches by combining multiple functions—replication with translation, compartmentalization with protometabolism, information storage with energy harvesting—into integrated systems whose capabilities exceeds that of their parts. Underlying many of these efforts is a growing appreciation of non-equilibrium dynamics approaches, and artificial intelligence recurs throughout as an enabler for exploring vast spaces and inverting the function-to-information map.

Research trajectory

Across all three areas, the research trajectory moves from recapitulating terrestrial life toward building genuinely novel systems, from engineering toward harnessing evolution, and from treating energy, information, and AI as separate tools toward integrating them—supported by a parallel build-out of definitions, datasets, platforms, and trained researchers. The near-term emphasizes foundations: sharpening the questions that probe the boundary between living and non-living matter, characterizing the components and conditions from which life-like behavior can arise, and building enabling models, databases, metrics, and AI tools. The mid-term shifts toward integrating and coupling previously separate functions, supported by standardized platforms that allow results to be compared across laboratories. The far-term converges on a shared ambition: genuinely new forms of adaptive matter—a life-like chemical system not derived from terrestrial life, de novo evolutionary systems on alternative informational architectures, and evolvable artificial cells and self-replicating robots capable of adapting to, and even constructing, their own environments. Realizing this vision will require sustained, interdisciplinary collaboration and long-horizon support, but success would deepen our understanding of life as a general phenomenon and lay the foundation for transformative technologies built on adaptive, evolvable, life-like matter.

Since no single laboratory, discipline, or short-cycle program can assemble the geochemical models, standardized platforms, curated datasets, and cross-trained researchers on which the science depends (and no commercial timelines reward the effort), it will require public-private partnerships to ensure the future of this science. As advances in the field continue worldwide, SELAS will ultimately be developed. While the United States retains the disciplinary breadth to lead this effort, leadership will depend on deliberate, long-horizon support for the connective infrastructure between fields as much as for the research within them.

Introduction

Living systems have, when compared to non-living systems, quite extraordinary properties—so extraordinary that some researchers have wondered whether they even follow the same laws of physics. Living systems are intricately adapted to their specific environment (their ``niche"), which implies that they are nearly optimal in function, given that environment. At the same time, they are extraordinarily robust to a vast array of perturbations. Today we know what mechanism enabled the emergence of these extraordinary structures: the process of biological evolution. While evolution has given rise to an enormous variety of types inhabiting essentially every possible habitat on Earth, those types still only occupy a negligible fraction of the available "design space". We can imagine a myriad of living systems that evolution never produced, for example because past and/or current constraints (imposed by the physical environment and other species inhabiting the niche) make such a type inferior, or because an environment where such an organism would thrive has never existed in Earth's history. The Earth of today is a very different place from the early Earth environments where life first emerged; however, life may be capable of additional functions beyond those which evolution had a chance to fill, and which may be relevant to the demands of our industrialized world. Unfortunately, while we understand how natural evolution works, it is unlikely that we will be able to use this process as it functions on Earth today, to evolve the full range of life-like systems whose functions are suited to our needs (energy sufficiency, health, new materials, agriculture, etc.). There are two main impediments. First, all forms of life on Earth have a common ancestor, and as a consequence using any terrestrial organism as a starting point for evolutionary adaptation already severely limits the "design space" to what is essentially already available. Synthetic biology does not escape this limitation: editing a genome, rewiring a metabolic pathway, or minimizing a cell all begin from an organism evolution has already built, and so inherit its common origin. Second, the time it takes to evolve highly functional and robust systems from any starting point is, under standard conditions, too long. Evolution had billions of years and extraordinarily large population sizes to achieve the end products we admire today. We do not have this kind of time.

Constructing a new starting point with radically different chemistry would be a game changer for creating a new form of life that is better suited to novel functions that can support some of today's needs. Such a new starting point—an "artificial living system" or artificial "life-like" system[1]—would affect research in multiple ways:

- A single successful artificial life (or life-like) form will have taught us enough about the design of these systems that we may be able to design variants suited to our needs: drug delivery devices, systems creating novel therapeutics, swarms of robots that can colonize and terraform entire planets, systems that grow structures according to designs we specify.

- Having constructed a living system without ancestral relation to terrestrial life implies that we have understood what are the fundamental principles that make life possible. Such research would help us to understand the origin of life on Earth and its potential elsewhere in the universe. Understanding how life can emerge from planetary settings naturally reveals how order spontaneously arises from non-living disordered systems, which could provide principles for designing autonomous, self-organizing life-like systems that do not require continuous human intervention.

- Determining how life began would address one of the most ancient and unresolved questions in science, that has been of interest to humans throughout history. It also furthers the implications of our current understanding of the natural world and our place in it.

- Having mastered the principles of life will allow us to search for extraterrestrial life using a set of "biosignatures" that are less dependent on the particulars of terrestrial biochemistry, vastly increasing the chances that we detect them if they are where we are looking.

- Because artificial living systems do not have to adhere to the same limitations that evolutionary genetics presents, we may be able to significantly speed up the process of evolution using nonstandard genetics so as to use it for design purposes.

Mastering the synthesis of life, or life-like systems, is bound to become a milestone in the history of our species on this planet. The potential payoffs are likely to be far greater than those that we can imagine today. However, we also should be vigilant about the potential difficulty of predicting and controlling life-like systems, and the potential dangers they pose. Thus, each step on a path towards synthetic life needs to be conducted with the appropriate care and oversight. Since it is inevitable that humans will eventually seek to accomplish this technology development, it is important to establish an ethical framework for development of life-like systems, regardless of the specific progress made in the near-term.

The workshop was designed to examine future directions of Synthesis and Evolution of Life-Like Artificial Systems (SELAS) along three subtopics: the Emergence (of life-like systems), the Evolution of such systems, and the Future that such systems would enable.

1 The distinction between artificial living systems and "life-like" systems is that "living" is generally reserved for systems exhibiting the full complement of properties associated with life (self-maintenance far from equilibrium, self-replication, and capable of biological evolution) while "life-like" describes systems that display some of these properties without the complete set.

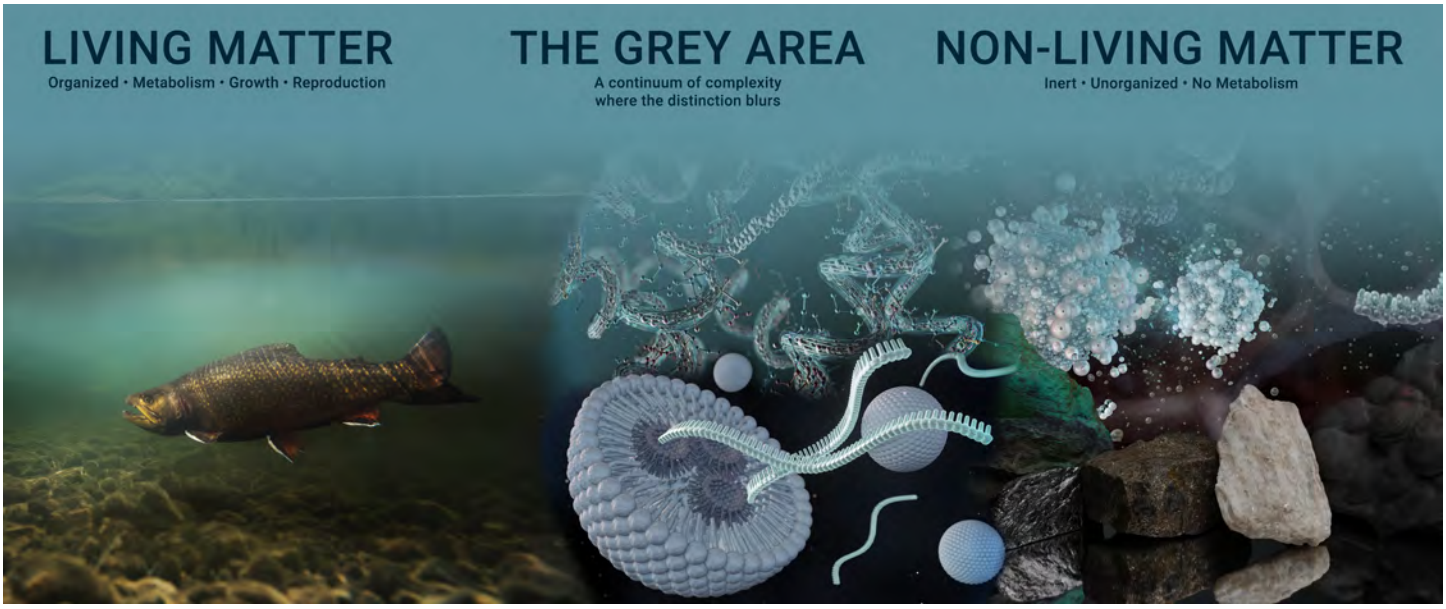


Figure 1: *The boundary between non-living and living matter is a continuum of increasingly life-like systems rather than a sharp division, and that grey area is the domain of SELAS research.*

Emergence

To address SELAS questions about the distinctions between living, biological systems and complex, non-living systems requires a deeper understanding of both. In particular, understanding this grey area between living and merely life-like (as represented in Figure 1) will help us understand how the gap was bridged in the emergence of life on Earth, and to what extent it can be bridged in the future through synthetic biology efforts. Emergence research approaches this grey area from two directions. Origin of life research seeks to uncover the mechanisms that kickstarted the biosphere on our planet, an endeavor which requires scientists to view our prebiotic Earth as a dynamic geochemical system that naturally drove the emergence of a biosphere (examples of some early Earth environments represented in Figure 2). Origin of life research therefore involves designing abiotic chemical systems that can successfully reproduce various life-like properties, ideally in the context of life as we know it and early Earth environments. In parallel, synthetic life research seeks to generate entirely artificial, life-like (or living) systems whose foundational properties can be understood and controlled, unconstrained by historical or environmental prebiotic contexts. The objective here is to create chemical systems that can escalate in complexity toward increasingly life-like behaviors.



Figure 2: *Early Earth contained various environments which have been studied for their potential ability to drive the emergence of prebiotic or life-like chemistry. Some similar conditions to the early Earth might exist on other worlds such as early Mars, ocean worlds, and/or exoplanets.*

While origin of life and synthetic biology research both seek to create a fully functional, biological system from abiotic ingredients, these fields share an underlying challenge with astrobiology (the study of the origin, evolution, distribution and future of life in the universe): establishing criteria to define when a complex organic system has crossed the threshold into an actual living system. SELAS research intersects heavily with astrobiology and planetary science. Astrobiology is invested in these topics because the search for life elsewhere requires concrete, operational definitions of life suitable for defining instrument or mission requirements, rather than purely philosophical abstractions. For this reason,

the astrobiology community has dedicated immense effort to developing formal, structured frameworks to precisely identify what constitutes a biosignature, as is reflected in various guiding documents (e.g., Green et al. 2021; Meadows et al. 2022; National Academies of Sciences, Engineering, and Medicine, 2019, 2023; Neveu et al. 2018). In this planetary exploration context, life is recognized through the cumulative presence of specific, intersecting properties—e.g. informational polymers, metabolism, compartmentalization—and consequently, a life detection claim would require multiple independent corroborating lines of evidence.

This astrobiological framing also connects to extraterrestrial targets that may be devoid of biology, but yet still able to host complex organic chemistry. Organics have been detected in various planetary environments, including Mars, asteroid Bennu, and Saturn's moon Enceladus; and these as well as other bodies remain relevant to the SELAS framework. Even environments that may turn out to not harbor life or life-like systems, can provide invaluable "negative controls" that reveal how organic chemistry can proceed in natural environments completely uninfluenced by biological reactions / consumption / recycling—baselines that are impossible to obtain on modern Earth where the biosphere has so strongly modified abiotic organic chemistry. Though we are fundamentally constrained by the fact that we only have one example of naturally occurring emergent life, Earth (i.e., the "n = 1" problem), these extraterrestrial examples offer a valuable point of comparison for origin of life research, validating or challenging assumptions about how prebiotic or abiotic organic systems behave in planetary settings. Ultimately, SELAS research will require insights gleaned from laboratory synthesis, astrobiology, and traditional origin of life research.

