Future Directions Workshop on Embodied Intelligence

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Contents

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 Basic Research Office of the Office of the Under Secretary of Defense for Research and Engineering (OUSD(R&E)), 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 May 19-20, 2024 in Seoul, South Korea on the future of Embodied Intelligence research, as an essential and critical aspect of future robotics that are agile and enduring, as well as damage tolerant. 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

Embodied Intelligence (EI) is a rapidly evolving field that seeks to address new ideas about the nature of machine intelligence. EI blurs the lines between Artificial and Physical Intelligence (AI and PI, respectively); it creates a diffuse interface between artificial and natural components of a system. EI aims to incorporate into machines the multimodal and multiscale adaptation observed in natural organisms, for a wholly new approach to robotic technology, allowing a future filled with autonomous, useful, and safe machines. Consider a world in which every machine is morphologically and neurologically unique. Such technologies would be immune to unintentional surprise (novel environments) or intentional surprise (adversarial attacks) because no two machines would share a common Achilles heel. Imagine machines that, when cleaved in two, form two smaller yet distinct versions of the original machine. Imagine machines that can devolve into swarms of independent components and reform into a physical unity on demand. Consider autonomous machines in which there is no clear distinction between control, actuation, sensation, communication, computation, and power, rendering such machines immune to complete failure of any one sub-system. These machines might also incorporate living and non-living components, further combining the best of the biotic and abiotic worlds and blurring the distinction between "us" (humans) and "them" (machines).

Past efforts in embodied intelligence science have proceeded with little interaction between the broad fields in which R&D was pursued. In the present, there are many efforts surrounding the integration of new AI and machines, leading to a need to integrate the brain and body of these systems. Biological systems have served as inspiration for many of the modern applications and for these systems. There is an opportunity within embodied intelligence to cause responses intermediate to pre-flex, reflex, and centralized decision making.

An octopus tentacle provides a good example of a higher level, yet localized Observe, Orient, Decide, Act (OODA) loop. While the whole octopus has a centralized brain, it also has a large number of neurons in its tentacles. Even when separated from the body, the suckers of a tentacle are able to sense the chemical environment, locally decide if an object is food or not, grasp it if it is food and pull it towards its concept of where its beak is located. Sensing, actuation, computation, and energy is distributed through every mm3 of an octopus's flesh; a living, autonomous material system.

While AI excels at handling large amounts of data, the underlying statistical process of learning is not conducive to causal and abstract reasoning. Attempts to create such capability within that framework have generally not yielded consistently accurate results, and this likely relates to the difference between how engineered (AI) and natural organisms learn. These are fundamental questions: what is learning and, to a deeper level, what is intelligence?

Advances in these fields could lead to further integration between humans and machines, creating new ecosystems in which all can co-exist.

The Future Directions Workshop on Embodied Intelligence was held on 19-20 May 2024 in Seoul, South Korea to examine the prospects for applying new approaches, theories, and tools in basic research to enable these capabilities over the next 10-20 years. It gathered 28 researchers from a variety of fields, including soft robotics, motion control, biomechanics, mechanical engineering, control theory, systems biology, physics, mathematics, computer science, and bioethics. The workshop included researchers from the Republic of Korea (ROK) and the United States (US) and served as a foundation for collaboration in the field between the two countries.

The workshop was organized for highly interactive small group discussions with whole-group synthesis on the challenges, opportunities and trajectory of research across three pillars of embodied intelligence: *perception, motion, and adaptation.*

Research Challenges

Participants identified the following challenges for each technical pillar of EI and identified the key research areas to realize the envisioned future of embodied intelligence.

Perception

The ability for machines to sense their surroundings/environment and glean information from it has been explored utilizing several methods. Several sensing modalities have emerged that interface the body with the environment (exteroception) and provide more detailed knowledge about the body's state internally (proprioception). Perception goes beyond this by incorporating senses such as olfactory (smell, or the ability to detect chemical information) and nociception (the ability to detect harmful environmental stimuli), which are more exotic methodologies that can be utilized for environmental navigation.

The main research challenges for Perception are linked to the fundamental questions surrounding sensing and the ability to infer information from sensors. For all natural organisms, knowledge representation is highly dependent on the sensory modes, and their processing and fusion. Thus, learning cannot be dissociated from the sensors used to acquire information. In addition, using sensing in the artificial world revolves around vision, while in the natural world, a plethora of other methods are used. The main Perception research challenges include:

> **Sensitivity:** Increasing the signal to noise ratio by localizing signals of interest and amplifying is a dynamic and computationally challenging process that has the potential to increase agility and energy efficiency if performed at the embodied level.

Innervation: Multiplexing many sensors and laying them out sensibly inside a complex structure is a manufacturing challenge that has the potential to greatly increase perceptive capabilities with the ability to localize all sensing and actuation.

Encoding: Achieving high information throughput by sifting through large data amounts effectively by leveraging optical modes, biological spiking, etc. is a data challenge that has the potential to provide massive data rates for information fusion without exploding the practical wiring and assembly requirements to sensing hardware.

Motion

Traversing and navigating the environment is a staple of any system/body. This feat is done directly by locomotion, or by changing the environment to suit the needs of the system/body. The degrees of freedom (DOF) are directly correlated to the complexity of the system, but can change over its lifetime, providing increased adaptability for movement.

The main research challenges for Motion are linked toward the current technological trends to dominate the environment rather than leveraging it. Being able to utilize it effectively will greatly increase the energy efficiency and synergy of the body and the environment. The main motion research challenges are listed below:

Agility: Increasing responsiveness and power, without increasing DOF, will need to be done by supplying power and data to actuators; mimicking nature's bottom-up approach of self-assembly allows for far more architectural complexity.

Endurance: Withstanding many cycles of use, or using less energy for operations by being efficient, will need the utilization of multifunctional energy storage and transduction, high energy density fuels, storage and release of elastic energy, and center of mass adjustments during locomotion.

Growth: Changing to the environment (or changing the environment) by adding, subtracting, or changing dimensions, body segments, and/or DOF with increased ability to utilize energy will be a major challenge for the machine's body.

Adaptation

The natural world has solved many design problems via evolution. Artificial systems can be imbued with this capability by utilizing a wide variety of computational techniques designed to optimally modify the body to the environment. An additional feature to be explored is the use of collective adaptation, in which many bodies act as a whole to perform specific tasks, and thus can be changed to better fit their environment.

The main research challenges for Adaptation are centered around the co-design of brain and the body. While natural systems use evolution, artificial ones adapt from centralized computation. Efficient management of energy expenditure also will be challenging, but taking advantage of materials science and additive manufacturing may ameliorate these engineering contradictions. The main adaptation research challenges are listed below:

Learning: Logic links will need to be increased based upon new experiences and will extend beyond traditional neural plasticity to the bodies of robots. The bodies as well as the brains of future robots may learn how best to detect co-occurring features of external challenges (or internal challenges, such as injury), and prepare themselves morphologically and neurologically to handle those challenges when the re-occur.

Language: Verbal claims could be demonstrated physically as a self-correcting mechanism for confabulation; this task could use Large Language Models (LLMs) as a supplement, but not a sole use – as they suffer from hallucinations and the generation of non-factual verbal statements.

Control: By adding DOF (and reducing the discreet boundaries between the body and the environment), the control of the systems will be a challenge; there will be kinematic redundancy for systems with too many DOF for their tasks (but adding the appropriate DOF will allow for more flexibility); this inefficiency will need to be addressed by selectively removing DOF (or adding more).

A Tapestry of Challenges

Perception, Motion, and Adaptation are interdependent topics that will require concurrent research efforts. Subjects such as information density will need to be addressed utilizing all three to be effective: Perception to amplify or filter data, Adaptation to understand the resulting information, and Motion to adjust for it. Indeed, organisms change based on their environments utilizing all three of these. In biology, organisms focus on relevant stimuli utilizing sensing organs and develop behavioral responses which filter out unimportant inputs. They respond based on the organisms' needs, based upon its internal state and due to limited attention/energy. They leverage the past experiences of the organism via learning and memory, which leads to innate responses and reflexes which help save energy and assist in remodeling and growth of the organism.

The interdependent nature of artificial systems also requires feature integration. The system first selects the features that it deems useful, then extracts them (or their information). In order to use the new features, the system will then regularize the newly acquired features and optimize algorithms to reproduce the features for use by the system. Unlike biological systems, however, these processes consume large amounts of energy and are subjected to significant latency.

To tackle these interconnected research challenges, a concerted effort must be made to foster collaboration and communication among researchers in diverse fields. Increasing knowledge transfer between groups of researchers with defined taxonomy and common language is a first step to this goal. Concerted

Testing, Evaluation, and Validation (TEV) will also be paramount to realizing this objective. Transdisciplinary research, which includes materials science, manufacturing, computer science, mechanical engineering, and EI design will need to be woven together.

Research Opportunities

As engineering advances produce ever more sophisticated artificial systems, there are tremendous research opportunities to learn from biological ones. Indeed, organismal biology already shows the ability to focus on relevant stimuli, respond based on needs, and leverage past experiences. These systems can also be studied to observe their ability to identify and integrate new features from the environment, perhaps revealing key insights to be able to translate such features to synthetic systems. With the advancements of other fields, there exists many opportunities for exciting developments and research to be conducted in the field of embodied intelligence. Some of these include additive manufacturing, neuromorphic computing, biohybrid robotics, autonomous material systems, and electrochemistry.

Research Trajectory

The workshop participants developed a trajectory for the research opportunities identified for the field of embodied intelligence with a vision for the 5-, 10-, and 20-year horizons.

Five-year goals

In the immediate future, EI will augment existing robot architectures. These robots, equipped with simple control loops informed by analog sensing and processing layers, commanding actuators (e.g., continuum, compliant, standard) will be capable of reduced energy expenditure during mobility tasks or more dextrous performance in assembly tasks for example. These robots may feature, as an example, endoskeletal structures with soft actuators and skins, mediating reconfigurability based on task requirements. The use of compliant manipulators and soft skins will improve their agility and endurance compared to non-EI systems.

Key Goals:

- Develop consensus metrics for energy consumption during state transitions (e.g., trotting to cantoring), as well as agility (e.g., acceleration and turn radius).
- Establish foundational control strategies using logical basis functions for coordination of tasks.

Over the next decade, EI is expected to leverage prior results in analog sense-act-respond functions to produce a set of low level robots that demonstrate these principles with specific functions, akin to organs or “polyps” seen in biology (Figure 5). The results may be akin to reconfigurable systems of modules mediated by analog computational layers that can configure for (as an example) external dexterity or (another example) internal operational efficiency for existing tasks. Importantly, the development of basis functions for the set of modules will play a critical role in this phase, allowing robots to be dynamically assembled and disassembled in response to environmental or task changes.

Key Goals:

- Enumeration of agility and endurance requirements for general purpose robotics (these numbers should be arrived at beyond just EI community)
- Define a set of low-level EI modules that address the requirements for agility and endurance
- Algorithms developed that provide the basis for coordination between these modules (digital and analog solutions)

Long-Term (20 Years)

In the long term, EI researchers will understand how to best leverage living and synthetic approaches to build low-level EI modules. The basis functions to coordinate the low-level biohybrid robots to autonomously assemble and disassemble themselves into more complex, high-level robots will be known. These high-level robots are more sophisticated, capable of performing complex tasks and adapting to changing environments. This synthesis will enable the development of general-purpose robots capable of growth, reconfiguration, and continuous adaptation. Logical basis functions (e.g., autonomous material computation)(Yamada et al., 2022) will be fully integrated into the robot’s architecture, enabling seamless coordination across multiple robots in various environments. In addition to the coordination of low-level robots, we also anticipate autonomous coordination between multiple (and different) high-level robots.

Key Goals:

- Develop autonomous material systems (AMS) that allow for independent sensing and dynamic reconfiguration.
- Implement neuron-based computing for accelerated adaptation and coordination of large robot assemblies.
- Advance multiplexed high-DOF actuator arrays to support sophisticated motion and structural integrity during assembly and disassembly.
- Robust approaches to maintaining life in real world environments, as well as mediating their interface with artifices.
- Communication protocols in addition to RF and visual spectrum signaling, such as acoustic and chemical.