Evolution

One of the defining characteristics of living systems is their ability to evolve. Evolution enables populations to adapt to changing environments, generate novel functions, and produce increasing levels of complexity over time. While significant progress has been made in constructing synthetic compartments, reconstituting biological processes, and engineering increasingly sophisticated systems consisting of biological and nonbiological parts, the realization of artificial life-like systems capable of sustained evolution remains a major scientific challenge. Achieving this capability is critical not only for understanding the fundamental principles underlying living matter, but also for developing a new generation of technologies that can adapt and autonomously respond to unforeseen conditions and opportunities.

The vast majority of current research in synthetic biology and artificial life has at its foundation the specific solutions discovered by terrestrial biology. DNA, RNA, proteins, and lipid membranes provide powerful examples of information storage, inheritance, catalysis, and compartmentalization, but it remains unclear whether these represent unique solutions or simply one possible realization among many possible evolutionary architectures. A central question for the field is therefore whether the core principles of evolution such as information storage, variation, inheritance, selection, and adaptation can be implemented in alternative chemical systems that differ substantially from those used by living organisms. Addressing this question requires moving beyond the reconstitution of known biology and toward identifying general principles that enable evolution in complex chemical matter.

There is a need to establish new forms of genotype-phenotype coupling in synthetic systems. In biological organisms, genetic information is linked to functional traits through highly evolved molecular machinery. For artificial systems, however, unique mechanisms by which information can be encoded, expressed, transmitted, and selected remains less understood and explored. Progress will require understanding how information can be stored not only in canonical biopolymers, but also in alternative polymers, dynamic chemical networks, self-assembled structures, and compositional states. The development of such systems would expand the range of possible evolutionary substrates and provide new opportunities to explore adaptive behavior beyond the constraints of contemporary biology.

The evolution of life-like artificial systems also requires a deeper understanding of how energy, information, and function become coupled in non-equilibrium chemical environments. Living systems continuously consume and transform energy to maintain organization, generate variation, and support adaptation. Similar principles are likely to govern synthetic evolutionary systems, yet the relevant energy currencies, selection pressures, and adaptive environments are understudied. Determining how chemical systems can harness energy to sustain information processing and functional adaptation represents a critical step toward the realization of evolvable artificial matter.

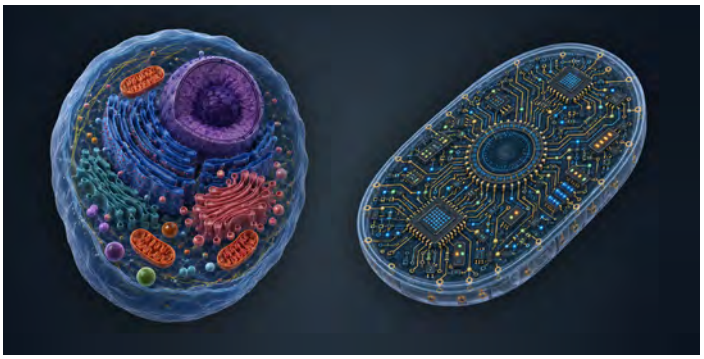


Figure 3: *Biological cells and synthetic cell-like systems compared. Biology provides the functional blueprint rather than the parts list: artificial systems can implement the essential capabilities of a living cell through alternative chemistry.*

Ultimately, the goal of this research area is not to reproduce existing biological systems, but to uncover the general principles that govern adaptive evolution across diverse forms of matter. By developing new informational architectures, alternative evolutionary substrates, and experimental synthetic systems capable of adaptation and innovation, researchers may establish entirely new classes of life-like structures. These structures can be unique from existing biological forms and take inspiration

from them (as shown in Figure 3). Such advances would deepen our understanding of evolution and provide a foundation for transformative technologies based on adaptive, resilient, and evolvable synthetic matter.

Futures

Because the synthesis of artificial life-like systems is likely to be extraordinarily difficult (barring unexpected discoveries), it is important to clearly articulate the future technological need for such systems. What distinguishes living systems from engineered systems is primarily their robustness and resilience while being nearly perfectly adapted to the particular niche they inhabit: in other words, the result of eons of evolution under challenging circumstances. Thus, artificial life-like systems primarily will play an important role in applications where evolution has not already provided a solution, or where current human-engineered solutions are too fragile. Systems that can autonomously acquire information and use that information to improve their function will also play a role in the future. Such systems are likely to be built at different scales: from the microscopic scale of single cells to the macroscopic scale of autonomous robots or even groups of robots.

Whether or not artificial life-like systems have been created in the past depends on definitions of what constitutes life: a discussion that is ongoing (Benner, 2010 and Bender et al., 2026). However, it is clear that artificial life in the form of self-replicating computer programs that live and evolve in special-purpose computers (Adami, 1998) has had tremendous success as a platform for evolution experiments, and this has led to the discovery of novel effects that were later found in biochemical life as well. While limited in scope, such efforts can serve as proof that it is possible to create systems that exhibit some hallmarks of life.

Creating artificial life-like systems that can survive outside the special environment afforded by a computer is likely to have a tremendous impact and a variety of applications, but also carries with it risks that need careful assessment. By construction, life-like systems could have the capacity to exponentially amplify their numbers, leading to potentially explosive growth. While this growth will always be resource-limited, the synthesis of life-like systems will always necessitate multiple safety protocols.

The idea of artificial life rests on the assumption that the principles that make life possible do not depend on the substrate used to implement those principles. This is particularly clear in digital life, which is based on self-replicating information where the information is not encoded in non-branching heteropolymers, but rather in sequences of ones and zeros, appropriate for the computer environment. What physical systems lend themselves to the synthesis of life outside of a computer is one of the primary unanswered questions and knowledge gaps. Efforts to engineer life-like systems using the molecules of terrestrial biochemical life are under way, but such molecules may not be the medium of choice for macroscopic artificial life, or artificial life destined for environments drastically different from terrestrial ones (for example, for terraforming purposes).

The research trajectory for these systems therefore proceeds along two complementary tracks: biochemical artificial life (built from cellular or alternative molecular components) and robotic artificial life (built from autonomous machines); each advancing from engineered systems toward genuinely evolvable ones.

To explore these questions and the promise and challenges of synthesizing and evolving life-like artificial systems, a future directions workshop was held on April 29-30, 2026, in Arlington, VA. This workshop gathered 21 distinguished researchers from academia, industry and government with expertise in chemistry, biology, physics, planetary science, computer science, and ethics, for unfettered discussion and debate on the current research challenges, opportunities, and trajectory for research over the next 10 to 20 years. The two-day workshop was organized to encourage lively discussion and debate and to maximize the interaction of participants. The first day began with short, introductory presentation from the co-chairs to frame the workshop goals. The remainder of the day was spent in small group discussions on the fundamental challenges to progress and technical capabilities and research opportunities. These breakout sessions covered specific subtopics: emergence, evolution, and futures of life-like systems. Each session was led by two experts in the field and was followed by an outbriefing to the whole group. The second day of the workshop began by reviewing the discussions of Day 1 followed by whole group discussion of any topics not covered in the first day, cross-cutting themes, and high-risk and high-impact ideas.

With this framework in mind, the following sections describe the research challenges and opportunities outlined at the workshop and map a research trajectory for SELAS research over the next twenty years.

Research Challenges

The first day of the workshop organized participants into three working groups for in-depth discussion of the challenges and opportunities for three subtopics: the Emergence of life-like systems, their Evolution, and the Futures they would enable. This section presents the research challenges for each subtopic, as well as the common fundamental obstacles that surfaced independently in each working group. These shared obstacles reflect deeper structural features of SELAS research and are likely to constrain progress across the field until addressed. The most significant are summarized here followed by the challenges specific to each subtopic.

Common fundamental obstacles

Because life on Earth is the only known instance of emergent and evolving matter (the "n = 1" problem), every effort to understand emergence, to generalize the principles of evolution, or to engineer life-like systems is hindered by the challenge of distinguishing what is universal about life from what is merely an accident of terrestrial history. The n=1 problem also appears as the difficulty of recognizing a biosignature without an abiotic baseline; as the question of whether DNA, RNA, and proteins are necessary or just one solution among many; and as the absence of a proven blueprint from which to engineer synthetic life. In each case these difficulties bias research toward recapitulating "life as we know it," narrowing the possibility space precisely when it most needs widening.

Another important obstacle is the challenge of information flow: researchers can move readily from information to function but struggle to invert that relationship. It appears as a gulf between the unknown pathways of inheritance from non-living to living matter, as the missing genotype-phenotype coupling in synthetic systems, and as the "inverse mapping" obstacle to design.

Reinforcing these conceptual barriers are the more technical obstacles of efficiently exploiting the vastness of the chemical and evolutionary search spaces, the difficulty of harnessing and measuring energy flow far from equilibrium, and the unsettled question of how to apply artificial intelligence to problems for which large, high-quality datasets do not yet exist.

Finally, the field faces structural challenges that transcend any subtopic: including its inherently multidisciplinary character, and the long-time horizons of chemical and evolutionary processes which sit poorly with short funding cycles and conventional training pathways, all of which must be confronted for the field to cohere and advance.

Emergence

A foundational challenge for Emergence (and SELAS in general) is that **there is no consensus on the definition of "life"**. Disagreement on how to define life is a longstanding challenge in SELAS research, which encompasses research from origin of life, astrobiology, and synthetic biology—all separate fields which have attempted to create rigorous definitions of life for different purposes. The issue of how to define life is one that is unlikely to find resolution in the near-term. Rather than attempting to unambiguously define life, using the points of disagreement to identify "edge cases" for further study across SELAS research areas is likely to be more fruitful. Additionally, focus on "life-like properties" and the continuum of escalating complexity from abiotic chemistry to biology is a productive path forward. Nonetheless, the absence of a clear definition presents practical challenges, for example in designing missions to identify life elsewhere in the universe and for effectively communicating SELAS goals and advances across disciplinary boundaries, where edge cases and even the primary identifying features of life-like systems may be viewed differently.

Just as modern biology is tightly coupled to its environment, the origin of life cannot be decoupled from the geological or laboratory conditions in which it occurred. Life and life-like chemistries are fundamentally driven, shaped, and constrained by their environments, whether that be the natural geochemical/geophysical environments of planetary surfaces or the chosen conditions of laboratory environments. Environmental parameters dictate the availability of energy sources, reactants, interferents, selective pressures, etc. The inseparability of emergence from environmental context presents challenges for both mission science and laboratory experiments.

For extraterrestrial mission science, strategies must incorporate an understanding of environmental context before interpreting any organic signal [this concept is also prominent in NASA relevant biosignature strategies (Meadows et al. 2022)]. However, when comparing to laboratory science (synthetic biology / origin of life experiments), this is a piece that could be missing if we are mistakenly analyzing organic products without appropriately considering their connection to the environment. Criteria are needed that will allow discrimination between environmentally driven abiotic organic complexity, vs. a true biosignature, or a post-biotic remnant, or a pre-biotic system. On Earth, organic matter (like soil) even when it is not alive, mostly consists of remnants from our pervasive biosphere, and while true abiotic chemistry is also present it is more limited. Additionally, as missions uncover increasingly complex organic chemical states on other worlds (e.g. Bennu, Enceladus, Ceres, Mars) we will need better criteria to distinguish purely abiotic macromolecules from true biomarkers, especially since we lack an appropriate abiotic baseline from Earth context.