Opportunities to Achieve these Goals

This workshop report outlines the opportunities and a path forward for research in the field of embodied intelligence. One aspect is the utilization of DOF, both to manipulate and understand the limitations, that will be integral to the advancement of the field. Challenges of manufacturing and computational efficiency must be addressed alongside long-term testing protocols and energy considerations. A concerted effort must be made to bring together the community to address these challenges through interdisciplinary research and collaboration. Improving communication and idea-sharing within the community is imperative for the future of this field. The participants emphasized the importance of the following technology areas:

Materials and Manufacturing: Advances in materials and manufacturing will enable robots to be designed with more heterogeneous materials which reduce and eventually eliminate the need for subsystems. Autonomous Material Systems will allow for a high degree of adaptability in robots, with reduced cost in manufacturing.

Adaptation and Computation: Advances in computational hardware will enable hyper-efficient computation systems that integrates seamlessly with physical substrates, enabling more efficient and adaptive behaviors. These systems will operate beyond current digital communications and memory and rather use analog and biotic computation with enhanced response speeds and/or reduced power consumption. As more complex Large Language Models (LLMs) are developed and integrated with other interaction modes, the communication between Perception, Adaptation, and Motion domains will become more efficient and capable, allowing for higher complexity and compute.

Application Focus Areas

There exist many applications for these new technologies. Focus areas for these use-cases include:

Daily Life and Labor Replacement: Society will thrive in a new era in which robotic assistance reduces human work, addressing labor shortages and removing risk from human workers.

Healthcare and Robotics: Affordable soft robots for patient care will allow for precise and enhanced patient recovery, with hard exoskeletons utilized for rehabilitation and emergency response.

Advanced Task-Specific Robots: Low-cost robots will be available for unique tasks, which will be simpler but more effective than current robots.

Accelerating the Field

The participants discussed means for accelerating the field. They note that an increased focus on partnerships with industry will yield more efficient and viable advances. Key enablers include:

Collaboration and Community: Interdisciplinary collaboration between robotics, biology, AI/ML will need to develop to lay the foundation for ubiquitous use of robots in society. Training programs will also need to mirror these collaborations, with holistic and comprehensive learning and teaching of the next generation of researchers.

Metrics and Evaluation: standardized testing and assessment will be necessary to streamline the advancements in the field. A DARPA Robotics Challenge for Embodied Intelligence, for example, would push the frontiers of robotics by promoting integration of Embodied Intelligence within existing robots. Successful projects that displayed true mastery of perception, motion, and adaptation with low energy expenditures would be crucial to drive forth future Embodied Intelligence research and development.

Introduction

The idea that the body and brain are separated is an assumption about machine intelligence that was formed in the distant past but continues to constrain how we approach AI and robot technology development today. This report is an attempt to formulate a new view of embodied intelligence, free of prior assumptions, to promote step changes in robotics. We anticipate progress in this domain will dramatically improve agility, endurance, and damage tolerance in our automated machinery. We note that in this emerging field, the terminology used to label it is confusing: Artificial Intelligence, Physical Intelligence, Embodied Intelligence, as well as several other phrases are used synonymously and sometimes antonymously. To aid in reading this report, we make a brief attempt at clarifying some of the more important terms:

- **Artificial Intelligence (AI)** is used to describe algorithms represented, typically, in software that provides output (e.g., recommendations or actuations) based on inputs (e.g., instrumented measurements or human suggestions).
- **Physical Intelligence (PI)**, is used for robots that have AI embedded in firmware and operating locally on autonomous hardware as well as a synonym for Embodied Intelligence. For the former definition, PI tends to assume a thermodynamically closed machine (the mass and energy available to the machine come from within).
- **Embodied Intelligence (EI)** is used to describe systems that blur the lines between the machine's body and the environment in which it is interacting; ultimately, it will be an analog approach to interacting with the world. EI envisions thermodynamically open machines that can incorporate new mass and energy to recover or expand their capability.

Embodied Intelligence blurs the interface between machine and environment, and between the boundaries of internal components or modules. In external interactions with the environment, for example, EI systems allow the gravel below a robot's foot to change the shape of the foot—storing energy, adding stability, and becoming part of the machine for milliseconds prior to release. A projectile impacting a surface may partially and reversibly imbed itself into the volume, the newly formed object can make a decision whether to accept or reject the new form at the speed of sound. A chemical spray may change the macromolecular orientation of the surface, changing its optical and mechanical properties, displaying a warning to human teams and changing the trajectory of a robot away or towards the source. Internal to a machine, multiple interacting low-level robotic subsystems could synthesize more complex autonomy; this function is seen biologically in zootic animals such as the Portuguese man o'war.

The past.

EI is a broad but as yet disjointed effort to heal a millennia-old assumption in Western thought, which is that the mind and body are distinct. The late Daniel Dennett referred to this bias in Western thinking as Cartesian gravity: it is so ubiquitous that it usually escapes notice, yet it influences the action of everyone and everything. Researchers attempting to create intelligent technologies are not immune to this pull. Although a philosophical bias dating back to Descartes and Plato, such "Cartesian Dualism" influences how the research community currently approaches the creation of autonomous and safe machines. Proof of Cartesian Dualism's influence can be seen in the bicameral shape of the field itself. Researchers tend to work on purely non-physical "AI" technologies such as large language models, or physical machines such as robots or autonomous vehicles. In practice, there is little overlap between researchers in these fields.

Eastern thought tends to adopt a more holistic stance to the natural world, and to intelligent organisms by extension: no obvious distinction is made between the mechanical, chemical, and electrical supports of intelligent behavior in humans or animals. This fact alone demands a better integration between Western and Eastern researchers in the basic approach to realizing intelligent machines that use their bodies, as well as their control policies to realize useful and safe behavior.

The present.

Evidence increasingly demonstrates that non-embodied and embodied approaches to autonomous and safe machines need each other. Software LLMs are now capable of facilitating a wide range of use cases, but they are dangerous: no guarantees exist that they will not err or fabulate in a way that escapes the human user's notice, especially in applications where human safety is involved directly (i.e. seeking medical advice from a chatbot) or indirectly (AI-generated code that controls medical equipment). Conversely, autonomous robots are increasingly reliable, but only within very narrow applications and environments, such as autonomous driving on pedestrian-free roads in normal lighting and dust-free air. Living systems, in contrast, are capable of handling internal surprise (injury) and external surprise (novel stimuli) while performing a wide range of tasks such as feeding, migrating, or problem solving, in a wide range of environments. Organisms balance generality and safety by generating behavior as a function of their bodies and nervous systems at a deep level. The ways in which they achieve this are only now becoming clear. Channeling such discoveries from nature into machines could pave the way toward a future populated by complex, general-purpose and capable machines that can work safely alongside, and even inside, humans, but only if this integration is done correctly.

There is a growing interest in Physical Intelligence, or "Embodied AI", in basic research labs and applied technology companies. Usually, in such cases, no regard is given to how natural systems deeply integrate electrical, chemical, and mechanical adaptation at all spatial and temporal scales. Instead, non-physical foundation models are dropped into machine "shells" that have a few components capable of adaptation, such as motors and sensors, but are otherwise built from inert materials such as metal and plastic. Such superficial couplings could lead to the worst of both worlds rather than the best of both worlds: robots could inherit foundation models' unpredictability when confronted with novel stimuli, and robots with fixed bodies that generate narrow sensorimotor experiences could narrow the understanding of non-embodied AIs trained on that data. Thus, there is a pressing need for basic research to understand "how" best to integrate mind and body in machines.

The future.

If discoveries about how organisms realize multimodal and multiscale adaptation could be successfully incorporated into machines, a wholly new future filled with autonomous, useful, and safe technologies becomes possible. Consider a world in which every machine is morphologically and neurologically unique. Such technologies would be immune to unintentional surprise (novel environments) or intentional surprise (adversarial attacks) because no two machines would share a common Achilles heel. Imagine machines that, when cleaved in two, form two smaller versions of the original machine. Imagine machines that can devolve into swarms of independent components and reform into a physical unity on demand. A common recombinant basis for their functional synthesis would be defined. Consider autonomous machines in which there is no clear distinction between control, actuation, sensation, communication, computation, and power, rendering such machines immune to complete failure of any one sub-system. Consider autonomous vehicles that effortlessly switch between visual navigation in normal conditions, inertial navigation in dust-choked air, thermotactic navigation in smoke-filled air, chemotaxis for chemical spill escape, and biological sensing in pathogen-laced air. Consider machines that are unique combinations of living and non-living components, further combining the best of the organic and inorganic worlds and blurring the distinction between "us" (humans) and "them" (machines). Such technologies would not become an additional layer of unpredictable actors on top of an already complicated society. They would become reliable due to interdependence; they would become a reliable ecosystem among themselves, and with the natural and human worlds.

The above is not science fiction, but extrapolations from current theory and physical prototypes. This vision is what Embodied Intelligence could be, and how it could support and enrich society, if basic research thoroughly investigates the intertwined roles of physicality and cogitation in nature, and how best to translate that unity into machines.

Research Challenges

Embodied Intelligence expands the computational framework of biological and artificial autonomy beyond a centralized computer (e.g., brain or microchip) and into the architecture of the body. This embodiment of intelligence is aided by a theory of "morphological computation," where the input of environmental stress is processed by the materials and structures, reducing computational load on a central computer for a command response, or negating the need for a traditional computing architecture altogether (i.e., reflex action). The last decade has seen proliferation of these concepts, publications and citations seeing exponential growth. In parallel, new advances in material science, neural networks, soft robotics, biohybrids, additive manufacturing, parallel computing, and signal processing have made it important to revisit and refine these concepts.

With these new scientific models and technologies come new opportunities and challenges. To contextualize the challenges, we have created three technical pillars with exemplar sub-domains that give specific examples of areas in which research must be performed to realize the future we have envisioned. We briefly define what we intend by the sub-domain names in Figure 1:

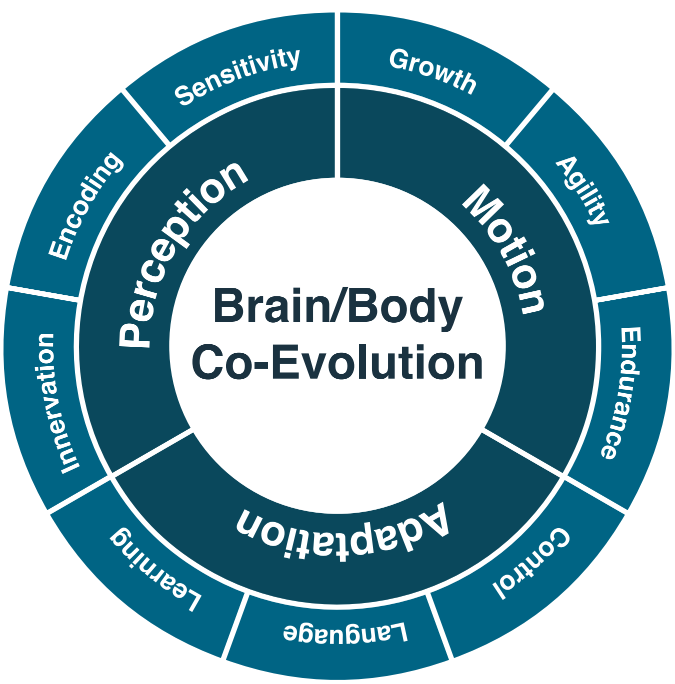


Figure 1. *Hierarchy of topics related to brain/body co-evolution*

Perception

Innervation – Distributing sensing, communication, and computation into the volume of the machine
Encoding – The process of converting information into a format that can be stored, transmitted, or processed by a robot
Sensitivity – The ability of a robot to detect and respond to subtle changes or stimuli in its environment

Motion

Growth – Adding or subtracting mass in response to environmental triggers or time
Agility– Moving quickly and nimbly, often in response to changing conditions or unexpected obstacles
Endurance – The ability of a robot to operate continuously for extended periods without needing maintenance or recharging

Adaptation

Control – The ability to command and regulate the behavior of a robot
Language – Contextualizing interactions between humans and other robots
Learning – Acquiring new knowledge or skills through experience or interaction with its environment

Pillar 1: Perception

While AI excels at handling large amounts of data, the underlying statistical process of learning is not conducive to causal and abstract reasoning. Attempts to create such capability within that framework have generally not yielded consistently accurate results, and this likely relates to the difference between how engineered (AI) and natural organisms learn. These are fundamental questions: what is learning, and to a deeper level, what is intelligence? For all natural organisms, knowledge representation is highly dependent on the sensory modes, and their processing and fusion. Thus, learning cannot be dissociated from the sensors used to acquire information. A variety of sensing modalities have emerged that interface the body with the environment (exteroception) and provide more detailed knowledge about the body's state internally (proprioception). These sensors are typically fused with traditional analog-to-digital converters for processing by standard computer architectures, but there is an opportunity within embodied intelligence to cause responses more like reflex actions using analog computation, and using a variety of fields (electrical, magnetic, mechanical, chemical, etc.). Sometimes these sensors may also be fused with computation, preprocessing information; a human eye, for example, not only measures the properties of light, but it also performs preprocessing functions akin to wavelet transforms.

Artificially, we use vision almost exclusively for navigation. Nature, however, is not so reliant on vision. There are many examples of complex organisms that do not use vision (Figure 2); however, there are no examples of animals we are aware of that do not use touch. A blind mole rat navigates intricate tunnel systems, a Kaua'i cave spider actively hunts by feeling its prey's vibration signature, and blind Mexican Tetras can school by feeling the complex hydrodynamic interactions of the group. This huge discrepancy in perception between the artificial and natural world is an example of how EI will leverage unused environmental cues for improved maneuverability and efficiency. These natural examples of navigation, hunting, and schooling by feel could create the basis functions for the constitution of independent low-level robotic systems into larger, high-level physical agents.

Kaua'i Cave Wolf Spider *Lesser Blind Mole-Rat* *Mexican Tetra (Blind Cave Fish)* *School of Mexican Tetra*

Figure 2. *Examples of complex organisms that do not use vision. [Source: Wikipedia, 2024]*

Within this pillar of EI, we have identified non-exhaustive grand challenges for research.

Sensitivity is certainly one of these challenges, typically measured in Signal to Noise Ratio with units of decibels. Localizing signals of interest and amplifying them above those not important at the time is a dynamic process and computationally challenging; performing it at the embodied level would increase agility and energy efficiency.

Innervation of machine volumes to assess the environment and internal state of the machine is a manufacturing challenge. As the most obvious way to increase perceptive capabilities is with more sensors, simple wiring of them will become intractable without new materials and manufacturing methods. Autonomous Material Systems have the potential to localize all sensing and actuation.

Encoding data for high information throughput (e.g., bits/s; bits/s/W; bits/s/cm3; bits/s/kg) is another challenge. Leveraging optical modes, biological spiking, etc. would be an important way to provide massive data rates for information fusion without exploding the practical wiring and assembly requirements to sensing hardware.

Pillar 2: Motion

Intelligence is a developmental process: (i) within an organism's lifetime and (ii) throughout a species' evolution. In the first example, the "curse of dimensionality" is somehow solved by nature, whereby complex organisms learn to control their large number of degrees of freedom (DOFs) using large numbers of sensory inputs. An interesting hypothesis as to how nature accomplishes this task is that through the developmental process, DOFs are initially frozen and released, or added with growth. Furthermore, the organism is not passive; it can actively probe and modify the environment, using various actuators and tools. Learning and, by association, intelligence, are a function of available modes of sensing and action. For example, human babies learn their environment sequentially, according to their ability to move and manipulate. This creates a challenging co-design problem for robotics, for which mechanical operation, sensors, neural processors and training/learning strategies must then be designed concurrently, and these concurrent designs derivative of prior instantiations. The components will grow and rearrange, grow and shrink, over time.

Examples of how research in motion can reduce the disparity between our present artifices and nature via EI are shown in Figure 3. Figure 3A shows how we presently use our technology to dominate the environment (ailerons to manage turbulence) whereas birds leverage turbulence to save energy. Figure 3B shows how we engineer our landscape to be flat to handle tires, but a frog will store and release elastic energy in the environment (e.g., leaves) to save energy and traverse complex terrain.

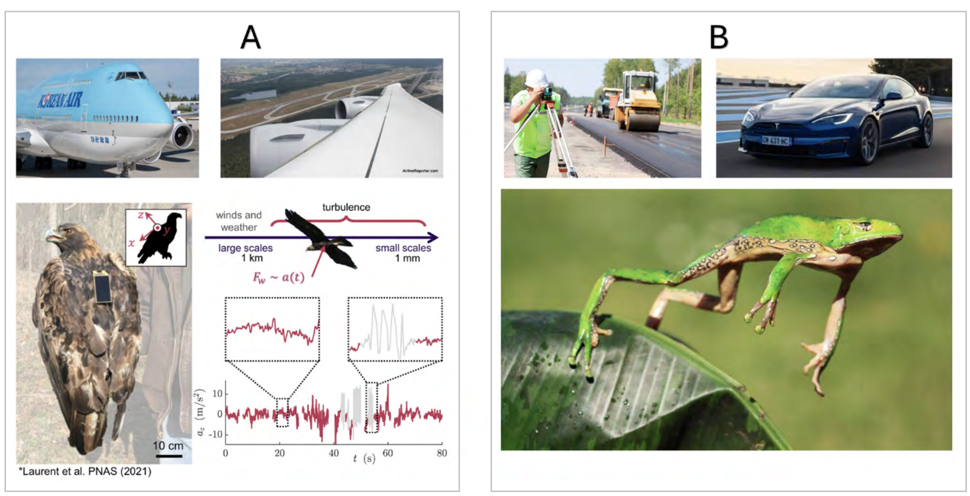


Figure 3. *Examples of research in motion to improve the relation between artificial and natural sources. A: Examples of how to use our technology or to dominate the aerial environment in contrast to birds. B: Examples of how we engineer our landscape to be flat to handle tires in contrast to a frog which stores and releases elastic energy in the environment. [Sources: Laurent et al. 2021, Kirstines.Dk. (2016, June 14)]*

Agility is not only a hard-to-define characteristic; it is a feat that is difficult to achieve artificially. Increasing the acceleration and deceleration of objects with precision trajectories requires high power actuators and high number of DOFs, while being lightweight. Supplying power and data to these actuators is a difficult manufacturing challenge from the top down. Nature's bottom-up approach of self-assembly allows for far more architectural complexity; e.g., the co-existence of neurons for sensing and information processing along with muscle for actuation in every mm3 of an octopus's tentacle.

Endurance while being agile is a paradox ripe for improve with EI. Animals are far more capable than our machinery of being highly responsive to the environment while being able to operate for days and weeks without additional fuel consumption. The challenges here revolve around multifunctional use of energy storage and transduction, high energy density fuels, storage and release of elastic energy, and center of mass adjustments during locomotion (Aubin et al., 2022).

Growth of the machine's body to allow for learning, circumventing obstacles, or manipulating objects is a challenge. The challenge is to build a machine that can change dimensions, add or remove body segments, freeze or add DOFs, or even literally grow are material science and manufacturing challenges.

Pillar 3: Adaptation

In nature, this co-design problem is solved through evolutionary processes. Indeed, hardware also evolves over time to account for inefficiencies in design or changing end-user needs. Using sim2real (the process of transferring skills learned in simulation to real-world applications), evolutionary algorithms, and other advanced computation-based techniques, we can better design autonomous systems that are more adaptable to changing environments, perhaps an organism's best indicator of intelligence. This ability to tune the energy landscape of the autonomous system, and impedance match it to environmental inputs and outputs, is at the core of embodied intelligence. Indeed, another true measure of intelligence beyond mammals and bird examples would not be the capability of expending huge amounts of energy, but managing it instead. By taking advantage of materials science, additive manufacturing, or building new approaches, this artificial species' ability to tune the I/O and energy landscape can be evolved more rapidly.

Adaptation, artificially, is primarily achieved from centralized computation (Figure 4). However, biology relies far more on lower order feedback loops and structural organization. From examples like the peripheral nervous system, to colonial organisms, to even collective work from swarms for simpler organisms. The Portuguese man o'war, an example of a colonial organism (i.e., zooid) comprised of different species, have separate chemical and mechanical functions (e.g., pneumatophores that inflate a sail via synthesis of carbon monoxide) that fuse to appear as a single organism. EI stands poised to leverage these alternative strategies to environmental adaptation to improve maneuverability, agility, and efficiency in achieving tasks.

Learning. Many challenges remain when considering how best to enable embodied intelligent machines to learn. Traditionally, learning has implied neural plasticity. But, with the construction of robots from increasingly exotic and pliable materials, the bodies of future robots will also likely "learn." As an example, Hebbian learning has long served as a cornerstone for neural plasticity in AI: synapses strengthen when their pre- and post-synaptic neurons fire together and weaken when they do not. There is a morphological analogue of this process in nature, which is known as Wolff's law: bone strengthens under specific load signatures and weakens under other load conditions. To date, however, there are few examples of robots built from materials capable of dynamic stiffening and softening. Recently, however, there is an example of a 2D network of motors and flexible beams capable of tuning itself for learning, a true mechanical neural network (Lee et al., 2022). When examples like this use materials that can be processed more intricately, the bodies as well as the brains of future robots may be able to learn how best to detect co-occurring features of external challenges (or internal challenges, such as injury), and prepare themselves, morphologically and neurally, to grapple with those challenges when the re-occur. How EI systems should best transform their bodies in general, and how such change may complement more traditional neural learning, has yet to be determined.

Language. Embodied intelligence stands poised to rectify many of the fundamental problems currently plaguing non-embodied AI, exemplified by the current state of the art in Large Language Models (LLMs). For example, all LLMs suffer from hallucinations: the generation of non-factual verbal statements. If future embodied intelligences are required to demonstrate, physically, their verbal claims, a self-correcting mechanism for confabulation becomes possible. Another route to embodied brakes on verbal

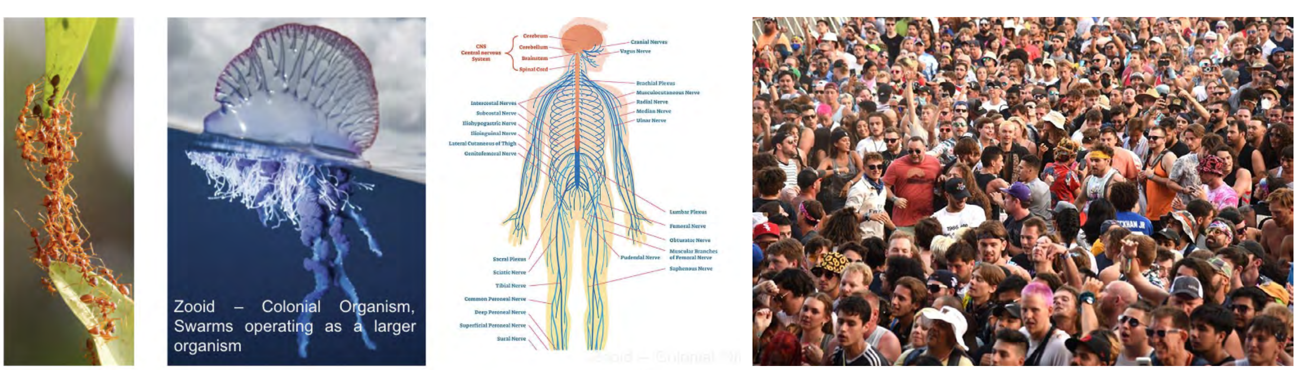


Figure 4. *Examples of adaptation in biology, in comparison to artificial systems. [Sources: Fathtabar et al., 2023 & dOliveira, 2021]*

confabulation could be for embodied intelligences to self-narrate their actions. If a loss function ties those verbal descriptions to those actions, and an LLM is trained on these narrations, there is less likelihood for confabulation as all verbal training data would be factual and physically plausible. However, whether these or other ways for embodiment to constrain LLM pathologies will be effective remains an open challenge.