For laboratory experiments, the challenges of mimicking such contexts, compounded by the wide range of potential planetary environments even for a single time and place such as the ancient Earth, and by the uncertainty in relevant details of past geochemical conditions, present obstacles to routine consideration of planetary context in laboratory experiments. The propensity of laboratory experiments to choose conditions meant to favor emergence of life-like properties, regardless of their faithfulness to the origins of life on Earth or other planetary

contexts, may skew our expectations for biosignatures on other worlds, making it more difficult to distinguish biotic from abiotic signatures. It is equally interesting to ask "what could happen" as to ask "what did happen" when considering the transition from abiotic to increasingly life-like, biotic matter. This could include conditions not anticipated to occur naturally anywhere in the universe, as well as those inspired by other worlds. At the same time, redoubling efforts to better capture the geochemical and geophysical aspects of the environment that enabled the one known instance of life's emergence that we know of is worthwhile.

The mechanisms / pathways of inheritance from non-living to living systems are unknown. The divide between top-down (working backward from extant life) and bottom-up (building forward from abiotic chemistry) research approaches is not just limited to logistical or communication issues but also the difficulty of knowing the degree of inheritance of properties from the prebiotic world to life. While some primitive processes may go directly from the prebiotic world to the Last Universal Common Ancestor (LUCA) and thus modern life (direct inheritance), there are also shared features that may simply represent accessible / convergent chemical solutions rather than direct lineages (functional convergence). Also, some ancestral chemical networks may have been analogous to biological systems but used different molecules from what biology uses and thus left no direct trace in modern biology. Processes like this present a challenge for bridging the top-down/bottom-up gap (Figure 4).

"Life as we know it" tends to limit our imagination. SELAS research is often focused on attempts to recapitulate modern Earth life, reconstituting biochemistry by combining molecules from extant biology or encapsulating minimal versions of modern biological machinery, rather than constructing new and alternative pathways that never existed in Earth's prebiotic state or biosphere. Research on 'life as we don't know it' is also necessary to understand the probability of life elsewhere and the diversity of chemical systems that could exhibit life-like behavior.

Life-like properties in virtual systems may be especially difficult to identify with confidence. Research on emergence of virtual life (i.e., inside of computers) differs greatly from studies of life's emergence in the physical world. At present, there is little communication between SELAS researchers focused on emergence of virtual vs physical life-like systems. Particular emphasis should be placed on the thermodynamic properties of virtual systems, because in virtual systems the largest possible entropy can always be calculated (given the components of the systems and the constraints acting on them). Sustained maintenance of observed entropy levels below that maximum indicate stored information that is maintained, since the conservation of entropy (total entropy equals observed conditional entropy plus information) is a universal law.

Structural challenges to SELAS research are associated with its multidisciplinary nature and the dearth of examples of life's emergence (n=1). Because understanding the emergence of

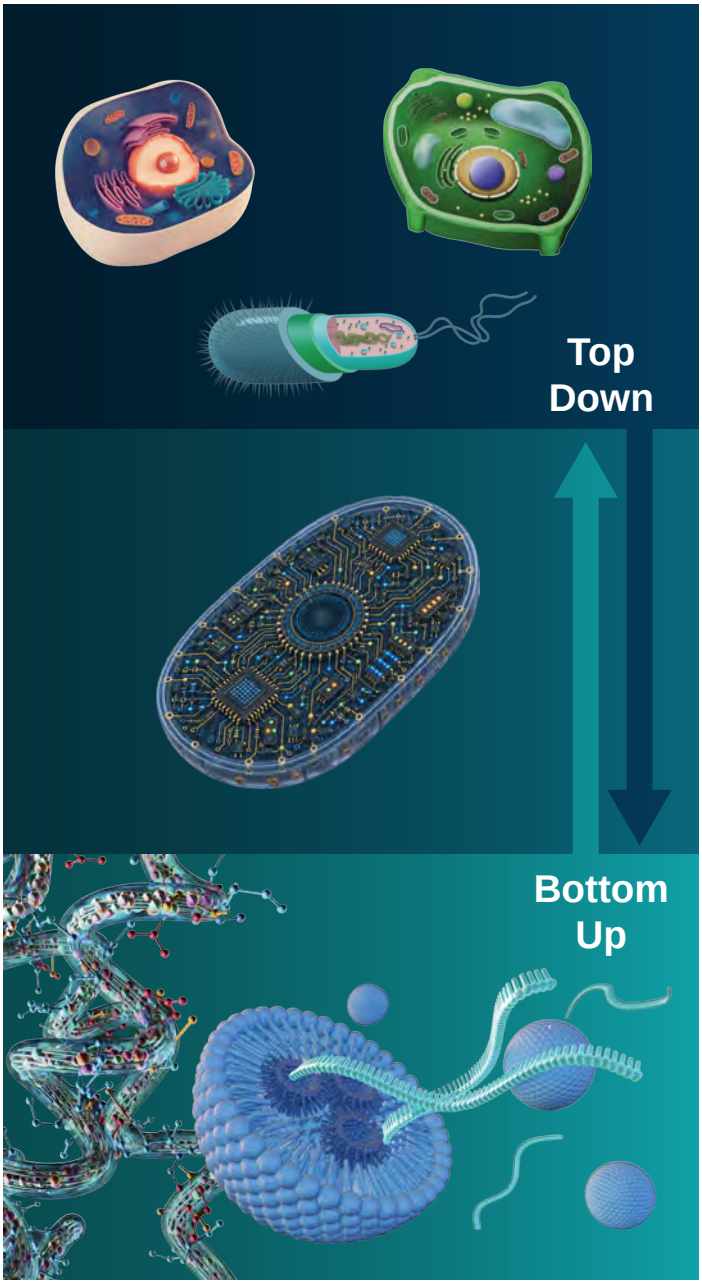


Figure 4: *Emergence is studied top-down, by reasoning backward from LUCA and modern life, and bottom-up, by building forward from prebiotic chemistry. Bridging the two approaches is important to move toward the synthesis of artificial life-like systems.*

life-like systems requires synchronized progress across disparate fields including geology, chemistry, biochemistry/biology, and planetary science, SELAS advancement can be structurally bottlenecked by whichever area is the slowest moving. Knowledge gaps that produce such bottlenecks can be due to real difficulties in determining the desired information or to inadequate cross-field communication. A related challenge is the lack of high specificity datasets on SELAS that could be used to train AI/ML. While AI/ML holds immense promise for predicting complex systems and even non canonical biology beyond Earth, more work is needed to figure out the details of how AI will be used in origin of life and SELAS work.

Evolution

Despite substantial advances in synthetic biology, molecular evolution, and artificial life research, the creation of life-like artificial systems capable of sustained adaptation and evolution remains an unfulfilled goal. While many of the individual components associated with living systems can now be engineered or reconstituted, the principles that enable open-ended evolutionary innovation are poorly understood. The Evolution working group identified several major scientific and technological barriers that must be overcome to enable future generations of adaptive synthetic systems.

A primary challenge is the development of alternative systems for information storage, inheritance, and genotype-phenotype coupling. Modern biology provides a highly successful framework based on DNA, RNA, proteins, and cellular organization, but it remains unclear whether these represent absolute requirements for evolution or only one realization among many possible solutions. Current research is heavily influenced by existing biological systems, making it difficult to explore fundamentally different evolutionary architectures. Developing synthetic systems that can store information, generate heritable variation, and couple that information to functional outcomes remains one of the most important unresolved challenges in the field.

A second challenge is understanding how evolutionary systems generate novelty. Existing approaches to molecular engineering and directed evolution are highly effective at optimizing known functions but are less capable of discovering entirely new functions or forms of behavior. Biological evolution has repeatedly produced innovations that could not have been predicted from the starting conditions alone, suggesting that important mechanistic principles governing the emergence of novel functions remain undiscovered. Determining how evolutionary systems explore vast functional landscapes, identify rare solutions, and generate increasing levels of complexity will be essential for the design of future life-like artificial systems.

Another major challenge involves the relationship between energy, information, and adaptation. Living systems continuously operate far from thermodynamic equilibrium through the consumption and transformation of energy. However, the general principles linking energy flow to information processing, adaptation, and evolutionary success remain poorly understood. Future synthetic systems may require alternative energy currencies, non-equilibrium reaction networks, or novel mechanisms of environmental interaction that differ substantially from those used by contemporary organisms. Identifying these principles and determining how they can support adaptive evolution represent critical research needs.

The field also faces significant challenges associated with prediction and control. Evolution is inherently difficult to forecast, even in well-characterized biological systems. As researchers begin to explore non-canonical chemical systems and alternative forms of inheritance, the ability to anticipate evolutionary trajectories may become even more limited. A key challenge will be developing predictive frameworks that allow researchers to understand, guide, and constrain evolutionary processes without eliminating the capacity for innovation. Closely related is the need to design systems that remain functional and robust while still retaining the ability to adapt to changing conditions.

A further challenge is the enormous scale of the chemical and evolutionary search spaces that must be explored. Evolutionary innovation often depends on rare events and complex interactions that are difficult to identify using traditional experimental approaches. We lack adequate tools to accelerate exploration of these spaces, including high-throughput experimentation, automation, advanced simulation methods, and artificial intelligence approaches capable of identifying promising regions of chemical and functional diversity. At present, the lack of large datasets describing non-canonical biochemical systems further limits the application of machine learning and other predictive methods.

Finally, significant organizational and infrastructure challenges must be addressed. Research on synthetic evolution requires close integration of chemistry, biology, physics, computer science, engineering, and information theory, yet existing academic and funding structures often discourage the sustained interdisciplinary collaboration required to address such problems. The long timescales associated with evolutionary processes create additional challenges, as transformative advances may require decades of coordinated effort. Long-term funding mechanisms, shared experimental infrastructure, standardized platforms, and community resources for data sharing and replication will therefore be essential to support progress.

Collectively, these challenges highlight that the evolution of life-like artificial systems is not simply an engineering problem, but a fundamental scientific effort to uncover the general principles that govern adaptation, innovation, and the emergence of complexity in chemical matter. Addressing these barriers will be essential for realizing synthetic systems capable of sustained evolution and for expanding our understanding of the possible forms that life-like systems may take.

Futures

While we have access to the approach that created living systems in the first place (evolution) both in biochemistry and inside of a computer, we have as yet not been able to usefully harness this process for engineering artificial life-like systems because of the spatial and temporal scales involved. As a consequence, we are forced to engineer such systems using the insights that we have gained by studying them over decades. It is not that we are wholly ignorant about what it takes to create such systems: John von Neumann (1951) imagined a robot that can use a set of instructions (a "genome") to assemble a copy of itself and of the genome (an interpretation of this idea is shown in Figure 5), given an environment where the parts necessary for assembly are available in a local environment (a "compartment").

The engineering expertise to carry out this vision does not yet exist, but steps toward it are possible.

The technical challenges depend on the scale of the desired system: microscopic vs. macroscopic. Von Neumann's vision was a macroscopic artificial living system, and achieving it requires progress on two fronts: first, encoding the information that is sufficient to assemble the system in such a manner that it can be faithfully interpreted by a robot, and second creating a robot that can carry out those instructions. These two challenges are intimately linked and it is unlikely that they can be solved independently from each other. No research team is known to be tackling this problem at present. While progress on humanoid (and non-humanoid) robots has been swift in the last decade, they have yet to achieve autonomy. With the advent of AI, this is foreseeable within the next five years, however. Once this is achieved, it is in principle possible to provide such a robot with instructions to construct a replica robot, but significant challenges are expected if the parts are not already pre-assembled.

On the microscopic front the challenge is conceptually the same, except that assembly might proceed without guidance (self-assembly). Furthermore, while macroscopic systems can often be engineered in such a way that the parts are optimized independently, this is rarely the case in molecular systems, where the function of one component usually depends crucially on the function of many others. The central challenge of creating artificial living systems in the real world is therefore that the required degree of optimization has up to now only been achieved by evolution, and that progress on this front depends on how well we can develop new methods that efficiently search vast design spaces.

From a fundamental point of view, the foremost obstacle to engineer artificial life-like systems is the "inverse mapping" problem: the path from information to function (forward mapping) is understood; the artificial life approach requires the inverse map, from function to the information that encodes it. There is some optimism among researchers that the current crop of AI methods can help in shaping this inverse map, but it would only explore the space of existing forms, not the exploration of novel forms of artificial life.

For both chemical and robotic artificial life, the design of an integrated system where the parts are adapted to each other may be elusive because the search space is extraordinarily large. In the absence of a "key discovery", the prototype systems may have to be discovered via intelligent search of design space. Sophisticated AI systems may one day be able to infer the "rules of harmonious assembly" from existing forms of life, and adapt them to new chemistries/materials.



Figure 5: *An interpretation of von Neumann's self-replicating machine. The concept shows that self-replication need not be biochemical.*

Research Opportunities

Several cross-cutting opportunities appeared from across the three subtopics, which exemplifies a convergence on prospects for the future. The most pervasive is the deliberate exploration of "life as we don't know it"—pursuing non-canonical information systems, reaction networks that omit standard nucleic acids, and substrates chosen for a particular application rather than inherited from Earth's biosphere, both to widen the possibility space and to sharpen our sense of which features of life are truly universal. A second is bridging the gulfs the challenges exposed: between bottom-up and top-down accounts of emergence, between encoded information and function, and between reconstitution and genuine de novo design. Progress here depends less on mastering any single component than on combining multiple functions—replication with translation, compartmentalization with protometabolism, information storage with energy harvesting—into integrated systems whose behavior exceeds that of their parts. Underlying many of these efforts is a growing appreciation of non-equilibrium and dissipative dynamics approaches, since living systems persist only by continuously consuming energy. Artificial intelligence recurs throughout as a cross-cutting enabler—to explore vast chemical and parameter spaces, reveal hidden connections, and help invert the function-to-information map—though the field must still learn how to frame SELAS problems so that current methods can act on them. Realizing these opportunities will require not only new tools, but a sustained, interdisciplinary community equipped to pursue them.

Emergence

Bridging the gaps between bottom-up and top-down approaches presents a major opportunity for the SELAS field. A central opportunity lies in connecting abiotic chemical networks with early biological systems. Of particular interest are the steps toward achieving the ribosome or alternative systems able to translate information encoded in one type of molecule into another to perform functions (metabolic, structural). Novel insight may come from computer science, where a variety of different compiler architectures translate information (human-written code) to function (the execution of a set of fixed subroutines). The central intuition here is that all information-translating systems are in essence compilers.

A promising direction is examining how systems that support life-like systems (e.g., information maintenance, metabolism, compartmentalization) can change over time, while maintaining a continuity of the life-like system or processes. This could include how proto-metabolic cycles are replaced with reaction cycles that increasingly resemble those of extant biology; how prebiotic molecules that differ from those of extant biology could have preceded them and maintained functions throughout their chemical transformation to their current forms; and how prebiotic compartments could have been replaced by increasingly biotic versions as availability of molecular components and functional requirements changed. Investigating how coupling can be maintained between multiple systems (e.g., information, metabolism, reproduction) throughout these types of conversions could be especially edifying. There are opportunities to consider which molecules and processes could have transitioned prebiotic to biological systems via direct inheritance and which may have instead followed a pathway of functional convergence.

Cultivating a cohort of researchers at the interface of prebiotic chemistry and ancient biochemistry would open the space between the two, where non-living (but life-like) systems transition into actual living systems.

Embedding life-like systems in geochemical contexts can help constrain parameter space while providing driving forces for SELAS. The origin of life occurred in a planetary context, and throughout Earth history biological systems have been strongly shaped by their environment. If life is found elsewhere in the universe it will also be shaped by local planetary conditions. Therefore, rather than viewing planetary geological settings as passive backdrops or isolated experimental parameters, understanding how abiotic and early biotic systems functioned embedded in their planetary context is needed. There is an opportunity to advance "systems geochemistry" research to evaluate how diverse nonequilibrium environments can generate the thermodynamic disequilibria to drive reactions that could lead toward the emergence of life. While this workshop explicitly discussed water-rock serpentinizing systems or hydrothermal vents, there are many kinds of geological environments that can generate disequilibria. In environmental settings, long term, persistent spatial gradients can be continually layered with other environmental non-equilibrium processes, including: dynamic environmental cycling like freeze-thaw or wet-dry cycles, plumes, aerosols, heating/cooling cycles. Leveraging such natural settings would allow researchers to observe and model how processes such as organic accumulation, selection, and reactions can occur in non-equilibrium conditions.

Molecular self-assembly and compartment formation in complex systems of chemical reactions

Binding interactions between molecules of the same or different types (e.g., nucleic acids and peptides) can select them for survival or removal from a complex chemical mixture. The emergence of compartments, such as lipid vesicles or coacervate droplets, can similarly provide advantages or disadvantages for persistence, accumulation and further activity, of not only the compartment-forming molecules but also those that become encapsulated, and those that are excluded. Pre-genetic life-like systems can be investigated to elucidate how primitive self-replicating structures that existed before genetics could offer a pathway to understanding how physical / chemical laws alone might have kickstarted biological (life-like) organization. Understanding how such processes select molecular "winners" under different conditions could shed light not only on how the molecules of extant biology came to be, but also into the potential for other molecules to have become dominant, if conditions were different (as in another world, or in an artificial laboratory experiment).

Opportunities for synergies to arise as multiple processes/ functions are combined

Research into the emergence of life-like properties should seek synergies built upon combining multiple functional systems, for example replication and translation, or compartmentalization and protometabolism. Recent years have seen many advances in the study of individual systems (e.g., ribozymes, compartments, metabolism), and in beginning to combine pairwise, relatively low complexity systems. Going forward, increasingly complex, "messy" versions of such efforts hold promise in understanding how life-like properties could emerge. Protocell research is poised to go beyond encapsulation of biological / prebiotic molecules to understanding the nonequilibrium dynamics that prevent an assembled system from decaying toward an equilibrium/inactive state.

Alternatives to the molecules, processes, and constraints of extant biology

Research on "life as we don't know it" can expand our understanding of SELAS. Could life, or a subset of life-like properties, be envisioned with different molecules than the ones we are familiar with? Alternatives to RNA offer one avenue: non-canonical reaction systems that can execute genetic and metabolic functions without relying on standard nucleic acids. Research could also explore SELAS that would intentionally omit some aspects of living organisms, for example eliminating reproductive capability to increase safety. Considering alternative building blocks and processes could enable SELAS design for capabilities not possible for any living organism.

Opportunities for leveraging AI

Research that takes advantage of new AI capabilities to analyze complex datasets and generate predictive understanding of how complex systems change over time could be transformational for SELAS. For example, it could aid understanding of nonequilibrium questions (e.g. the geological settings and the far from equilibrium organic structures like protocells). AI tools may enable identification of hidden connections such as chemical pathways shared across different systems. Meanwhile, AI / ML tools can be deployed to explore vast parameter spaces, like the many permutations of conditions in planetary settings, or the many states of multi component chemical reactions and compartmentalization.

Opportunities for emergence of life-like properties in virtual systems

Previous research on the emergence of life in virtual systems (Greenbaum & Pargellis 2017, Agüera y Arcas et al, 2024) suggests that the emergence of life is associated with a sudden and sustained drop in Shannon entropy. Because of the explicit equivalence of Shannon and statistical (Gibbs) entropy, such observations cement the idea that life-like properties can be inferred from keeping track of the thermodynamic properties of the system. While accounting for the relevant degrees of freedom (relevant for the calculation or measurement of entropies) is usually straightforward in virtual systems, this endeavor is usually far less obvious in real environments. Learning how to find the information-carrying degrees of freedom from experience in virtual systems thus provides opportunities to observe and monitor the emergence of life-like properties in real systems.

Instrumentation for field/mission studies

Achieving further breakthroughs will require an upgrade in robust, miniaturized field / mission-ready instrumentation capable of non-targeted analytical approaches. This is an identified goal for NASA already (as seen in foundational documents, e.g., the Origins, Worlds, and Life Planetary Science and Astrobiology Decadal Survey, and the 2019 Astrobiology Strategy (National Academies of Sciences, Engineering, and Medicine, 2019, 2023)) and therefore not discussed further here beyond affirming that instrumentation development to advance astrobiological discovery remains an essential part of SELAS research.

Evolution

The pursuit of life-like artificial systems capable of adaptation and evolution presents a unique opportunity to expand the boundaries of both biology and chemistry. While contemporary life provides a single example of an evolutionary system, it remains unknown whether the principles underlying adaptation, inheritance, and innovation are specific to terrestrial biology or represent more general properties of organized matter. Research in this area therefore offers the possibility not only of understanding life as it exists today, but also of discovering alternative evolutionary pathways and new forms of adaptive matter.

Development of non-canonical information systems

One of the most promising opportunities lies in the development of non-canonical information systems. Biological evolution is built upon DNA, RNA, and proteins, yet there is no fundamental reason to assume that these are the only molecular architectures capable of supporting inheritance and adaptation. Alternative polymers, dynamic molecular networks, self-assembled structures, and compositional states may provide new mechanisms for storing and transmitting information. Developing such systems could reveal whether the core requirements for evolution can be realized in entirely different chemical contexts and may uncover principles that are inaccessible through the study of contemporary organisms alone.

Creation of synthetic systems that directly link information, function, and selection

Establishing robust genotype-phenotype coupling remains a major challenge, but successful solutions would enable experimental exploration of evolutionary processes in systems that are not constrained by the historical contingencies of biology. Such platforms could provide unprecedented opportunities to investigate how adaptation emerges, how complexity evolves, and how novel functions arise. More broadly, they could serve as testbeds for exploring evolutionary principles that are difficult or impossible to study in naturally occurring organisms.

Protocellular systems

Research on adaptive compartments and protocellular systems represents another particularly promising direction. Compartments provide a means to localize information, concentrate resources, establish individuality, and create units upon which selection can act. Future studies may reveal new mechanisms by which chemical systems acquire heritable traits, interact with their environments, and undergo adaptive change. The development of compartment-based evolutionary systems could provide a bridge between molecular evolution and higher-order evolutionary processes, enabling the emergence of increasingly sophisticated forms of organization.

How energy flow can be coupled to adaptation and evolutionary innovation

Living systems continuously exploit non-equilibrium energy sources to maintain organization and support growth, repair, and reproduction. Future synthetic systems may utilize alternative energy currencies, reaction networks, or environmental feedback mechanisms that differ substantially from those found in biology. Investigating these possibilities may reveal general design principles governing adaptive systems and provide new routes toward self-sustaining, evolvable matter.

Artificial Intelligence

Advances in artificial intelligence, automation, and high-throughput experimentation create additional opportunities to accelerate discovery. Evolutionary processes explore vast chemical and functional landscapes that are often inaccessible using traditional experimental approaches. AI-guided design, autonomous experimentation, and integrated simulation-experiment workflows may enable researchers to identify rare functional solutions, explore non-canonical chemistries, and discover entirely new evolutionary architectures. At the same time, these technologies may help establish predictive frameworks that connect molecular composition, environmental conditions, and evolutionary outcomes.

Realizing these opportunities will require overcoming significant technical hurdles. Key challenges include developing experimentally tractable systems that exhibit inheritance and selection, identifying measurable indicators of adaptation and evolutionary success, coupling energy flow to information processing, and generating sufficiently large datasets to support predictive modeling. Progress will also depend on new tools for monitoring rare events, exploring large chemical spaces, and characterizing dynamic systems operating far from equilibrium. Addressing these hurdles will require close integration of chemistry, biology, physics, engineering, and computational science.

Taken together, these research opportunities position the field to move beyond the recreation of known biological systems and toward the discovery of general principles governing adaptive evolution. Success would provide a deeper understanding of life itself while enabling the development of entirely new classes of life-like systems capable of adaptation, innovation, and evolutionary change.