Control of the EI systems could initially be more difficult than those with a discrete boundary on their bodies and fewer DOFs. Machines with more DOFs than necessary to perform a task are considered kinematically redundant. While offering flexibility, the kinematic redundancy also introduces challenges in choosing the most efficient or smoothest motion. Further, more joints translate to more variables to control. Instructing the robot on how to move each joint in a coordinated way to achieve a specific goal becomes intricate and requires sophisticated programming techniques. In EI, however, there is an opportunity to selectively remove DOFs or add more.

A Tapestry of Challenges

Perception, Motion, and Adaptation, while we list them as separate pillars, are really an interdependent tapestry that requires concurrent research efforts. One important example of a common thread between them is the challenge of information density. Too little data interpreted from the environment and the system will not have enough information to be considered useful, and too much data and the machine will not be able to interpret the environment to process a state and respond in time to be agile. Perception needs to amplify or filter data, Adaptation needs to understand the resulting information, and Motion needs to adjust for it. Handling the data throughput requires a basis of communication and processing information between the pillars.

It is often misconstrued that organisms are optimal for their environment; however, these ostensibly optimal solutions are usually examples of exaptation. The adaptation of a prior trait for a new function is rarely optimal, but "good enough" for survival. A non-exhaustive set of (good enough) solutions to this problem lies in organismal biology; where animals use at least three approaches:

1. **Focusing on Relevant Stimuli** using (i) Sensory Organs: Each sense organ (eyes, ears, nose) is specialized to detect a specific type of information. This reduces the overall data intake by focusing on relevant stimuli. For example, an owl's highly sensitive ears allow it to pinpoint prey location in the dark, filtering out irrelevant visual cues. (ii) Behavioral Responses: Organisms learn to associate specific stimuli with threats, food, or mates. This approach allows them to focus attention on these important cues and ignore the rest. For instance, a bee recognizes the scent of flowers and focuses on following it, filtering out other odors in the environment.
2. **Responding Based on Needs** via (i) Internal State: An organism's internal state (hunger, thirst, fear) influences how it interprets sensory information. A hungry animal might prioritize food-related cues, filtering out others. (ii) Limited Attention: Brains dedicate processing power to the most important tasks at hand. This approach helps filter out less critical information during complex situations. For example, a gazelle being chased by a cheetah will focus on escape routes, filtering out background details like potential food sources.
3. **Leveraging Past Experiences** by (i) Learning and Memory: Organisms learn from past experiences to identify patterns and predict future events. This allows them to filter out unexpected or irrelevant information. For example, a bird that has been stung by a brightly colored caterpillar will avoid similarly colored ones in the future. (ii) Innate Responses: Many organisms have pre-programmed responses to specific stimuli, filtering out the need to analyze complex information every time. This phenomenon is often seen in escape reflexes or predator recognition in young animals. (iii) Remodeling and Growth: one of many examples include bone's strengthening of areas where stress is common–getting stronger based on use.

By using these strategies, organisms can effectively survive in the real world. They focus on the information crucial for survival and reproduction, filtering out the vast amount of irrelevant data.

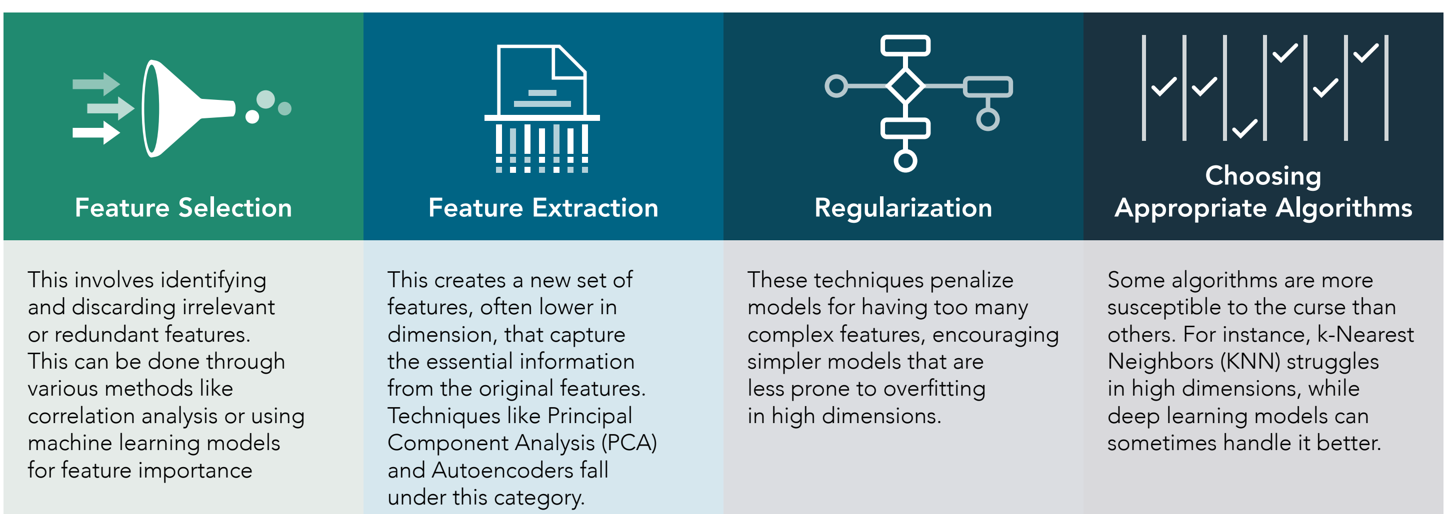


Figure 5. *Four stages of feature integration in artificial systems.*

Further Challenges

Our workshop on the Future Directions of Embodied Intelligence identified these key challenges and opportunities related to the synthesis of these pillars. For example, the challenge described in Adaptation describes the problem of controlling high DOFs systems; however, a potential solution of growth is described in the Motion pillar. The entangled nature of challenges and solutions is a problem due to the transdisciplinary knowledge requirements. The difficulty in solving this challenge, however, is what motivates the collaboration of research disciplines to solve them. Correspondingly, a huge challenge is to reduce the barriers to knowledge transfer between groups of researchers in EI. Therefore, the workshop participants felt that clear definitions and taxonomy are crucial. Interestingly, LLM's may actually play a crucial role in easing collaboration in this respect.

The participants also highlighted the need for metrics to measure progress and standards to ensure consistency. Physically, the discussion on that topic focused on fundamental limits of information rate and energetic limitations of materials. The workshop also identified many successful examples of EI; however, their reliability issues and the difficulty to manufacture are limiting their utility. The importance of Testing - Evaluation - Validation (TEV) was also made clear throughout discussions.

The synthesis of these pillars into a cohesive and global EI program requires transdisciplinary researchers. Materials science, manufacturing, computer science, mechanical engineering, and EI design need to be tightly integrated. Researchers need to explore new materials suitable for EI and determine if existing materials can be sufficiently engineered to provide the necessary physical substrate for EI. Further, the workshop emphasized fostering a diverse research community and the importance of advancements in energy storage technologies for powering EI systems.

Research Opportunities

In the next 20 years, robotics will use EI to better leverage hardware examples from the animal world, interface with the world and within themselves in increasingly analog fashion, as well as adapt artificial computational approaches to command machines. As new technologies such as Additive Manufacturing (AM), General Pretrained Transformers (GPTs), etc. permit improvements-in and fusion-of Perception, Motion, and Adaptation, the body and brain of autonomous intelligent machines will become more tightly coupled, blurring the distinction of the two. As EI becomes a ubiquitous and transformative force across various domains, it will reshape daily life, healthcare, manufacturing, and more.

Overview

EI improves the compromise between agility (e.g., acceleration and turn radius) and endurance (i.e., how long it can operate for) in robots. Figure 4 outlined the organismal examples we believe best exemplify the potential of EI. Figure 6, in turn, describes an exciting potential approach to achieving similar capabilities using the coordination of low level, EI enabled, robot modules. Following this high level roadmap, we expect that, in the near term, EI will provide analog sensing, actuation, and computation layers for improved compromises between agility and efficiency on traditional robot bodies with some examples of artificial "organ systems" within these robots. In the next 10 years, we expect a set of functional modules (akin to organs) to emerge with a basis function that defines their coordination for particular tasks. In the longer term (20 years), we expect that biohybrid modules (including features of muscle, neuron, mycelium, plant cell, etc.) will coordinate into more complex, synthetic animals, that coordinate to perform more generalized jobs (e.g., health care, agriculture, disaster relief).

Research Trajectory

Near-Term (5 Years)

In the immediate future, EI will augment existing robot architectures. These robots, equipped with simple control loops (informed by analog sensing and processing layers) and commanding actuators (e.g., continuum, compliant, standard) will be capable of reduced energy expenditure during mobility tasks or more dextrous performance in assembly tasks, for example. These robots may feature, as an example, endoskeletal structures with soft actuators and skins, mediating reconfigurability based on task requirements. The use of compliant manipulators and soft skins will improve their agility and endurance compared to non-EI systems.

5-year goals

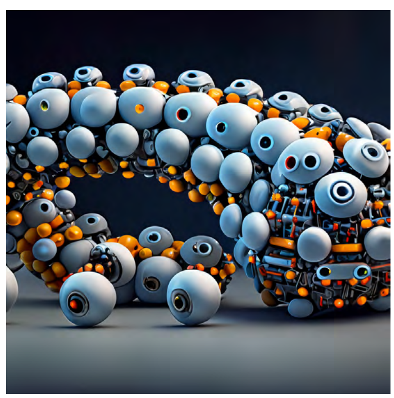
- Develop consensus metrics for energy consumption during state transitions (e.g., trotting to cantering), as well as agility (e.g., acceleration and turn radius).
- Establish foundational control strategies using logical basis functions for coordination of tasks.

Mid-Term (10 Years)

Over the next decade, EI is expected to leverage prior results in analog sense-act-respond functions to produce a set of low-level robots that demonstrate these principles with specific functions, akin to organs or "polyps" seen in biology (Figure 4). The results may be akin to reconfigurable systems of modules mediated by analog computational layers that can configure for (as an example) external dexterity or (another example) internal operational efficiency for existing tasks. Importantly, the development of basis functions for the set of modules will play a critical role in this phase, allowing robots to be dynamically assembled and disassembled in response to environmental or task changes.

Near term (5 years)

There is some amount of embodied intelligence layered on traditional physical agents.



Mid-term (10 years)

Functional modules are developed with a set of associated basis functions that describe their potential coordination.

Long-term (20 years)

Biohybrid modules are able to be configured in order to accomplish generalized job tasks.

Figure 6. *Visual representations of artificial systems at 5, 10, and 20 years years that utilize embodied intelligence. Initially, robots will have layers of analog sensing and processing layers that inform simple control loops and a mixture of electric motors and continuum compliant mechanisms. After decades of research, these layers will become modules that can assemble into more and more complex volumes using algorithms informed by basis functions that coordinate module linkages.*

10-year goals

- Enumeration of agility and endurance requirements for general purpose robotics (these numbers should be arrived at beyond just EI community)
- Define a set of low-level EI modules that address the requirements for agility and endurance
- Algorithms developed that provide the basis for coordination between these modules (digital and analog solutions)

Long-Term (20 Years)

In the long term, EI researchers will understand how to best leverage living and synthetic approaches to build low-level EI modules. The basis functions to coordinate the low-level biohybrid robots to autonomously assemble and disassemble themselves into more complex, high-level robots will be known. These high-level robots are more sophisticated, capable of performing complex tasks and adapting to changing environments. This synthesis will enable the development of general-purpose robots capable of growth, reconfiguration, and continuous adaptation. Logical basis functions (e.g., autonomous material computation) (Yamada et al., 2022) will be fully integrated into the robot's architecture, enabling seamless coordination across multiple robots in various environments. In addition to the coordination of low-level robots, we also anticipate autonomous coordination between multiple (and different) high-level robots.