Futures

There are many important areas where SELAS research could benefit human civilization. In the future, designed synthetic life-like systems could advance energy sufficiency, human and ecosystem health, materials science, and more. In the following, the opportunities such systems present are discussed for medicine, operation in hazardous environments, space exploration, materials synthesis, and manufacturing.

Biomedicine/health care

Biological organisms are marvels of robust autonomous homeostasis and self-maintenance, but still are susceptible to disease for which evolution has not yet found a cure. Modern science has alleviated or even eliminated many of those, but some remain as humanity's specters. Making progress towards alleviating or even removing the remaining major threats (cancer, heart disease, infections) requires not only new drugs, but also new methods to deliver drugs to the intended targets.

Drug discovery

About two-thirds of all drugs have their origin in nature (Newman & Cragg, 2012), implying that their specificity is due to an evolutionary process. As the rate-limiting step in drug development is drug discovery, a new approach to drug discovery using artificial life-like systems would be transformative. Standard approaches such as combinatorial chemistry and directed evolution are too slow to search the vast chemical space. Organisms modified or synthesized to replicate and mutate quickly could be used to accelerate drug discovery by searching at rates unattainable by current methods, while multicellular engineered living systems could be used as "organs-on-chips" for the purpose of drug screening or as disease models (Kamm et al., 2018). Establishing selection pressures that favor therapeutically relevant products may prove as consequential as the platforms themselves.

Drug delivery

Many drugs can only be effective if they are protected while being delivered to their target. Within the last decade significant efforts have been expended to create artificial cells as drug delivery systems, but the attempts to use parts from different organisms in a new synthetic vehicle always seem to hit a wall when it is discovered that those parts do not work together well and need to be modified. Artificial life approaches could play a role in the design of drug delivery systems by harnessing the power of evolution to optimize the components of the system, for example by creating a "minimal cell" first. Optimizing component compatibility by selection rather than by design could succeed where the assembly of parts drawn from different organisms has stalled.

Regeneration/aging

Research using frogs and planarian flatworms suggests that cells can be reprogrammed to be more robust and to self-repair, up to the regeneration of whole organs or limbs. Identifying the signals and control architectures that govern regenerative capacity could reveal whether such capacity can be installed in systems that lack it, including synthetic ones, and could open routes to reprogramming cells to avoid senescence.

Search/Rescue/Repair

Robots are often used to investigate, search, and explore dangerous environments (such as post-disaster areas). However, such robots are often ineffective as they are unable to adapt to unforeseen circumstances and learn. Artificial life-like systems with the capacity to assess, plan, and execute as a function of an overarching goal could benefit such efforts and lead to improved outcomes. Here, an integration of advanced robotics with state-of-the-art Artificial Intelligence (AI) could lead to significant advances on a short (< 5 years) time frame.

Space Exploration

Various far-reaching topics related to space exploration were brought up by workshop participants in discussions. For example, artificial life-like systems might enhance planetary exploration beyond what robotic spacecraft are currently capable of, in particular, for deep space missions where light-time makes real time control impossible. In the context of potential future human exploration, it was discussed that such robots (or swarms of robots) could also be used to construct habitats prior to human colonization (e.g., via stigmergic building). Decentralized coordination among many agents, as in stigmergic construction, offers a route to assembling structures without central control. The potential for exponential growth of robotic artificial life-like systems would allow planet wide efforts (e.g. terraforming) to reach the necessary scale. That same potential makes containment a design requirement and understanding how growth-based systems can be bounded represents an opportunity in its own right.

Material synthesis

The search for new materials is constrained by the same factors that constrain the search for new drugs: the standard approach of "forward screening" does not scale with the search space, so that only small modifications of existing materials are found with these methods. Evolutionary algorithms have been used for "inverse design" but suffer from the usual limitations: excessive computational cost of iterative evaluation of candidate solutions, premature convergence to local maxima, and limited population sizes (Cheng et al., 2026). Artificial living systems could not only help in the discovery of new materials but also in their synthesis, for example by actively controlling the reaction environment during materials synthesis to embed complex functional gradients in composition and properties. Dissipative nonequilibrium materials in which fuel consumption is ongoing bring new properties and behaviors not observed in traditional, static materials. Such materials assemble in response to chemical or physical energy inputs and return to their pre-assembly state once this energy source is depleted. Understanding how the lifetime, responsiveness, and stability of such materials can be tuned could establish an entirely new class of functional matter.

Manufacturing

Today, designed objects are manufactured according to carefully crafted programs that are executed in a centralized manner. In contrast, biological systems grow in a decentralized manner, following a developmental process. A growth process has many advantages over a top-down controlled assembly process, foremost of them is its robustness. While small defects can quickly lead to non-functional devices in top-down assembly, a growth process handles defects easily, and can create highly-functional systems from imperfect components. While still far in the future, an inverse process that generates a genome that—if executed within the right environment—grows a product would revolutionize manufacturing. Such growth-based manufacturing could enable more resilient, responsive materials. Examples are materials able to self-repair and undergo structural optimization based on environmental challenges, or strengthening when exposed to mechanical stresses like living bone or muscle.

Research Trajectory

This section presents the research trajectory for the Emergence, Evolution, and Futures subtopics as well as the cross-cutting trajectory of the SELAS field.

Across all three topics the trajectory moves from recapitulating terrestrial life toward building genuinely novel systems; from engineering systems by hand toward harnessing evolution to produce them; and from treating energy, information, and artificial intelligence as separate tools toward integrating them into unified, adaptive systems. Underlying all of this is a parallel build-out of the definitions, datasets, platforms, and trained researchers without which none of the scientific goals can be reached. This trajectory is shared across near, mid, and far-term horizons.

In the *near-term*, the field's emphasis falls on foundations: sharpening questions, characterizing systems, and building the tools to study them. This means concentrating on the "edge cases" that probe the boundary between living and non-living matter, identifying the components and conditions—dissipative chemical networks, non-canonical information-bearing molecules, geochemically realistic environments—from which life-like behavior can arise, and developing the genotype-phenotype couplings and autonomous sensory-motor loops on which later work depends. Across all three areas, this period also calls for the enabling infrastructure that science cannot proceed without: clear geochemical and formal models, better databases of prebiotic and non-canonical chemistry, quantitative metrics of "what constitutes being alive" and adaptation, and the first deployment of AI to detect commonalities across vast chemical and functional spaces.

In the *mid-term*, these foundations support a shift from characterizing components toward integrating and coupling them. Emergence research aims to bridge the top-down and bottom-up divide, generating prebiotic systems recognizable to contemporary biology. Evolution research engineers experimentally accessible platforms in which inheritance, variation, and selection can be directly observed. Finally, Futures research couples artificial cells to energy metabolism and information replication, while autonomous robots gain the capacity to learn. The common thread is the deliberate combination of previously separate functions—information with metabolism, compartmentalization with replication, energy flow with adaptation—into integrated systems, supported by standardized platforms and metrics that allow results to be compared across laboratories, and by AI that increasingly guides experimental design rather than merely analyzing its results.

In the *far-term*, the trajectories converge on a shared ambition: systems that are not simplified imitations of existing biology but genuinely new forms of adaptive matter, and that improve themselves through evolution rather than design. This is expressed as the synthesis of a life-like chemical system not derived from terrestrial life, as de novo evolutionary systems built on alternative informational and inheritance architectures, and as evolvable artificial cells and self-replicating robots capable of adapting to, and even constructing, their own environments. Reaching these goals will require field-specific working definitions of life, sustained interdisciplinary communities, and long-horizon funding mechanisms identified across all three areas, since the questions at stake unfold over timescales that conventional research cycles cannot accommodate. Together, these advances would not only expand our understanding of life as a general phenomenon but also lay the foundation for transformative technologies built on adaptive, evolvable, life-like matter.

Table 1: Emergence

Key Concept	Near-Term (5 Years)	Mid-Term (10 Years)	Far-Term (20 Years)
Consensus definition(s) of life	• Understanding "edge cases" • Recognize the life-like nature of an existing system	• Generate quantitative continua of "aliveness" / framework to allow comparisons	• Field-specific consensus working definitions of life
Bridging the top-down/bottom -up divide	• Prioritize study of aspects of life directly inheritable from the prebiotic world • Apply constraints from one approach to the other (e.g. genetics to constrain prebiotic chemistry)	• Prebiotic experiments generate something that is recognizable by contemporary biology as potentially present in the last universal common ancestor	

Key Concept	Near-Term (5 Years)	Mid-Term (10 Years)	Far-Term (20 Years)
Where else could/ did life emerge?	• Clear geochemical models of different environments that provide the conditions that support life. • Time and space resolved measurements of experiments / analog systems / other worlds • AI detects commonalities within the vast space of prebiotic chemistry • Better databases for prebiotic systems chemistry	• Identify early components of terrestrial life achievable by prebiotic chemists • Formal models that capture key dimensions of prebiotic chemistry	• Understanding if there is life elsewhere in universe • Understanding what life-like systems are compatible with alternative worlds
Synthesize a novel (bio)chemical life-like system/ community from the bottom-up	• Emergence of dissipative abiotic systems/networks • Changes in complex mixtures over time in dissipative/reacting abiotic systems • Emergence of physical boundaries	• Exploring radical alternatives to extant biology	• Synthesize a novel (bio) chemical life-like system/ community not derived from existing life

The Emergence trajectory spans four intertwined concepts: arriving at consensus definition(s) of life, bridging the top-down/ bottom-up divide, determining where else life could or did emerge, and synthesizing a novel life-like system or community from the bottom-up. Progress on these fronts is mutually reinforcing. The trajectory for each is shown in Table 1 for near, mid, and far-term horizons.

In the *near-term*, research should focus on sharpening the questions rather than prematurely resolving them. On the problem of defining life, this means concentrating on the "edge cases" where disagreement is greatest, building qualitative and quantitative understanding of these cases relative to systems that are by consensus alive or not alive—and asking whether the life-like nature of an existing system, such as digital life, a prion, or emergent AI properties, can be recognized on the same terms.

Bridging the top-down and bottom-up approaches calls for identifying the overlapping molecules and processes most likely to have been directly inherited from the prebiotic world, since these represent high-priority study targets; possible examples include the ribosome, metabolic cofactors, and/ or transition metals. The two approaches can also constrain one another by using genetic constraints and inferences of ancestral cellular states to narrow the vast possibility space of prebiotic chemistry from the top-down, and using environmental parameters such as water/rock ratios, temperature gradients, and minerals as predictive frameworks for what can emerge from the bottom-up. Understanding where life could emerge depends on clear geochemical models of the environments that support life (e.g., specifying abiotic background, temperature, pH, and stoichiometry) supported by time and space-resolved measurements of experiments, analog systems, and other worlds, better databases for prebiotic systems chemistry, and AI capable of detecting commonalities within that vast chemical space. Finally, progress toward bottom-up synthesis turns on the dynamics of non-equilibrium chemistry: identifying the processes and conditions that lead to dissipative abiotic systems and chemical networks, characterizing how complex mixtures change over time in such reacting systems, and achieving the emergence of physical boundaries (e.g. vesicles, coacervates, and other protocells, as well as inorganic membranes) that confine chemistry into organized reactions and harness energy through spatial separation and gradients.

In the *mid-term*, these foundations should yield more integrative results. The accumulated understanding of edge cases can be built into quantitative continua of "aliveness" along different axes of interest, perhaps serving different purposes in different fields, together with a framework to meaningfully compare these different cases of SELAS. A key milestone in bridging the divide would be prebiotic experiments that generate something recognizable by contemporary biology as potentially present in the last universal common ancestor (LUCA). In parallel, researchers should aim to identify the early components of terrestrial life achievable by prebiotic chemists, supported by formal models that capture the key dimensions of prebiotic chemistry, while advances in "life as we don't know it" begin to explore radical alternatives to extant biology. Throughout this period, researchers should remain open to the possibility of multiple origins of life, which top-down work would register as highly divergent deep lineage roots and bottom-up work as multiple viable pathways for reaching a given level of organic complexity.

In the *far-term*, the field should aspire to consensus working definitions of life—not necessarily a single universal definition, but field-specific definitions rigorous enough for the distinct purposes the community requires of them. In an astrobiology context, research should mature into an assessment of the potential for life elsewhere in the solar system and the Universe, and an understanding of which life-like systems would be compatible with, and viable in, alternative worlds. The culminating goal is the synthesis of a novel (bio)chemical life-like system or community from the bottom-up—one not derived from existing life, and whose foundational properties are understood and controlled precisely because it owes nothing to terrestrial ancestry.

Table 2: Evolution

Key Concept	Near-Term (5 Years)	Mid-Term (10 Years)	Far-Term (20 Years)
Information storage, inheritance, and genotype-phenotype coupling	• Develop experimentally tractable genotype-phenotype coupling in synthetic chemical and protocellular systems; identify and characterize non-canonical information-bearing molecules and inheritance mechanisms	• Create synthetic compartments and adaptive chemical systems capable of inheritance and evolutionary change	• Establish alternative informational and inheritance architectures distinct from terrestrial biology
Generation of evolutionary novelty	• Determine generalized principles governing evolutionary novelty, neutrality, and resilience	• Demonstrate directed evolution of novel functions in non-biological or hybrid informational substrates	• Demonstrate synthetic systems that generate genuinely novel functions through evolutionary processes
Coupling energy, selection, and adaptation	• Establish experimental systems that couple information processing, energy flow, and adaptive behavior	• Demonstrate sustained adaptive responses in synthetic systems exposed to changing environments	• Create new classes of adaptive, evolvable matter that expand the known space of life-like systems
Measurement, metrics, and predictive frameworks	• Establish quantitative methods for measuring adaptation, selection, robustness, and innovation in synthetic populations	• Establish standardized platforms and metrics across laboratories; develop predictive models linking information, selection, and emergent function	• Develop a generalized framework for evolution independent of specific biological chemistry
AI-guided design and autonomous experimentation	• Develop AI-assisted platforms for exploring non-canonical chemical and evolutionary landscapes	• Integrate AI-guided design with autonomous experimentation to accelerate evolutionary discovery	• Enable the rational design and deployment of synthetic evolutionary systems for scientific and technological applications

While substantial progress has been made in reconstructing biological functions and reconstituting increasingly sophisticated biomolecular systems, much of current research remains constrained by the specific solutions discovered by terrestrial biology. A central challenge for the coming decades is to determine whether the fundamental properties of evolution—information storage, inheritance, adaptation, and the generation of novelty—can be realized in alternative chemical substrates and organizational frameworks that extend beyond canonical biological systems. The anticipated research trajectory can be delineated along five key concepts, as shown in Table 2 for near, mid, and far-term horizons.

In the *near-term*, research should focus on establishing the foundations of synthetic evolution. A major priority is the development of experimentally tractable forms of genotype-phenotype coupling that do not rely exclusively on DNA, RNA, or proteins. While modern biology provides powerful examples of evolutionary systems, it remains unclear whether alternative informational architectures could support adaptation and innovation. Research is therefore needed to identify and characterize non-canonical information-bearing molecules, dynamic chemical networks, compositional inheritance mechanisms, and compartment-based systems capable of linking encoded information to functional outcomes. Particular emphasis should be placed on understanding how information can be stored, transmitted, and selected in chemical systems that differ substantially from contemporary biology.

At the same time, fundamental studies are needed to understand the mechanisms by which evolution generates novelty. Biological evolution is remarkable not simply because it produces adaptation, but because it continuously explores vast spaces of possible solutions. Current efforts in directed evolution and synthetic biology largely optimize existing functions, whereas future life-like systems may require entirely new evolutionary substrates and search strategies. Research should therefore investigate the roles of robustness, neutrality, historical contingency, and environmental feedback in shaping evolutionary trajectories. Such studies may reveal general principles governing innovation that are independent of the particular chemistry used by biological organisms.

A second major research direction concerns the relationship between energy, selection, and adaptation. Evolutionary systems cannot be understood solely through the lens of information storage; they must also be sustained by continuous flows of energy and matter that create opportunities for selection and innovation. Future research should seek to identify alternative energy currencies, non-equilibrium processes, and adaptive environments capable of supporting synthetic evolutionary systems. Understanding how energy transduction, information processing, and functional behavior become coupled in chemical systems represents a critical step toward establishing truly evolvable artificial matter.

In the *mid-term*, these foundational studies should enable the development of synthetic systems capable of sustained adaptive behavior. Research efforts should increasingly focus on engineering experimentally accessible evolutionary platforms in which inheritance, variation, and selection can be directly observed and manipulated. Such systems may include protocells, self-assembled compartments, adaptive materials, or entirely new classes of chemical organizations. Standardized experimental platforms and quantitative metrics will be required to compare different evolutionary architectures and identify design principles that promote resilience, innovation, and open-ended exploration of functional space. Advances in artificial intelligence and machine learning are expected to play an important supporting role by helping to navigate enormous chemical and evolutionary search spaces, identifying rare functional solutions, and guiding experimental exploration of non-canonical chemistries.

In the *far-term*, the field should aspire to create de novo evolutionary systems that are not merely simplified versions of existing biology but represent genuinely new forms of adaptive matter. Such systems may employ alternative informational substrates, novel modes of inheritance, and previously unexplored mechanisms of energy transduction and environmental interaction. The ultimate objective is to establish experimentally tractable systems capable of sustained adaptation and the generation of novel functions, thereby revealing general principles of evolution that transcend the particular solutions found in Earth's biosphere. Achieving this goal would fundamentally expand our understanding of life and provide a foundation for future technologies based on evolvable synthetic matter.

Realizing this vision will require substantial infrastructure investments. Evolutionary processes often unfold over long timescales and require exploration of large parameter spaces, making automation, high-throughput experimentation, and shared cloud-based laboratory infrastructure particularly important. Long-term funding mechanisms that support sustained, interdisciplinary research efforts will be essential, as many of the key questions cannot be addressed within conventional funding cycles. The field would also benefit from community resources such as repositories of negative results, standardized experimental platforms, and curated datasets for training AI models on non-canonical biochemical and evolutionary systems. Finally, stronger integration among chemistry, biology, physics, computer science, and engineering will be necessary to develop the conceptual and technical foundations required for synthetic evolution.

Table 3: Futures

Key Concept	Near-Term (5 Years)	Mid-Term (10 Years)	Far-Term (20 Years)
Biochemical artificial life: cellular	• Engineer an artificial cell from cellular components (unable to self-replicate) for special purposes (e.g., drug delivery)	• Couple artificial cell with energy metabolism allowing active signaling with other cells	• Couple artificial cell, energy metabolism, and information replication to create evolvable artificial cell
Biochemical artificial life: alternative molecular components	• Research alternative molecules that could be used as components of an artificial cell, suited for novel (non-medical) applications	• Engineer artificial cell (membrane and components) from alternative molecules	• Couple alternative cell to energy metabolism and information storage/ replication
Robotic artificial life: self-replicating robotic systems	• Harness AI as a control system for a mobile robot to create agents with a fully autonomous sensory/motor loop	• Mobile autonomous robots with capacity to learn	• Mobile autonomous robots that are able to assemble a replicate robot from available parts
Robotic artificial life: harnessing development for manufacturing	• Use systems biology techniques to engineer cells with a programmable developmental block	• Cells with programmable developmental genes that can grow structures on demand	• Evolvable programmable cells that can grow structures on demand

The research trajectory for Futures can be framed around two complementary tracks of life-like technology: biochemical artificial life, built from cellular or alternative molecular components, and robotic artificial life, built from autonomous machines and harnessing development for manufacturing. Both are pursued across near, mid, and far-term horizons, advancing in parallel from engineered systems toward genuinely evolvable ones.

In the *near-term*, in the biochemical track, the priority is learning to create functional whole cellular systems from parts—a key technology for biomedical applications ranging from drug delivery vehicles to drug discovery and testing assays. Making progress here requires adapting tools from systems biology to systems chemistry: just as systems biology taught us how to assemble components of biological systems ("biobricks") into novel genetic systems that evolution never produced, systems chemistry tools must be developed to integrate information replication, vesicle replication, and energy harvesting. In parallel, researchers should investigate the use of novel molecules—ones not used by existing biochemical life—to create artificial cells adapted to novel environments such as other planets or moons. In the robotic track, the corresponding objective is to interface a robotic system with an artificial cognitive system ("AI") to create an autonomous mobile robot capable of agency, autonomous exploration, and sensing—a complete, self-contained sensory-motor loop.

In the *mid-term*, the central biochemical goal of this period is the self-replicating artificial cell, which requires connecting cellular structures to both an energy metabolism and an information-replication cycle. Such cells will be able to convert environmental resources into usable energy, shuttling molecules, sending signals, and interacting with other cells. Reaching this point depends on several enabling advances: an automated system that generates the biochemical genetic information necessary to build any engineered construct, the construction of an artificial cell from novel components, and the creation of a "developmental programming language" that makes it possible to grow designed structures. In the robotic track, autonomous mobile robots that can learn and communicate with humans and with one another are likely to develop their own distinct behaviors over time; as they do, research in robot social science and "robot psychology" will need to keep pace with the technology.

In the *far-term*, while an artificial cell designed to perform novel functions is itself a key milestone, the longer-term biochemical aim is to learn to evolve artificial cells, opening new use cases. Systems biology has shown that many engineered systems are unstable, reverting to their components or evolving to eliminate a design element; harnessing the evolution of artificial cells would not only eliminate the long and costly design phase but also yield more robust cells. Building on this, the goal is to create multi-cellular artificial systems capable of adapting to novel environments and modifying their own surroundings—including systems that grow into arbitrary, designed structures that cannot be manufactured by standard methods. In the robotic track, the defining goal is self-replication: modular robotics that enable robots to construct other robots, together with an evolvable instruction language—inspired by evolvable digital life—that allows robots themselves to evolve. Such self-replicating robots could be adapted for construction and terraforming in hostile or alien environments, and ultimately could synthesize their modules from primary materials available locally, on Earth or on other worlds, enabling robot colonies that grow.

In order to achieve the anticipated trajectory, the participants note the need for training and infrastructure.

- There exists a communication problem across fields that is worthy of investment, so that researchers from different subfields of SELAS can work together effectively. As noted earlier, different "life definitions" serve different purposes; rather than pursuing a single unifying definition, further study of the edge cases of life-like behavior would benefit all SELAS-related fields.

- Cross-disciplinary training of young researchers in SELAS is difficult to accomplish institutionally and sustain at the university level. Formal training pathways in SELAS would combine fields such as advanced geology, nonequilibrium physics, synthetic biology, and prebiotic chemistry. One way to accomplish this while maintaining depth of expertise is by having people train in “foundational” disciplines (chemistry, geoscience, etc.) and then build the SELAS community through targeted educational activities outside of the formal degree programs, similar to how it has worked in bioethics and astrobiology (which have relied heavily on community building through programmatically funded summer schools, interdisciplinary conferences, etc.)

- The long-arc nature of this research—potentially requiring 10-20 year horizons to observe slow chemical evolution or explore other planets—is fundamentally incompatible with current short term, fragmented, and non-dedicated funding cycles.

Conclusion

The Future Directions Workshop on the Synthesis and Evolution of Life-like Artificial Systems (SELAS) affirmed that the deliberate construction of life-like systems, built on fundamental principles rather than inherited from terrestrial ancestry, represents a grand challenge for the scientific community, one that sits at the intersection of chemistry, biology, physics, planetary science, computer science, and ethics. Participants converged on a central reframing: progress depends less on recapitulating "life as we know it" than on understanding which properties of living matter are universal and which are accidents of Earth's singular evolutionary history. Pursuing that question across the emergence, evolution, and futures of life-like systems would not only illuminate the origin of life on Earth and sharpen the search for life elsewhere, but also lay the groundwork for a new class of adaptive, resilient, and evolvable technologies that no engineered system can match today.