20-year goals

- Develop autonomous material systems (AMS) that allow for independent sensing and dynamic reconfiguration.
- Implement neuron-based computing for accelerated adaptation and coordination of large robot assemblies.
- Advance multiplexed high-DOF actuator arrays to support sophisticated motion and structural integrity during assembly and disassembly.
- Robust approaches to maintaining life in real world environments, as well as mediating their interface with artifices.
- Communication protocols in addition to radio frequency and visual spectrum signaling, such as acoustic and chemical.

Opportunities to Achieve these Goals

Materials and Manufacturing

Advancements in voxel-based manufacturing, such as Volumetric Additive Manufacturing, (Kelly et al, 2019) will enable the creation of multifunctional materials with integrated sensing, actuation, and planning capabilities. Robots will be designed with heterogeneous materials that eliminate the need for distinct subsystems, streamlining production and enhancing functionality. Sustainable design principles will lead to robots that grow, reconfigure, and strengthen over time, with minimal environmental impact. These robots will naturally degrade at the end of their life cycle, contributing to a circular economy. The synthesis of *Autonomous Material Systems* (AMS) (Howard et al, 2019) will fuse sensing-computing-responding to formable elements that allow the construction of EI machinery. AMS's were a prominent discussion in the Motion, Perception, and Adaptation pillars–forming a basis of material science research effort where sensing, actuation, and computation become part of a single material element. An early example of an AMS was given as a Belousov–Zhabotinsky redox reaction inside a thermally swellable gel to maintain a reaction clock speed independent of external temperature conditions (Yamada et al., 2022).

Specific Example of Autonomous Materials

Autonomous material systems are a class of composites that can independently perform tasks by sensing, processing, and responding to environmental stimuli without external intervention. This capability could accelerate the development of robots with embodied intelligence, where intelligence is not just a function of computational processing but is distributed throughout the robot's body, integrated into its physical structure.

Embodied intelligence in robotics refers to the concept that a robot's intelligence emerges from the interaction between its body and the environment. Autonomous materials play a critical role in this by enabling the robot to react and adapt at the material level. For example, a robot could be constructed using materials that change shape or stiffness in response to temperature, light, or mechanical stress. These changes could alter the robot's behavior in real-time, enabling it to navigate complex terrains, avoid obstacles, or even repair itself (an aspect of improved endurance).

Robots built using autonomous materials can exhibit a high degree of adaptability and responsiveness to their surroundings. These materials can be designed to possess different levels of autonomy, from simple feedforward actions to complex decision-making processes. By embedding intelligence directly into the material (Yamada et al., 2022), robots could operate more efficiently in dynamic environments, reducing the need for centralized control systems.

As a guideline for EI development using AMS, it is essential to consider the structural complexity and autonomy of the materials used. The framework categorizes materials based on their structural complexity (N) and autonomy (A). For instance, a robot made of N=3 materials (such as composite materials with engineered microstructures) and A=3 autonomy (such as smart materials that can sense and actuate) would have a moderate level of embodied intelligence, suitable for tasks like environmental monitoring or exploration in hazardous conditions.

By advancing the integration of autonomous materials into robotic systems, it could be possible to build (maybe grow) robots that are more resilient, efficient, and capable of performing tasks in unpredictable and unstructured environments. The evolution of these systems could lead to robots that are not only more independent but also more harmonious in their interaction with the world, much like biological organisms.

The development of AMS for embodied intelligence in robotics is still in its infancy. However, as our understanding of these materials deepens, and as manufacturing techniques improve, we can expect to see a new generation of robots that are smarter, more adaptable, and capable of undertaking tasks that were previously unimaginable. The intersection of materials science, robotics, and artificial intelligence will be the driving force behind this innovation, leading to a future where robots with embodied intelligence become a vital part of our technological landscape.

Adaptation and Computation

Future EI systems will feature hyper-embedded computation that integrates seamlessly with physical substrates, enabling more efficient and adaptive behaviors. Moving beyond digital, a return to analog and biotic computation will enhance response speeds and/or reduce power consumption significantly. Robots will develop unified perception and motion capabilities, allowing them to adapt actively and autonomously to diverse environments. Decentralized adaptation mechanisms could aid in cohesive sensing and actuation, making robots more responsive and versatile. As GPTs become more sophisticated and allow for better Large Language Models (LLMs), as well as other interactions modes (perhaps a Large Touch Model or Large Smell Model), the communication between Perception, Adaptation, and Motion domains will become more efficient and capable. Independent robot modules can take advantage of EI layers representing GPTs physically, could operate as swarms, high level assemblies, and swarms of high-level assemblies – their fusion guided by a set of basis functions defined as these modules converge on a set of low-level functions (akin to organ systems).

Specific Example of Basis Functions for the Coordination of Organ Modules

Embodied Intelligence (EI) presents a promising avenue for advancing the coordination of low-level robot modules with high-level robotic interfaces in complex environments. Before proposing a basis function that could enhance such coordination, it's essential to first consider the inherent complexities involved in the process of robotic self-assembly.

One of the primary challenges is ensuring **module compatibility**. Each module must have interfaces that are not only compatible for attachment but also capable of facilitating the seamless transfer of power and data. Furthermore, **communication** between modules is critical. Each module needs a reliable method to communicate its identity, current status, and desired configuration with other modules to enable coordinated assembly.

Another critical consideration is the availability of an **energy source**. Without a steady power supply, modules cannot activate or move, rendering the assembly process impossible. Additionally, **environmental factors** such as temperature, gravity, and other external conditions can significantly influence the assembly process, adding another layer of complexity.

Given these challenges, a potential solution lies in developing a multi-dimensional potential field as a basis function. This basis function would integrate several key components:

- **Geometric Compatibility:** This component would account for the shape and size of each module, as well as the configuration of their attachment points, ensuring that modules can physically connect with one another.
- **Functional Compatibility:** This would represent the capabilities of each module, such as sensing, actuation, or computation, allowing for the creation of functionally complementary assemblies.
- **Communication Protocol:** This component would define the method and format of data exchange between modules, ensuring that they can effectively communicate and coordinate their actions.
- **Energy State:** This would monitor the energy level of each module, ensuring that modules with adequate energy are prioritized in the assembly process.
- **Environmental Factors:** This component would include parameters for external conditions like temperature and gravity, allowing the system to adapt to varying environments.

The operation of the potential field would hinge on several interaction principles. Modules with compatible geometric and functional interfaces would experience an **attractive force**, drawing them together. Conversely, modules with incompatible interfaces or overlapping volumes would be subject to a **repulsive force**, preventing erroneous connections.

Communication between modules would allow them to exchange vital information regarding their status and desired configuration, directly influencing the dynamics of the potential field. Moreover, modules would seek to optimize their positions in the assembly to **maximize energy efficiency**, potentially extending the operational lifespan of the robotic system.

In response to changing environmental conditions, the modules would exhibit **environmental adaptation**, adjusting their behavior to ensure successful assembly despite external challenges.

Additional considerations include the necessity for a **dynamic potential field**. The field must be capable of evolving in real-time to accommodate changes in the environment or the configuration of the modules. Furthermore, an **error correction mechanism** would be essential to handle issues such as misaligned modules, ensuring that the assembly process can recover from mistakes.

For more complex robotic systems, **hierarchical assembly** might be required. In such cases, modules would first form subassemblies before being integrated into the final system. A higher-level **control system** could oversee this process, providing overall guidance and coordination to ensure the successful completion of the assembly.

However, several challenges remain. **Computational complexity** could become a significant issue, as calculating and updating the potential field for a large number of modules might be resource intensive. There is also the risk of the assembly process becoming trapped in **local minima**, resulting in suboptimal configurations. Additionally, **physical constraints** such as friction and elasticity could interfere with the intended assembly process.

Inspiration for overcoming these challenges could be drawn from natural systems of self-assembly, such as the formation of crystals or the behavior of biological cells. By studying these systems, valuable insights might be gained into the development of robust basis functions and optimization strategies.

In summary, by carefully addressing these considerations, it is possible to develop a sophisticated basis function that enables the self-assembly of robots with increasing complexity. Leveraging Embodied Intelligence (EI) in this context could allow robots to achieve greater autonomy and adaptability, significantly enhancing their ability to interact with and respond to dynamic environments. This focused research trajectory could lead to groundbreaking advancements in the field of robotics, particularly in the assembly and disassembly of modular robotic systems.

By focusing on the use of Embodied Intelligence to coordinate the assembly and disassembly of low-level robots through logical basis functions, this research trajectory aims to advance the field of robotics significantly. Achieving these goals will require continued innovation in materials science, AI, and manufacturing techniques, as well as a strong commitment to interdisciplinary collaboration and policy development. The successful integration of EI into robotic systems will pave the way for more agile, adaptable, and autonomous machines capable of meeting the demands of a rapidly changing world.

Application Focus Areas

Daily Life and Labor Replacement

EI will be deeply embedded in everyday appliances, dramatically reducing the time and effort required for routine tasks. For instance, robotic cleaners will save hours each week, while wearable exosuits will enhance human physical capabilities. Biohybrid robots, mimicking the responsiveness and efficiency of animals, will assist with various tasks. These advancements will address labor shortages in developed regions by automating tasks currently performed by humans due to cost advantages or need for safe decision-making and motion adaptability, especially in dangerous conditions.

Healthcare and Robotics

The healthcare sector will see a significant influx of soft robots designed for patient transfer and rehabilitation. These robots will be more affordable and accessible, driven by advances in soft robotics and biohybrid designs. This will alleviate the strain on healthcare systems and improve patient care. Soft, adaptable robots will offer gentle and precise assistance, enhancing recovery and comfort for patients, while EI-enabled robotic prosthetics or exo-skeletons will greatly augment the quality of life. They can also allow or facilitate emergency responses in hazardous situations.

Advanced Task-Specific Robots

Innovative robots like personal assistants capable of retrieving objects and self-cleaning will become commonplace. These ultra-low-cost robots will handle specific tasks efficiently and adapt to disturbances, offering practical solutions for everyday problems. This new generation of robots will be simpler yet more effective, reflecting a shift towards task-specific designs that prioritize functionality and cost-efficiency.

How to Accelerate the Field

Overcoming time-scale challenges in additive manufacturing and leveraging new 3D printing technologies for example, will be vital. Enhanced design tools will allow early specification of goals and intents, streamlining the manufacturing process. *Competitions akin to DARPA challenges will foster innovation and interdisciplinary cooperation*, while funding for basic research and collaborative projects will drive continuous progress. Industry partnerships will provide access to cutting-edge technologies, and incentives will encourage the establishment of robotics departments and tenure opportunities for young researchers.

Collaboration and Community

Within two decades, EI will transform from a niche research area to a foundational technology embedded in all aspects of life. The integration of advanced computation, adaptive materials, and interdisciplinary collaboration will lead to smarter, more efficient, and more versatile robots. These advancements will not only improve daily life and healthcare but also drive new industries and economic growth, marking a new era of human-robot interaction and collaboration and laying the foundation for an ubiquitous robotic society.

Interdisciplinary collaboration will be crucial, with AI/ML researchers working alongside soft robotics designers, engineers and material scientists to achieve specific goals, such as building smart soft-legged robots. Training programs will evolve to prepare the next generation of EI researchers, emphasizing the integration of robots into larger systems. Common platforms for materials synthesis and machine learning will facilitate barrier-free collaboration, driving innovation and efficiency.

Metrics and Evaluation

A significant challenge in advancing EI is the lack of standardized metrics for evaluating progress in assembly and disassembly tasks. To address this, the establishment of an EI leaderboard (perhaps an online tool with oversight that tracks metrics in important categories, such as agility, endurance, and other critical attributes. Creating compelling challenges, similar to the DARPA Driverless Car challenge, will focus research efforts and inspire innovation in the field.