Realizing this vision will require sustained progress on a set of shared obstacles that recur across every part of the field: the constraint of having only a single known example of life, the difficulty of mapping from desired function back to the information that would encode it, the vastness of the chemical and evolutionary search spaces, and the challenge of coupling energy, information, and adaptation in systems far from equilibrium. None of these knowledge gaps is the province of a single discipline, and none can be resolved on the timescale of a conventional funding cycle. The workshop therefore emphasized that advancing this field is as much a structural challenge as a scientific one—requiring durable interdisciplinary communities, shared experimental and data infrastructure, new training pathways, and long-horizon support commensurate with the decades over which chemical and evolutionary processes unfold.

While there are multiple trajectories towards SELAS envisioned by the participants, they all point consistently in one direction: from recapitulating biology toward building genuinely novel systems, from engineering by hand toward harnessing evolution itself, and from isolated components toward integrated, self-sustaining matter. Meeting this challenge will demand careful attention to safety and oversight at every step, given the power that control over life-like systems would confer. Yet the potential payoff—a deeper understanding of life as a general phenomenon, and the transformative capabilities built upon it—is profound. This workshop represents an early step in building the community and the research agenda equal to that ambition.

Glossary

Abiotic — Not produced by or involving living organisms. Abiotic chemistry refers to chemical processes and products that arise from purely physical and geochemical causes, independent of biology.

Astrobiology — The study of the origin, evolution, distribution, and future of life in the universe, including the development of methods and criteria for detecting life beyond Earth.

Biosignature — A substance, pattern, or property that provides evidence of past or present life. A central challenge in the field is distinguishing genuine biosignatures from complex organic chemistry that can arise without life.

Coacervate — A droplet formed when certain molecules in aqueous solution spontaneously concentrate to form a distinct liquid phase; studied as a possible primitive compartment for organizing prebiotic chemistry.

Dissipative (non-equilibrium) system — A system that maintains its organization only by continuously consuming and dissipating energy, rather than settling into a static equilibrium. Living systems are dissipative, and sustaining such far-from-equilibrium dynamics is considered essential to life-like behavior.

Genotype–phenotype coupling — The link between encoded information (genotype) and the functional traits it produces (phenotype). In biology this link is mediated by evolved molecular machinery; establishing comparable coupling in synthetic systems is a key barrier to engineering systems that can evolve.

"Inverse mapping" problem — The difficulty of working backward from a desired function to the information that would encode it. Moving from information to function (the forward direction) is comparatively tractable; inverting that map is a foremost obstacle to designing artificial life-like systems.

LUCA (Last Universal Common Ancestor) — The most recent community of organisms from which all life on Earth descends. LUCA serves as a reference point for inferring features of the earliest life, some of which may trace back to the prebiotic world.

"n = 1" problem — The fundamental constraint that life on Earth is the only known example of emergent, evolving matter producing a biosphere, making it difficult to distinguish universal properties of life in general, from properties specific to Earth.

Origin of life research — The study of the mechanisms by which life first emerged on Earth, treating the prebiotic planet as a dynamic geochemical system that gave rise to a biosphere.

Prebiotic — Pertaining to the conditions, chemistry, and processes that existed before the emergence of life and that may have led to it.

Protocell — An artificial or primitive cell-like compartment that exhibits some properties of living cells (such as a boundary membrane, internal chemistry, or growth) without being fully alive.

Protometabolism — A network of linked chemical reactions, driven largely by environmental and geochemical factors, that resembles and may have preceded modern biological metabolism.

Self-assembly — The spontaneous organization of molecules into ordered structures—such as membranes or compartments—without external direction, driven by the physical and chemical properties of the components themselves.

Shannon entropy — measures the average uncertainty (or information content) of a random variable.

Stigmergic building — a building practice where the partially built structure is simultaneously the output of past work and the instruction set for future work.

Vesicle — A small compartment enclosed by a membrane (typically of lipids), studied as a model for the boundaries that separate a primitive cell's interior chemistry from its environment.

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Appendix I—Workshop Attendees

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Laurie Barge, *NASA Jet Propulsion Laboratory, California Institute of Technology*
Neal Devaraj, *University of California, San Diego*
Christine Keating, *Pennsylvania State University*

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Claudia Bonfio, *University of Cambridge*
Nicholas Evans, *University of Massachusetts Lowell*
Greg Fournier, *Massachusetts Institute of Technology*
Gregory E. Kaebnick, *Hastings Center*
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Susan Lang, *Woods Hole Oceanographic Institution*
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Juan Perez-Mercader, *Harvard University*
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Oliver Steinbock, *Florida State University*
Luis Zaman, *University of Michigan*

Government Observers

Chagaan Baatar, *Office of Naval Research (ONR)*
Patrick Bradshaw, *Air Force Office of Scientific Research (AFOSR)*
Jennifer Becker, *Army Research Office (ARO)*
Charles Cunningham, *National Science Foundation (NSF)*
Lola Fatunmbi, OUSW R&E, *Science and Technology/Foundations*
Aura Gimm, *Department of Energy (DOE)*
Ernie Glover, *Sloan Foundation*
Nandini Iyer, *Air Force Office of Scientific Research (AFOSR)*
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Workshop Participant Short Biographies



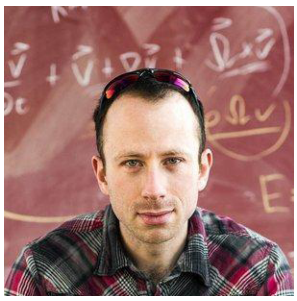
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Theoretical physicist working at understanding the origin, evolution, and maintenance of living systems, natural and artificial. Creator of the Avida Artificial Life System and author of the first Artificial Life textbook. Focus on understanding how the concept of information is essential to study life.



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Claudia completed her PhD in Biomolecular Sciences at the University of Trento (IT), working on the origin and catalytic activity of ancient proteins. Later, as a Marie Sklodowska Curie Fellow and 1851 Research Fellow, she moved to Cambridge, where she looked into the chemical origin of cell membrane signaling. In 2021, she started her independent research career at ISIS in Strasbourg before moving back to the University of Cambridge in 2024 as a University Associate Professor following the award of an ERC Starting Grant and a UKRI Future Leader Fellowship. Her group is interested in designing and developing functional primitive cells capable of Darwinian evolution.



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Christine D. Keating received her B.S. in Biology and Chemistry from St. Francis College (Loretto, PA) and her Ph.D. in Chemistry from Penn State University. Her postdoctoral research was also at Penn State and she joined the faculty there in 2001. Keating is currently the Shapiro Professor of Chemistry at Penn State. She is affiliated with the Penn State Astrobiology Research Center, Materials Research Institute and Huck Institute for Life Sciences. Dr. Keating has been honored as a Sloan Research Fellow, Beckman Young Investigator, Camille Dreyfus Teacher-Scholar, and Unilever Outstanding Young Investigator in Colloid and Surfactant Science. She has been named the Bodil Schmidt Nielsen Fellow & Bioengineer in Residence at Mount Desert Island Biological Laboratory, a Fellow of the American Association for the Advancement of Science, and a PSU Faculty Scholar Medal in Life and Health Sciences. In 2024, she received the Langmuir Lectureship Award, and in 2025 was named a Whitman Fellow at the Marine Biological Laboratory. Dr. Keating is a Senior Editor at Journal of Physical Chemistry. She has published over 140 scientific articles. Her research interests combine materials science, colloid chemistry, and cell biology, with a particular emphasis on self-assembly, compartmentalization, and artificial cells.



Ramanarayanan Krishnamurthy
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Ramanarayanan Krishnamurthy is currently a Professor of Chemistry in the department of chemistry at The Scripps Research Institute in California. His research focusses on employing the tools of synthetic organic chemistry to understand the prebiotic chemical roots of life's processes (the "Why") and its emergence (the "How") under early Earth Environments. His group employs a non-teleological (non-purposeful) approach which has led to the "18th camel paradigm" in their research endeavors, raising the question of whether the actual historical pathways of life's origin on early Earth can be discovered or have to be (re)invented. Such a concept gives rise to the prospect that chemistry of life-as-we-know-it is not the only result ("destiny"), but one that has emerged among many potential possibilities ("destination").



Susan Lang
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Susan Lang is a geochemist who studies how interactions between water and rock in the deep subseafloor generate organic molecules, energy sources, and chemical gradients that can support life. Her work focuses on hydrothermal environments such as the Lost City hydrothermal field, where reactions between seawater and mantle-derived rocks produce hydrogen, methane, and other reduced compounds, along with ongoing abiotic synthesis of organic molecules, creating natural systems in which the building blocks and energy sources of life arise directly from geological processes. By combining seafloor sampling with chemical and isotopic analyses, she investigates how simple inorganic ingredients give rise to increasingly complex organic mixtures, and how these geologically driven systems shape the distribution and transformation of carbon. Her research also examines how microbial communities interact with and modify these compounds, with the goal of distinguishing abiotic from biological signatures in natural environments. These systems provide a window into how non-biological processes can generate the molecules and energy that underpin living systems, offering insight into the conditions that may have supported life's emergence on Earth and elsewhere. Lang is also Director of the National Ocean Sciences Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institution.



Allen Liu
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Allen Liu is a Professor of Mechanical Engineering, Biomedical Engineering, and Biophysics at the University of Michigan. Driven by a passion for understanding cellular mechanotransduction and bottom-up synthetic biology, his research integrates techniques from quantitative cell biology, synthetic biology, biophysics, and microfluidics. Dr. Liu holds a B.Sc. in Biochemistry (Honors) from the University of British Columbia and a Ph.D. in Biophysics from the University of California, Berkeley. He completed postdoctoral training at The Scripps Research Institute in La Jolla before launching his independent research group in 2012. His scientific contributions have earned him the NIH Director's New Innovator Award and recognition as a Young Innovator and Rising Star by the Cellular and Molecular Bioengineering Special Interest Group of the Biomedical Engineering Society (BMES). He is an elected Fellow of BMES and has received international fellowships, including the Endeavour Executive Fellowship (Australia) and the Alexander von Humboldt Fellowship for Experienced Researchers (Germany).



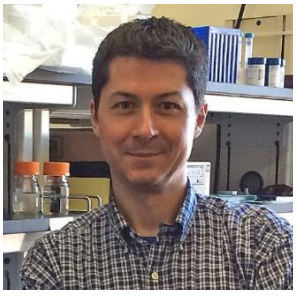
Joanna Masel
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A theoretical population geneticist with long-standing interests in evolution under high error rates. Their research group has branched out into protein evolution. They have a particular interest in very early proteins and the origin of the genetic code.



Sarah Maurer
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Sarah is interested in the abiogenesis from both the origins-of-life and synthetic biology perspectives. She builds model cells from amphiphiles, and examines possible life-like properties, such as metabolism or growth and division. Her work relies on a variety of techniques, including fluorescence microscopy, fluorescence spectroscopy, UV-Vis spectroscopy, ELISA, gas chromatography, and high-pressure liquid chromatography and mass spectrometry. She also focuses on exploring both compositional and environmental parameters for self-assembly using lab automation and machine learning. Most of the research is done with the help of undergraduate students at her predominately undergraduate institution (PUI).



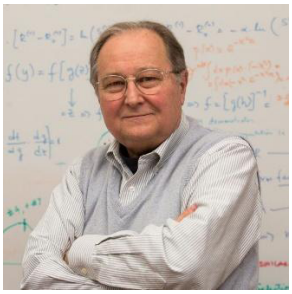
Vincent Noireaux
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Vincent Noireaux is a Professor of Synthetic Biology and Biological Physics at the University of Minnesota. His lab utilizes cell-free transcription-translation (TXTL) to engineer biochemical systems outside of cells, including gene circuits, phages, and synthetic cells. Dr. Noireaux earned a Ph.D. at the Curie Institute in Paris in 2000 and completed a postdoc at The Rockefeller University in New York City in 2005.