The DARPA Robotics Challenge for Embodied Intelligence would push the frontiers of robotics by focusing on the deep integration of Embodied Intelligence with existing robots (e.g., deformable, sensing skins overlaid onto a quadruped like Spot). This competition would require participants to design robots that can seamlessly interact with dynamic, unstructured environments, emphasizing the synergy between a robot's body and its decision-making processes.

In this challenge, robots would be tasked with completing complex, real-world scenarios such as disaster response or search and rescue missions. These tasks would demand not only physical robustness but also the ability to process sensory information in real-time, make autonomous decisions, and adapt to unforeseen circumstances. The essence of embodied intelligence lies in how the robot's physical form and sensory inputs are tightly interwoven with its cognitive functions, enabling more natural, fluid interactions with the environment.

For example, the competition would stress autonomy, with robots expected to navigate difficult terrains, manipulate objects, and interact with humans in cooperative tasks. Success would depend on the robot's ability to integrate learning and adaptability, improving performance as it encounters new challenges. Resilience would also be key, as robots must demonstrate the ability to operate under adverse conditions, recover from disruptions, and self-diagnose issues. Ultimately, the most successful robots would perform agile tasks at the lowest energy expenditures. Through this challenge, DARPA would drive advancements in embodied intelligence, encouraging the development of robots that are not only mechanically capable but also exhibit the adaptive, responsive behaviors necessary for real-world applications.

Conclusion

The workshop identified several key challenges and gaps that need to be addressed to make EI a critical component in the development of intelligent autonomous machines, including performance metrics and benchmarks. Some of these benchmarks include data rates for useful information processing, power, efficiency, and controllable degrees of freedom (DOFs). Even in these simple benchmarks, there are complex tradeoffs. For example, software processing benefits from reduced DOFs while additional DOFs from more complex hardware provides more maneuverability. Additionally, standards for robot components and their interconnectivity need to be developed alongside long-term reliability testing protocols (i.e. T-E-V) to ensure these systems can perform consistently over extended periods.

Technological and material advances play a critical role in the development of EI. Identifying and developing new materials suitable for EI, understanding their fundamental chemistry and physics, and leveraging advanced manufacturing techniques like volumetric printing, biohybrids, and AMS. Additionally, ensuring the reliability of EI systems through prolonged testing and real-world deployments is crucial. Developing systems that can continuously learn and adapt through interaction with their environment is equally important; transferring learning from one agent to the next is also a critical component to these systems.

Energy challenges, particularly regarding capacity and efficiency, must be addressed. Treating EI as a dynamic, adaptive process rather than a static state and designing systems that can adapt over time are key considerations. Integrating materials development with the design and manufacturing of EI systems is essential, requiring innovative paradigms to support dynamic and adaptable embodiments.

Balancing algorithmic and hardware integration is another significant challenge. It is important to optimize the roles of physical and digital algorithms and hardware to achieve the best EI results. Exploring neuromorphic computing and low-energy embedded intelligence can offer new solutions. Using AI to enhance the design and functionality of EI systems will also be beneficial.

Community cohesion and interdisciplinary collaboration are other significant areas requiring attention. There is a need to enhance cooperation across AI, materials science, manufacturing, and robotics communities, addressing divides between different research sectors and encouraging interdisciplinary discussions at conferences and other forums. Improving communication and idea-sharing within the community is vital for progress.

In summary, building a cohesive community, innovating in material science and energy solutions, implementing long-term and adaptive testing, and maintaining a strong interdisciplinary approach are all necessary steps to address the current challenges and advance the field of Embodied Intelligence. This workshop was a first step in building that community with researchers from US and South Korea mapping the future.

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Appendix I – Workshop Attendees

Workshop Co-chairs

Joshua Bongard, *University of Vermont*
Kyujin Cho, *Seoul National University*
Yong-Lae Park, *Seoul National University*
Robert Shepherd, *Cornell University*

Workshop Participants

Cameron Aubin, *University of Michigan*
Joonbum Bae, *Ulsan National Institute of Science and Technology*
Josh Bongard, *University of Vermont*
Mark Campbell, *Cornell University*
Kyujin Cho, *Seoul National University*
David Hu, *Georgia Tech University*
Ayoung Kim, *Seoul National University*
Daekyum Kim, *Korea University*
Hyoun Jin Kim, *Seoul National University*
Daniel E. Koditschek, *University of Pennsylvania*
Jesung Koh, *Ajou University*
Seung Hwan Koh, *Seoul National University*
Ki-Uk Kyung, *The Korea Advanced Institute of Science and Technology*
Jeffrey Lipton, *Northeastern University*
Rob MacCurdy, *Colorado University*
Lakshminarayanan Mahadevan, *Harvard University*
Frank Park, *Seoul National University*
Yong-Lae Park, *Seoul National University*
Daniela Rus, *Massachusetts Institute of Technology*
Jee-Hwan Ryu, *The Korea Advanced Institute of Science and Technology*
Robert Shepherd, *Cornell University*
Dongjun Shin, *Yonsei University*
Jeong-Yun Sun, *Seoul National University*
Michael Tolley, *University of California, San Diego*
Ryan Truby, *Northwestern University*
TJ Wallin, *Massachusetts Institute of Technology*
Victoria Webster-Wood, *Carnegie Melon University*
Jinkyu Yang, *Seoul National University*

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Dokeun Kang, *Agency for Defense Development*
Dai Hyun Kim, *OUSD(R&E)/OASD(CT)/TAIA*
Kiho Kwak, *Agency for Defense Development*
Wook-hyang Kwon, *Ministry of Trade, Industry and Energy*
Jihong Min, *Agency for Defense Development*
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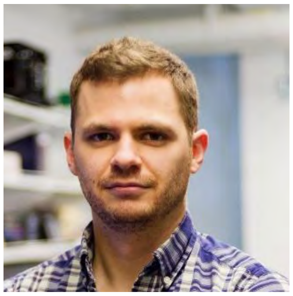
Kate Klemic, *Virginia Tech Applied Research Corporation*
Jae Kwak, *Virginia Tech Applied Research Corporation*
Sean Lemkey, *Virginia Tech Applied Research Corporation*
Sithira Ratnayaka, *Virginia Tech Applied Research Corporation*

Participant Short Biography



Cameron Aubin

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Cameron Aubin is an assistant professor in the Robotics Department at the University of Michigan. He previously conducted his graduated work at Cornell University, where he received his Ph.D. in Mechanical Engineering in 2023. Cameron's work centers on improving the endurance, adaptability, and autonomy of robots through the integration of multifunctional, biologically-inspired energy systems. His interests also include soft robotics, microrobotics, and advanced materials and manufacturing. He has published in a number of reputable journals, including Nature and Science, and his research has been featured by several popular media outlets, including CNN, PBS, BBC, Wired, New Scientist, ARS Technica, and more.

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Joonbum Bae is Professor of Department of Mechanical Engineering and the Director of Bio-Robotics and Control (BiRC) Lab of Ulsan National Institute of Science and Technology (UNIST). He earned his B.S. degree in mechanical and aerospace engineering from Seoul National University, followed by M.S. and Ph.D. degrees in mechanical engineering, along with an M.A. in statistics, from the University of California, Berkeley. His current research interests include modeling, design, and control of human-robot interaction systems, soft robotics, and biologically inspired robot systems. Additionally, he is a CEO and founder of a startup Feel the Same, Inc., which develops wearable soft sensor systems. Recognized for his academic achievements, he was appointed as a Rising-Star Distinguished Professor of UNIST. He has received prestigious awards including the Samsung Scholarship for his Ph.D. studies, the Young Researcher Award from the Korea Robotics Society, the Korean Government Minister Awards from the Ministry of Public Safety and Security and the Ministry of Science, ICT and Future Planning, Best Teaching Award from UNIST, and the Grand Prize from the UNIST Outstanding Faculty Awards. He led the Team UNIST at $10M ANA Avatar XPRIZE, which is a global avatar robot competition, achieving a sixth place in the finals.

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Josh Bongard is the Veinott Professor of Computer Science at the University of Vermont and director of the Morphology, Evolution & Cognition Laboratory. His work involves automated design and manufacture of soft-, evolved-, and crowdsourced robots, as well as AI-designed organisms. A PECASE, TR35, and Cozzarelli Prize recipient, he has received funding from NSF, NASA, DARPA, ARO and the Sloan Foundation. He is the co-author of the book How The Body Shapes the Way We Think, the instructor of a reddit-based evolutionary robotics MOOC, and director of the robotics outreach program Twitch Plays Robotics.

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Mark Campbell is the John A. Mellowes Professor of Mechanical & Aerospace Engineering at Cornell University. He received his B.S. in Mechanical Engineering from Carnegie Mellon, and his M.S. and Ph.D. in Aeronautics and Astronautics from MIT. His research interests are in the areas of autonomous systems including robots, self-driving cars, UAVs and spacecraft, with a focus on algorithms and hardware verification including estimation, machine learning, perception, sensor fusion, planning under uncertainty, multi-agent systems, and human-robotic teaming and decision making. Professor Campbell has led multiple collaborative research grants with DARPA, AFOSR, ARO, ONR and NSF, including leading Cornell's DARPA Urban Challenge self-driving car team, one of six finishers of the race. He also served as a member of the U.S. Air Force Science Advisory Board, advising leadership on science, technology and investments, reviewing research labs, and leading a study on Unintended Behaviors of Autonomy. For his work with the board, he received the U.S. Air Force Chief of Staff Award for Exceptional Public Service, the highest-level award granted by the U.S. Air Force to non-employee civilians. Prof. Campbell is a Fellow of the IEEE, AIAA and ASME.

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Kyu Jin Cho is a Professor of Mechanical Engineering and the Director of Soft Robotics Research Center and Biorobotics Lab at Seoul National University. He received his Ph.D. in mechanical engineering from MIT and his B.S and M.S. from Seoul National University. He was a post-doctoral fellow at Harvard Microrobotics Laboratory before joining SNU in 2008. He has been exploring novel soft bio-inspired robot designs, including a water jumping robot, various shape changing robots and soft wearable robots for the disabled. He has received the 2014 IEEE RAS Early Academic Career Award for his fundamental contributions to soft robotics and biologically inspired robot design. He has published a Science paper on water jumping robot and several papers in Science Robotics with novel robot designs. He served RAS as associate VP of Publication Activities Board for six years, and is currently serving RAS as Vice President of the Technical Activities Board.

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Dr. David Hu is Professor of Mechanical Engineering and Biology and Adjunct Professor of Physics at Georgia Institute of Technology. He earned degrees in mathematics and mechanical engineering from M.I.T. and was a National Science Foundation (NSF) Postdoctoral Fellow at New York University. He is a recipient of the APS Fellowship, the Ig Nobel Prize in Physics (twice), the NSF CAREER award, and the American Institute of Physics Science Communication Award. He sits on the editorial boards of Proceedings of the Royal Society B and Journal of Experimental Biology. He is the author of two books "How to walk on water and climb up walls," (Princeton University Press) and "The P Word" (Science, Naturally). He lives with his wife and two children in Atlanta, Georgia.

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Daekyum Kim received his B.S. degree in Mechanical Engineering from the University of California, Los Angeles, (Los Angeles, CA, USA), in 2015. He earned his Ph.D. degree in Computer Science at KAIST (Daejeon, Republic of Korea), in 2021. He was a Postdoctoral Research Fellow at the John A. Paulson School of Engineering and Applied Sciences, Harvard University (Cambridge, MA, USA), co-affiliated with Wyss Institute. Since September 2023, he has been an Assistant Professor with the School of Smart mobility and the School of Mechanical Engineering, Korea University (Seoul, Republic of Korea). His research interests are in the areas of machine learning, computer vision, robotics, and digital healthcare.

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H. Jin Kim is Professor/Chair in Aerospace Engineering at Seoul National University. She received MSc and PhD degrees from the University of California, Berkeley and BS from Korea Advanced Institute of Science and Technology (KAIST), Korea, all in Mechanical Engineering. Her research is on navigation, control and planning of autonomous robotic systems ranging from ground to flying robots. She has served on the editorial board of several journals and conferences including IEEE Transactions on Robotics, Mechatronics, an International Journal of IFAC, International Journal of Robotics Research, and IEEE Conference on Robotics and Automation, IEEE/RSJ International Conference on Intelligent Robots and Systems. She is a member of National Academy of Engineering of Korea.