Matthew Pasek
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Matthew Pasek is a professor at RPI. He studies phosphorus chemistry and its role in the evolution of life, focusing on alternative molecules to phosphate.



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Juan Perez-Mercader, Senior Research Fellow at Harvard University's Department of Earth and Planetary and Origins of Life Initiative, is a Theoretical Physicist and Experimental Polymer Chemist/Condensed Matter Physicist interested in the origin and evolution of life in the Universe. Prior to joining Harvard in 2010, he was a Research Professor in Spain's National Research Council and Founder and Director of Spain's Centro de Astrobiologia in Association with NASA. He is an External Professor at the Santa Fe Institute and a member of several international academies and of Spain's Royal Society of Physics. He has contributed to grand unification, the supergravitational extension of the Standard Model of particle physics, to quantum and classical gravitation, co-discovered the Einstein-Lense-Thirring effect, and contributed to astrobiology, exoplanet formation theories, chemical computing, and artificial synthetic life. In Harvard, he works on the ex-novo laboratory synthesis of the simplest self-booting chemistry-based abiotic systems capable of mimicking natural life. Recently (2025) he has produced systems mimicking natural life and self-reproducing with heritable variation. Funded by NSF, one of his patents (for a chemical Turing machine) is currently being built with IBM as a chemical computer. His distinctions and awards include several schools, venues and institutions named after him.



Hiroki Sayama
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Hiroki Sayama is a SUNY Distinguished Professor in the School of Systems Science and Industrial Engineering, Executive Assistant Dean for Graduate Studies of the Thomas J. Watson College of Engineering and Applied Science, and the Director of the Binghamton Center of Complex Systems (CoCo), at Binghamton University, State University of New York, USA. He received his B.Sc., M.Sc. and D.Sc. in Information Science, all from the University of Tokyo, Japan. His research interests include complex dynamical networks, human and social dynamics, collective behaviors, artificial life/chemistry, interactive systems, and complex systems education, among others. He is an expert on mathematical/computational modeling and analysis of various complex systems. He has published more than 250 peer-reviewed journal articles and conference proceedings papers and has written or edited 16 books and conference proceedings about complex systems related topics. He is a Senior Member of IEEE. He currently serves as the Vice Chair of the IEEE Computational Intelligence Society's Task Force on Artificial Life and Complex Adaptive Systems, an Elected Council / Executive Committee / CCS Steering Committee Member of the Complex Systems Society, and the Vice President and a Board member of the Network Science Society (NetSci).

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Dr. Steinbock studied at the Georg August University of Göttingen and the Max Planck Institute in Dortmund, where he earned both his Master's and doctoral degrees. During this time, he developed a sustained interest in self-organization and complexity in natural and synthetic systems. His research addresses how macroscopic order, hierarchical architectures, and complex temporal behavior emerge from simple processes such as autocatalytic reactions, diffusion, and fluid flow. His work spans biophysical studies of chemotaxis and morphogenesis, prebiotic chemistry, and materials science, unified by the question of how biological complexity can arise and be harnessed in non-living systems. Primarily experimental, his research also includes model development, numerical simulations, and machine learning-based analysis. Dr. Steinbock is a Fellow of the American Association for the Advancement of Science and a recipient of the Bessel Research Award. His research has been supported by the National Science Foundation, NASA, DARPA, and other national and international agencies. He has organized several international symposia and conferences, including a Gordon Research Conference in Italy and a workshop at the Lorentz Center in Leiden. He has co-authored over 180 peer-reviewed publications and is the Cottrell Professor of Chemistry at Florida State University.



Luis Zaman
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Luis Zaman is an Assistant Professor of Ecology and Evolutionary Biology and Complex Systems at the University of Michigan. He received a dual Ph.D. in Computer Science and Ecology, Evolutionary Biology & Behavior from Michigan State University in 2014, followed by an NSF Postdoctoral Fellowship in Biology working with Ben Kerr at the University of Washington. As a collaborative and interdisciplinary scientist, he combines computational, microbial, and theoretical approaches to study host-parasite coevolution and the evolution of complexity, evolvability, and novelty. Since joining Michigan, Zaman has built a productive, internationally recognized research program, with funding from the NSF, NIH, and DOE. His lab pursues two complementary research threads: one harnessing populations of self-replicating computer programs that evolve by natural selection, and another developing innovative microbial systems using bacteria and bacteriophages as lenses into the evolutionary process.

Appendix II—Workshop Agenda and Prospectus



Virginia Tech Executive Briefing Center (VT EBC): 900 N Glebe Rd, Suite 200, Arlington, VA 22203 | Second Floor

DAY 1—Wednesday, April 29, 2026

Time	Title	Speaker
8:00–8:15	Check-in	
8:15–8:20	Welcome and Introductions and Expectations	R&E Foundations
8:20–8:45	Workshop Framing Talk	Co-chair(s)
8:45–9:00	BREAK - *Breakout Instructions and Morning Break*	
9:00–10:45	Working Group I: Define the Problem *Small group discussions to frame a vision for research in synthesis and evolution of life-like artificial systems and identify the greatest hurdles to achieving it.* Group A—Emergence Group B—Evolution Group C—Futures	
10:45–11:00	BREAK - *Transition to main conference room / leads prepare outbriefing*	
11:00–12:00	Working Group I: Outbriefing	
12:00–1:00	LUNCH - *catering provided*	
1:00–3:45	Working Group II: Technical Capabilities and Opportunities *What are the promising research directions? What are the potential capabilities in the 10- to 20-year horizon?* Group A—Emergence Group B—Evolution Group C—Futures	
3:45–4:00	BREAK - *Transition to main room and leads prepare outbriefing*	
4:00–4:45	Working Group II: Outbriefing	
4:45–5:00	Summary of Day	Co-chair(s)
5:00	MEETING ADJOURNED FOR THE DAY	
5:30	Optional—No host social (location TBD)	

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DAY 2—Thursday, April 30, 2026

Time	Title	Speaker
8:00–8:15	Check-in	
8:15–8:30	Welcome	
8:30–9:00	Day 1 Recap	Co-chair(s)
9:00–10:00	**What's Missing?** Discussion of topics which did not fit into the framework of day 1 but need to be discussed.	
10:00–10:15	BREAK	
10:15–11:30	**Big Questions** Discussion of particularly far-out (or long-term), high-risk, high-impact ideas.	
11:30–11:50	Discussion of Key Ideas / Components for Report	
11:50–12:00	Closing Remarks	Co-chairs
12:00	MEETING ADJOURNED	

Future Directions Workshop
"Synthesis and Evolution of Life-like Artificial Systems"

Science and Technology Foundations Office, Office of the Undersecretary of War (R&E)

April 29-30, 2026
Arlington, Virginia

Co-chairs: Dr. Christoph Adami (Michigan State University), Dr. Laurie Barge (NASA Jet Propulsion Laboratory/ California Institute of Technology), Dr. Neal Devaraj (University of California, San Diego), Dr. Christine Keating (Pennsylvania State University)

The fundamental nature of life has held the attention of the scientific public for a long time, but recent advances and directions in scientific discovery have brought exciting new insights. With the ability to probe deeper into the biological mechanisms that are essential to living organisms and our exploration of their control, new questions and uncertainty arise, particularly around the distinction between biological and complex but non-biological (abiotic) systems, or "animate versus inanimate matter". The field of study that investigates the transition between biological and abiotic has attracted increasing interest in recent years: spurred by the search for life elsewhere in our solar system and the challenges of differentiating extraterrestrial biology from a complex abiotic background, as well as advances in biomimetic and complex synthetic chemistry that have potential for creating life-like systems in the laboratory. Artificial systems with biological properties can be created in the laboratory or virtually, either drawing on processes from existing life or building up from basic naturally available materials, and these "artificial biological systems" may be key to understanding life's origin and inform our search for life strategy.

Prebiotic chemistry and synthetic life research have shown that simple systems (in terms of rules and building blocks) can lead to highly complex products and/or behavior, and the manifestation of some properties that appear life-like. Non-biological complex systems can undergo chemical changes - e.g. directed by environmental parameter constraints - toward a self-assembling system that interacts with its surroundings and exhibits emergent behavior. As opposed to lab generated life-like processes, virtual life can be based on arbitrary rules far removed from chemical processes; which suggests the possibility that other physical phenomena and environments could lead to the emergence of life. However, these virtual or laboratory constructs lack an important ingredient of life itself: biological evolution, or the ability to change, learn, adapt. Although John Conway's "Game of Life" and its variants already show exponential complexity with simple fixed rules, for a more realistic representation of biological life, the software agents must be able to change the rules themselves. As artificial intelligence becomes more capable and human-like, the ability of AI agents to reproduce, adapt and change mimics evolution, and the question of AI as a new lifeform may become worthy of serious consideration.

This Future Directions Workshop aims to bring together radical thinkers across multiple disciplines, to discuss these questions and forge a path towards future research directions, with the goal of building a new scientific discipline at the intersection of chemistry, biology, physics, mathematics, complexity theory, computer science, and artificial intelligence, as well as geology, planetary science, and others. Ethical and safety considerations are another key component of the discussion, as the transformative benefits of the study of artificial biological systems must be balanced with the recognition and mitigation of risks. The workshop would aim at the far-term, visionary outcome while providing thoughtful considerations of the roadmap, constraints, and gaps that lead us to that goal. The workshop will be addressing fundamental questions, which can broadly be defined into themes.

Theme 1: Emergence and Properties of Life-like Systems. Recent findings frame the questions now driving the study of life-like systems. From "LUCA" to synthetic genomes, mirror-life, artificial cells, and the search for life on other worlds, is there a comprehensive picture of our understanding of life (as we know it) that emerges? What research must be accomplished to fill knowledge gaps in understanding life-like systems? The fundamental properties of biological systems may seem irreducible (e.g., adaptation, reproduction, learning, motion…); are they universal or can alternate biological systems exist with some but not all of these traits as they appear on Earth? Is the transition to living matter a question of degree of capability? How much of the complexity of living systems - and other complex systems on the way to the emergence of life - can we simulate in the laboratory or virtually? What is the role of the environment in the emergence of complex proto-biological systems and what does this imply for other planets? What experiments, real or virtual, can we conduct?

Theme 2: Evolution of Life-like Systems. A growing body of work now outlines the challenge of predicting and guiding the evolution of life-like systems. If artificial biological systems can be laboratory generated or realistically simulated (or both), how do we predict their evolution? What methods can we use to predict and constrain their evolution? How can changes in artificial biological systems be induced and/or manipulated by external input and/or environmental changes? What is the role of inorganic components in the evolution of complex organic / biological systems and how might artificial life interact with non-biological matter? How do interactions between individuals generate specialization, giving rise to differentiation, parasitism, symbioses and multicellularity? This is a formidable challenge in understanding and modeling extreme complexity, at a scale that may possibly dwarf that of other natural systems.

Theme 3: Futures of Life-like Systems. As the creation and control of life-like systems comes into reach, the focus shifts to what futures we choose to build and how we manage their impact. If we can create artificial life, and if we can control its evolution, what shall we aim for? What are the extraordinary benefits of doing so? What are the revolutionary outcomes along the way? What are the risks involved in creating or re-creating life forms at a fundamental level? What are the threats, can they be mitigated or derisked, and how would society react to these possibilities? What is the impact on educational programs? What are the resources required? What are the critical research directions that we must follow? How should we go about and who should be involved?

This workshop calls for a broad, diverse set of expertise, an open appreciation of different ideas and concepts, strong communication across several fields, and a far-reaching vision. An outcome of the workshop is the creation of a seed network of researchers and experts across various fields, linked by a common interest and vision of this very fundamental and novel science.