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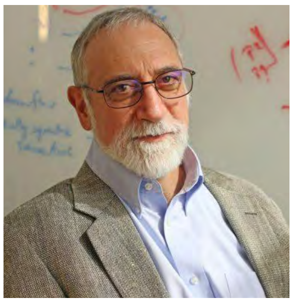
Ayound Kim is currently working as an associate professor in the department mechanical engineering at SNU since 2021 Sep. Before joining SNU, she was at the civil and environmental engineering, Korea Advanced Institute of Science and Technology (KAIST) from 2014 to 2021. Dr. Kim has earned both a B.S. and M.S. degree in mechanical engineering from SNU in 2005 and 2007, and a M.S. degree in electrical engineering and a Ph.D. degree in mechanical engineering from the University of Michigan (UM), Ann Arbor, in 2011 and 2012.



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Research in Daniel's group is focused on the application of dynamical systems theory to the design, construction and empirical testing of machines that juggle, run, climb, and in general, interact physically with their environment to perform useful work. Dan and his group seek to probe the foundations of autonomous robotics by reasoning formally about mathematical models that represent the successes and limitations of their physical platforms. They maintain close collaborations with biologists, whose insights about animal mobility and dexterity inspire their thinking and designs.

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Jesung Koh is an Assistant Professor at Ajou University in the Department of Mechanical Engineering. Dr. Koh received a PhD from Seoul National University in 2014. Dr. Koh's research interests include: Printable & Origami Inspired Robotics, Biologically Inspired Designs & Mechanisms for Robotic Applications, Micro Robots Based on the Fiber Reinforced Composite, Microfabrication & Assembly, and Artificial Muscle Actuators (e.g. Shape Memory Alloy actuators).

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Ki-Uk Kyung received BS, MS, and Ph.D. degrees in mechanical engineering from the Korea Advanced Institute of Science and Technology (KAIST) in 1999, 2001, and 2006, respectively. In 2006, he joined the Electronics and Telecommunications Research Institute and had been the Director of the Smart UI/UX Device Research Section. He had been a co-chair of the IEEE Technical Committee on Haptics (TCH) from 2018 to 2021. He received the IEEE TCH Early Career Award in 2015 and the Academic Career Award at Active Materials and Soft Mechatronics 2019. He is currently an associate professor of Mechanical Engineering and the director of the Human-Robot Interaction Research Center at KAIST, and adjunct professor of Tandon School of Engineering at New York University. His research interests are soft sensors and actuators, haptics, soft robots, and human-robot interaction.

Jeffrey Lipton

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Jeff Lipton's current work is currently focused on 3D printing and robotics. He focuses on how we can make torque responsive metamaterials and how we can leverage them to make systems with mechanical intelligence. His past work on 3D printed foods and 3D printing for the hospitality industry has influenced two of the largest 3D printing companies in America and garnered media attention from the New York Times, BBC, and others. He was the lead developer for the Fab@Home project which supported life science and food science researchers' 3D printing needs on all six habitable continents.

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Dr. Robert MacCurdy is an assistant professor in Mechanical Engineering (also by courtesy in CS and ECEE) at the University of Colorado Boulder where he leads the Matter Assembly Computation Lab (MACLab). He is developing new algorithms, materials, and fabrication tools to automatically design and manufacture electromechanical systems, with a focus on robotics. Rob did his PhD work with Hod Lipson at Cornell University and his postdoctoral work at MIT with Daniela Rus. He holds a B.A. in Physics from Ithaca College, a B.S. in Electrical Engineering from Cornell University, and an M.S. and PhD in Mechanical Engineering from Cornell University.

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Lakshminarayanan Mahadevan FRS is an Indian-American scientist. He is currently the Lola England de Valpine Professor of Applied Mathematics, Organismic and Evolutionary Biology and Physics at Harvard University. His work centers around understanding the organization of matter in space and time (that is, how it is shaped and how it flows, particularly at the scale observable by the unaided senses, in both physical and biological systems). Mahadevan is a 2009 MacArthur Fellow.

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Frank C. Park is Professor of Mechanical Engineering at Seoul National University. He received the B.S. in EECS from MIT in 1985, the Ph.D. in applied mathematics from Harvard in 1991, and was on the faculty of the University of California, Irvine from 1991 to 1994. He is a fellow of the IEEE, and has held adjunct faculty positions with the HKUST Robotics Institute in Hong Kong, the Interactive Computing Department at Georgia Tech, and the NYU Courant Institute. His research interests include robotics, computer vision, mathematical data science, and related areas of applied mathematics. He is a former Editor-in-Chief for the IEEE Transactions on Robotics, developer of the EDX course Robot Mechanics and Control I-II, and author (with Kevin Lynch) of the textbook Modern Robotics: Mechanics, Planning, and Control (Cambridge University Press, 2017). He served as president of the IEEE Robotics and Automation Society (2022-2023), and is a founder and CEO of the industrial AI startup Saige (http://saige.ai).

Research Interests: Robot mechanics, planning and control; mathematical systems theory; machine learning and mathematical data science; computer vision; related areas of applied mathematics.

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Yong-Lae Park is Professor in the Department of Mechanical Engineering at Seoul National University (SNU) (2016~present). Prof. Park completed his Ph.D. degree in Mechanical Engineering at Stanford University (2010). Prior to joining SNU, he was Assistant Professor in the Robotics Institute at Carnegie Mellon University (2013~2017) and Technology Development Fellow in the Wyss Institute for Biologically Inspired Engineering at Harvard University (2010~2013). His current research interests include artificial skins and muscles, soft robots, wearable robots, medical robots, and inflatable robots. He received the Best Application Paper Award from the IEEE Transactions on Haptics (2020), the Best Conference Paper Award in the IEEE International Conference on Soft Robotics (2019), Okawa Foundation Research Grant Award (2014), the Best Paper Award from the IEEE Sensors Journal (2013), the NASA Tech Brief Award (2012). His papers on soft artificial muscles and skin were selected as cover articles in various journals, including Soft Robotics, Advanced Intelligent Systems and the IEEE Sensors Journal, and his work on soft robots were featured in media, including Nature, Discovery News, New Scientist, PBS NOVA, and Reuters.

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Daniela Rus is the Andrew (1956) and Erna Viterbi Professor of Electrical Engineering and Computer Science, Director of the Computer Science and Artificial Intelligence Laboratory (CSAIL) at MIT, and Deputy Dean of Research in the Schwarzman College of Computing at MIT. Prof. Rus's research interests are in robotics and artificial intelligence. The key focus of her research is to develop the science and engineering of autonomy. Prof. Rus served as a member of the President's Council of Advisors on Science and Technology (PCAST) and on the Defense Innovation Board. She is a senior visiting fellow at MITRE Corporation. Prof. Rus is a MacArthur Fellow, a fellow of ACM, IEEE, AAAI and AAAS, a member of the National Academy of Engineering, and of the American Academy of Arts and Sciences. She is the recipient of the Engelberger Award for robotics, the IEEE RAS Pioneer award, Mass TLC Innovation Catalyst Award, and the IJCAI John McCarthy Award. She earned her PhD in Computer Science from Cornell University.

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Robert Shepherd is an associate professor at Cornell University in the Sibley School of Mechanical & Aerospace Engineering. He received his B.S. (Material Science & Engineering), Ph.D. (Material Science & Engineering), and M.B.A. from the University of Illinois. At Cornell, he runs the Organic Robotics Lab (ORL: http://orl.mae.cornell.edu), which focuses on using methods of invention, including bioinspired design approaches, in combination with material science and mechanical design to improve machine function and autonomy. We rely on new and established synthetic approaches for soft material composites that create new design opportunities in the field of robotics. He is the recipient of an Air Force Office of Scientific Research Young Investigator Award, an Office of Naval Research Young Investigator Award, is a Senior Member of the National Academy of Inventors, and his lab's work has been featured in popular media outlets such as the BBC, Discovery Channel, and PBS's NOVA documentary series. He is an advisor to the American Bionics Project (americanbionics.org) which aims to make wheelchairs obsolete. He is also the co-founder of the Organic Robotics Corporation, which aims to digitally record the tactile interactions of humans and machines with their environment.

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Dongjun Shin is a member of the Department of Mechanical Engineering at Yonsei University, working on soft wearables and actuators. Dr. Shin received a PhD in Mechnical Engineering from Stanford University.

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Jeong-Yun Sun is currently a professor in the Department of Materials Science and Engineering at Seoul National University (SNU), Republic of Korea. He got his B.S. (2005), M.S. (2007) and Ph.D. (2012) in Materials Science and Engineering at Seoul National University. During his Ph.D., he had stayed at Harvard University for 4 years as a visiting student. After getting Ph.D. (2012), he started to work as a postdoctoral fellow in School of Engineering and Applied Sciences at Harvard University. After his Post-Doc., he came back to SNU and worked as an assistant professor and an associate professor. His research was focused on developing soft and ionic materials. Based on the materials, he is developing many ionic devices such as sensors, actuators, energy harvesters etc. Dr. Sun has published many high impact peer-reviewed journal papers including Nature, Science, and Advanced Materials and so on. He became a member of the Young Korean Academy of Science and Technology (YKAST) in 2021. He has received honorable awards including "S-Oil Young Scientist Fellowship Award" from S-OIL Science and Culture Foundation (2023). "Top 100 National R&D Outstanding Achievements" from Korean Ministry of Science and ICT (2020), "Top 10 Nanotechnologies" from Korean Ministry of Science and ICT (2019), "Scientist in this Month" from Korean Ministry of Science (2018), "Young Scientist Award" from The Polymer Society of Korea (2017) and "Young Scientist Award" from Korean Materials Research Society (2016).

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Michael T. Tolley is Associate Professor in Mechanical and Aerospace Engineering, and director of the Bioinspired Robotics and Design Lab at the Jacobs School of Engineering, UC San Diego (bioinspired.eng.ucsd.edu). Before joining the mechanical engineering faculty at UCSD in the fall of 2014, he was a postdoctoral fellow at the Wyss Institute for Biologically Inspired Engineering, Harvard University. He received the Ph.D. and M.S. degrees in mechanical engineering with a minor in computer science from Cornell University in 2009 and 2011, respectively. His research seeks inspiration from nature to design robotic systems with the versatility, resilience, and efficiency of biological organisms. Example topics include soft robots, origami robots, and systems capable of self-assembly. His work has appeared in leading academic journals including Science and Nature, and has been recognized by awards including a US Office of Naval Research Young Investigator Program award and a 3M Non-Tenured Faculty Award. He is active in the robotics community, serving in multiple associate editor and conference organizer roles including as Program Chair of the IEEE International Conference on Soft Robotics (RoboSoft) in 2020 and General Chair in 2024.

Ryan Truby
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Ryan Truby is the June and Donald Brewer Junior Professor of Materials Science and Engineering and Mechanical Engineering at Northwestern University. His research broadly aims to advance machine intelligence by material design. He and his team in the Robotic Matter Lab are currently developing novel soft actuators and sensors, rapid multimaterial 3D printing methods, and machine learning-based control strategies for soft sensorized robots. Ryan's research also includes work in 3D printing vascularized tissue constructs, soft electronics, artificial muscles, and architected materials. Prior to Northwestern, Ryan was a Postdoctoral Associate at MIT's Computer Science and Artificial Intelligence Lab, and he received his Ph.D. in Applied Physics from Harvard University. Ryan is the recipient of a DARPA Young Faculty Award, Office of Naval Research Young Investigator Award, Air Force Office of Scientific Research Young Investigator Award, the Outstanding Paper Award at the 2019 IEEE International Conference on Soft Robotics, an Inaugural 2018 Schmidt Science Fellowship, and the Gold Award for Graduate Students from the Materials Research Society.

T.J. Wallin
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Thomas “T.J.” Wallin is an Assistant Professor in MIT’s Department of Materials Science and Engineering. Wallin’s interests lay in co-developing polymer photochemistries and advanced manufacturing techniques, with an emphasis on applications in soft wearable technologies and human-computer interfaces.

Victoria Webster-Wood
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Vickie Webster-Wood is an Associate Professor in the Department of Mechanical Engineering at Carnegie Mellon University with courtesy appointments in the Department of Biomedical Engineering, the McGowan Institute of Regenerative Medicine, and the Robotics Institute. She is the director of the C.M.U. Biohybrid and Organic Robotics Group and has a long-term research goal to develop completely organic, biodegradable, autonomous robots. Research in the C.M.U. B.O.R.G. brings together bio-inspired robotics, tissue engineering, and computational neuroscience to study and model neuromuscular control and translate findings to the creation of renewable robotic devices.

Dr. Webster-Wood completed her postdoc at Case Western Reserve University in the Tissue Fabrication and Mechanobiology Lab under the direction of Dr. Ozan Akkus. During her postdoc, Dr. Webster-Wood was supported by the T32 Training Grant in Musculoskeletal Research. She received her Ph.D. in Mechanical Engineering from the same institution as an N.S.F. Graduate Research Fellow in the Biologically Inspired Robotics Lab, during which time she was co-advised by Drs. Roger Quinn, Ozan Akkus, and Hillel Chiel. She received the NSF CAREER Award in 2021, is PI on an ARO MURI on Integrated Biohybrid Actuators, and is a co-PI of the N.S.F. NeuroNex Network on Communication, Coordination, and Control in Neuromechanical Systems (C3NS), and has received additional funding from the NSF Foundational Research in Robotics Program.

Jinkyu Yang
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Jinkyu Yang is a Professor in Mechanical Engineering at Seoul National University. He was formerly a Professor in Aeronautics & Astronautics at the University of Washington. He received his Ph.D. degree in Aeronautics and Astronautics from Stanford University (2005) and BS degree in Aerospace Engineering from KAIST (2000). His research has been directed towards developing novel engineered materials and structures, e.g., metamaterials, phononic crystals, and nonconventional composites, for aerospace, biomedical and mechanical applications. His research has been featured in news media, such as Reuters, NSF News, and U.S. Public Broadcasting Service, and he is currently an Associate Fellow in AIAA and an Associate Editor for AIAA’s Journal of Aircraft.

Appendix II – Workshop Agenda and Prospectus

The K Hotel, 70 Baumoe-ro 12-gil, Seocho-gu, Seoul, South Korea | Third Floor | Main Hall 3F, Bipa Room

DAY 1 – Sunday, MAY 19, 2024

Time	Title	Speaker
8:00 – 8:15	Check-in	
8:15 - 8:20	Welcome and Introductions and Expectations	Robert Shepherd Kyujin Cho
8:20 -8:45	Workshop Framing Talk	Co-chairs
8:45 – 9:00	Breakout Instructions and Morning Break	
9:00 – 10:45	Working Group I: Define the Problem *Small group discussions to frame a vision for embodied intelligence research and identify the greatest hurdles to achieving it.* Group A – Perception Group B – Motion Group C – Adaptation	
10:45 – 11:00	BREAK - *Transition to main conference room and leads prepare outbriefing*	
11:00 –12:00	Working Group 1: Outbriefing	
12:00 – 1:00	LUNCH (provided for participants) @ Ucello Restaurant	
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 – Perception Group B – Motion Group C – Adaptation	
3:45 – 4:00	BREAK - *Transition to main room and leads prepare outbriefing*	
4:00 – 4:45	Working Group II: Outbriefing	

DAY 1 – Sunday, MAY 19, 2024

Time	Title	Speaker
4:45 – 5:00	Summary of Day	Co-chairs
5:00	MEETING ADJOURNED FOR THE DAY	
6:00	Dinner @ Gayageum Hall	

DAY 2 – Monday, MAY 20, 2024

Time	Title	Speaker
8:00 – 8:15	Check-in	
8:15 – 8:30	Government welcome	Dr. Cambier & Dr. Woo
8:30 – 9:00	Day 1 Recap	Co-chairs
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 – 1:00	LUNCH (provided for participants) @ Ucello Restaurant	
1:00 – 3:00	"Open Café" networking session (Optional)	
3:00	Bus to Seoul National University for Laboratory Tours (Optional)	

Co-chairs: Dr. Dr. Kyu-Jin Cho (Seoul National University), Dr. Robert Shepherd (Cornell University), Dr. Yeong-Lae Park (Seoul National University), Dr. Joshua Bongard (U. Vermont)

Embodied Intelligence has emerged as a framework that expands the computational framework of biological and artificial autonomy beyond a centralized computer (e.g., brain or microchip) and into the architecture of the body. This embodiment of intelligence is aided by a theory of "morphological computation," where the input of mechanical stress is processed by the materials and structures, reducing computational load on a central computer for a command response, or negating the need for a traditional computing architecture altogether (i.e., reflex action). The last decade has seen proliferation of these concepts, publications and citations seeing exponential growth. In parallel, new advances in material science, neural networks, soft robotics, additive manufacturing, parallel computing, and signal processing have made it important to revisit and refine these concepts.

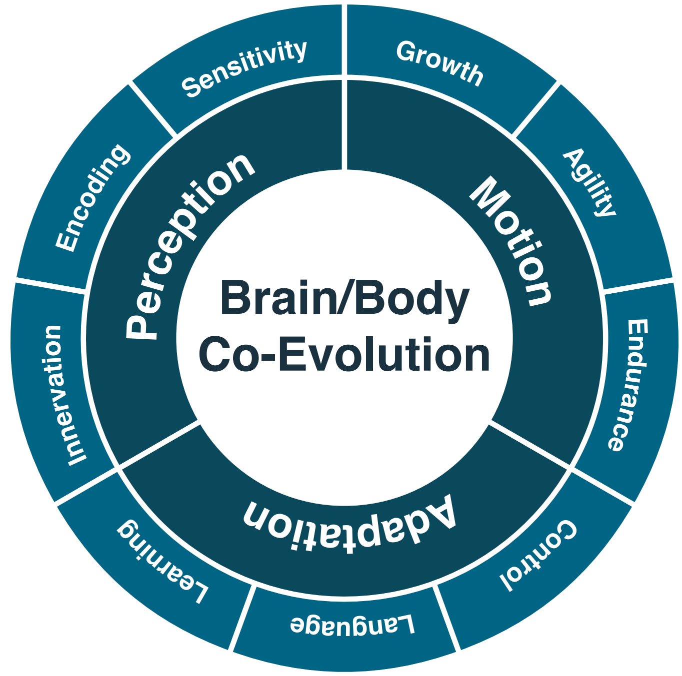
This workshop will bring together leading Korean and U.S. scientists to discuss what Embodied Intelligence means today, how it can expand going forward, and what we can leverage to maintain this exponential growth over the next decade. To aid in this discussion and to provide direction, we have identified what the central focus of Embodied Intelligence relies on- and enables Brain-Body Co-Evolution. Our workshop will focus on three emerging pillars of this framework: perception, motion, and adaptation. We expect these pillars will improve brain-body coevolution, resulting in more enduring, agile, and adaptive autonomous systems.

Perception. While AI excels at handling large amounts of data and extract features, the underlying statistical process of learning is not conducive to causal and abstract reasoning. Attempts to create such capability within that framework have generally not yielded consistently accurate results, and this likely relates to the difference between how engineered (AI) and natural organisms learn. These are fundamental questions: what is learning, and, to a deeper level, what is intelligence? For all natural organisms, knowledge representation is highly dependent on the sensory modes, and their processing and fusion. Thus, learning cannot be dissociated from the sensors used to acquire information. A variety of sensing modalities have emerged that interface the body with the environment (exteroception), and provide more detailed knowledge about the body's state internally (proprioception). These sensors are typically fused with traditional analog-to-digital converters for processing by standard computer architectures, but there is an opportunity within embodied intelligence to cause responses more like reflex actions using analog computation, and using a variety of fields (electrical, magnetic, mechanical, chemical, etc.). Sometimes, these sensors may also be fused with computation, preprocessing information; a human eye, for example, not only measures the properties of light, it also performs preprocessing functions akin to wavelet transforms.

Motion. Intelligence is a developmental process: (i) within an organism's lifetime and (ii) throughout a species's evolution. In the first example, the "curse of dimensionality" is somehow solved by nature, whereby complex organisms learn to control their large number of DOF's using large numbers of sensory inputs. An interesting hypothesis as to how nature accomplishes this task is that through the developmental process, DOFs are initially frozen and released, or added with growth. Furthermore, the organism is not passive; it can actively probe and modify the environment, using various actuators. Learning and, by association, intelligence, are a function of available modes of sensing and action. For example, human babies learn their environment sequentially, according to their ability to move and manipulate. This creates a challenging co-design problem for robotics, for which mechanical operation, sensors, neural processors and training/learning strategies must then be considered in a holistic fashion.

Adaptation. In nature, this co-design problem is also solved through evolutionary processes; indeed, hardware is also evolved over time to account for inefficiencies in design or changing end-user needs. Using sim2real, evolutionary algorithms, and other advanced computation based techniques, we can better design autonomous systems that are more adaptable to changing environments; perhaps an organism's best indicator of intelligence. This ability to tune the energy landscape of the autonomous system, and impedance match it to environmental inputs and outputs, is at the core of embodied intelligence. By taking advantage of materials science, additive manufacturing, or building new approaches, this artificial species' ability to tune the I/O and energy landscape can be evolved more rapidly.

This *Future Directions Workshop on Embodied Intelligence* aims to examine the fundamental questions regarding the nature of embodied intelligence. In particular; what will be the art of the possible in a decade or more? How do we proceed to achieve that vision? The workshop gathers researchers from the general practice of embodied intelligence and a variety of fields, including mechanical and electrical engineering, artificial intelligence, computer science, materials science (inorganic and organic), physics, chemistry, and biology. These experts will discuss the prospects of achieving more agile and efficient autonomous systems, likely leveraging insights from the evolution of biological systems – in particular, the use of learning, material science, and growth and how it allows for complex architectures that enhance the embodiment of intelligence.



While these three areas are closely coupled, each represents a separable extension of the previous. The workshop will endeavor to discuss and generate a comprehensive picture, and attempt to put forth ideas on research directions, challenges, opportunities, and resources necessary to leverage Embodied Intelligence to efficiently guide the Brain-Body Co-Evolution in autonomous machines. We have provided some guidance as to specific outcomes or enablers of the three pillars, but all portions of this framework are up for discussion.

Participants will discuss opportunities and challenges in these fields, primarily in small-group breakout sessions and whole-group discussions. The workshop aims to focus discussion around these overarching questions:

1. What are the visionary outcomes that the community believes can be realized?
2. How to impact research in the various scientific fields, to achieve this vision?
3. What is the trajectory of scientific research in those areas over the next 10-20 years?
4. What are the primary challenges to progress, and how can they be addressed?

A key outcome of this Workshop will be a roadmap of key basic science research needs that, if addressed in the next 10-20 years, can substantially advance this transformational vision. The discussions and ensuing distributed report will provide valuable long-term guidance to the DoD community, as well as the broader federal funding community, federal labs, and other stakeholders. Workshop attendees will emerge with a better ability to identify and seize potential opportunities in the different fields addressed. This workshop is sponsored by the Basic Research Office within the Office of Secretary of Defense, along with input and interest from the Services and other DoD components.

Agenda

Rather than a standard conference format, the workshop design emphasizes interactive dialogue with primarily small-group breakout sessions followed by whole-group synthesis of ideas.

Day One: The majority of the first day will be spent in small-group breakout sessions on fundamental challenges to progress and research opportunities for the three technical areas described above.

Day Two: The second day of the workshop is a half-day consisting of white-space, whole group discussions on topics that did not fall into the Day 1 framework or were especially ambitious and/or high-risk. Participants will also discuss cross cutting themes and the trajectory of the field over the next 10-20 years. At the end of the day, the whole group will discuss the overarching themes of the workshop that should be included in the final workshop report.