APL at 100: A Research and Exploratory Development Perspective

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ABSTRACT

Although predicting the future is a difficult task, in many ways the Research and Exploratory Development Department (REDD) at the Johns Hopkins University Applied Physics Laboratory (APL) exists to do just that. The department's researchers seek to envision future challenges for APL and the nation and develop innovative solutions to those challenges. This brief article begins with a framework for thinking about what APL research and development will look like when the Lab reaches its centennial. Then it discusses some key areas of research that we predict will be active in 2042.

The task of envisioning APL at its centennial celebration is both fascinating and daunting. We are, however, pleased to have this opportunity to look forward and offer a perspective on this topic. Of course, as researchers we are actively engaged in pioneering projects that will hopefully shape the future of the Laboratory in exciting and positive ways. In fact, the vision of the Research and Exploratory Development Department (REDD) is to: *Accelerate transformative innovation and invent the future for APL*. Therefore, it is perfectly reasonable to ask: *What sort of future does REDD seek to invent for APL?* This short article looks at some key areas of research and presents our best sense of where we feel they will be in the years ahead.

There is a point of view on science and technology that might be helpful in providing a basic context for this discussion. Let's think about mathematics for a moment. In mathematics there are *concepts* and there are *computations*. For example, consider the concept of a continuous function. Given a function f that maps a subset S of the real numbers into the real numbers, we say that f is continuous at a point a in S if for every real number $\varepsilon > 0$ there exists a real number $\delta > 0$ depending on ε such that

$$\text{if } x \text{ is a point in } S \text{ and } |x - a| < \delta \text{ then } |f(x) - f(a)| < \varepsilon.$$

It took a very long time for mathematicians to formulate this concept precisely, and it takes students a while to understand how this formal definition really captures the concept of continuity in a useful way. To get a better appreciation of the concept we do computations. For example, we might be asked to prove that the function $f(x) = x^2$ is continuous at the point $x = 5$. That's a computation. Anyone who ever took a calculus course might recall a lecture presenting the Fundamental Theorem of Calculus. This theorem is one of the most amazing conceptual advances in human history. It is more likely, however, that students will recall many hours spent computing derivatives and integrals. Concepts drive science forward, but computations are the essence of applications.

A crayon is a concept: a stick of colored wax that leaves a trail when dragged across a piece of paper. The drawings made with a box of crayons are the computations. The iPhone is an interesting example, too. Conceptually, it is a wireless device that fits in a pocket and enables access to a worldwide communications and knowledge network. The applications that reside on the iPhone, like the camera, the driving directions, and the stock market ticker, are the computations. When thinking about the future, it is sometimes useful to distinguish between a concept and a computation.

Now, this discussion of concepts and computations might sound as though the concepts are in some way superior to the computations. Not at all! In fact, while we might say that concepts drive computations, it is just as true that computations drive concepts. Scientific theory—that is, scientific concepts—evolve out of experiments, and the experiments are the computations. When an experiment cannot be explained by the existing scientific theory, we see computations driving new concepts. This is why predicting the future is so hard. Given the current inventory of concepts, it is relatively easy to perform endless computations. That's why we have millions of websites now on the internet. It's harder to carry out an interesting experiment that reveals the limitations of a concept or to take in the world around us and process what we see in a new way. One of my favorite quotes of all time is from the scientist Albert Szent-Györgyi, who was awarded a Nobel Prize in 1937 for his research on vitamin C and cell respiration. He said:

Discovery consists of seeing what everyone has seen and thinking what no one has thought.

Along with concepts and computations, there is another important aspect of science and technology that makes predicting the future very difficult: *innovation*. Innovation occurs when we mash together existing concepts, computations, and technologies to create something new and interesting. For example, we can think about the iPhone as a concept as we did above. However, the iPhone is also an innovation since it is a mash-up of microelectronics chips, a camera, a GPS sensor, an organic light-emitting diode screen display, a communications infrastructure that gives us real-time access to the internet, and a massive amount of software. Innovations are exciting because they are unexpected. It usually takes someone seeing what everyone has seen and thinking what no one has thought to realize a true innovation.

So, to recap, predicting the future is really hard because we would need to anticipate new concepts, imagine the flow of computations that derive from these concepts, foresee the way that computations challenge the existing concepts, and have unique insights into how extremely creative people will mash together existing concepts, computations, and technologies to create new innovations. Another point to make here, while explaining why the assignment to think about APL at 100 is so hard, is that there are a lot of concepts around but many of them are just plain bad ideas, at least right now. For example, people frequently ask, "Where's my flying car?" Our highways are full of people who appear to be just barely capable of driving a car in a safe manner on a road. Why in the world would we want them careening around in three dimensions?! Maybe when autonomy has reached the point where flying cars can fly by themselves we can revisit this concept. At the moment, it's just a bad idea. In any case, we will now charge forward and try to envision the concepts, computations, and innovations that will be critical to APL at its centennial.

Let's start with a current concept, artificial intelligence (AI). AI is a fantastic example of computations driving the concept. Starting from the basic notion that an intelligent system of some sort might be modeled on the neurons in a human brain, Frank Rosenblatt at Cornell University created the perceptron in 1958. The perceptron is a simple device that computes a weighted sum of *n* numbers, adds a constant, and compares the result to a threshold value. It was quickly realized that the decision-making capability of a single perceptron was limited, and people started thinking about systems composed of layers of perceptrons. However, the full capability of what we now call neural networks had to wait until the computing power of modern microprocessors and memory chips reached a point where one could really implement a supervised learning algorithm on a massive data set.

Moreover, what is really amazing and noteworthy here is that people had the intellectual curiosity and courage to try these computations. To be clear, there is some relevant theory. In 1989 George Cybenko proved the Universal Approximation Theorem, which states that any continuous function defined on a compact subset of Euclidean *n*-space can be approximated by a certain kind of neural network. However, this existence theorem does not tell us how to write down the parameters of a neural network that approximates a given function. In practice, discovering the parameters of a neural network that can recognize pictures of cats, for example, requires a large training set of cat pictures and a massive amount of computing using an algorithm called backpropagation. It was never clear based on any theory that the neural networks obtained in this way would perform so well in practice. The world is now applying the computational technique of backpropagation, or deep learning as it is often called, to all sorts of problems, including computer vision and speech recognition. In particular, no one is waiting around for the conceptual foundations of AI to reach a certain level of maturity before charging ahead on the applications. Concerned citizens suggest that maybe it would be good to have some "explainable AI," but at this point in time AI for fun and profit has a life of its own.

In the decades ahead we expect that AI will permeate every aspect of our technical work at APL. In fact, we are already seeing very important applications of AI to critical challenges in the Lab's sectors: Air and Missile

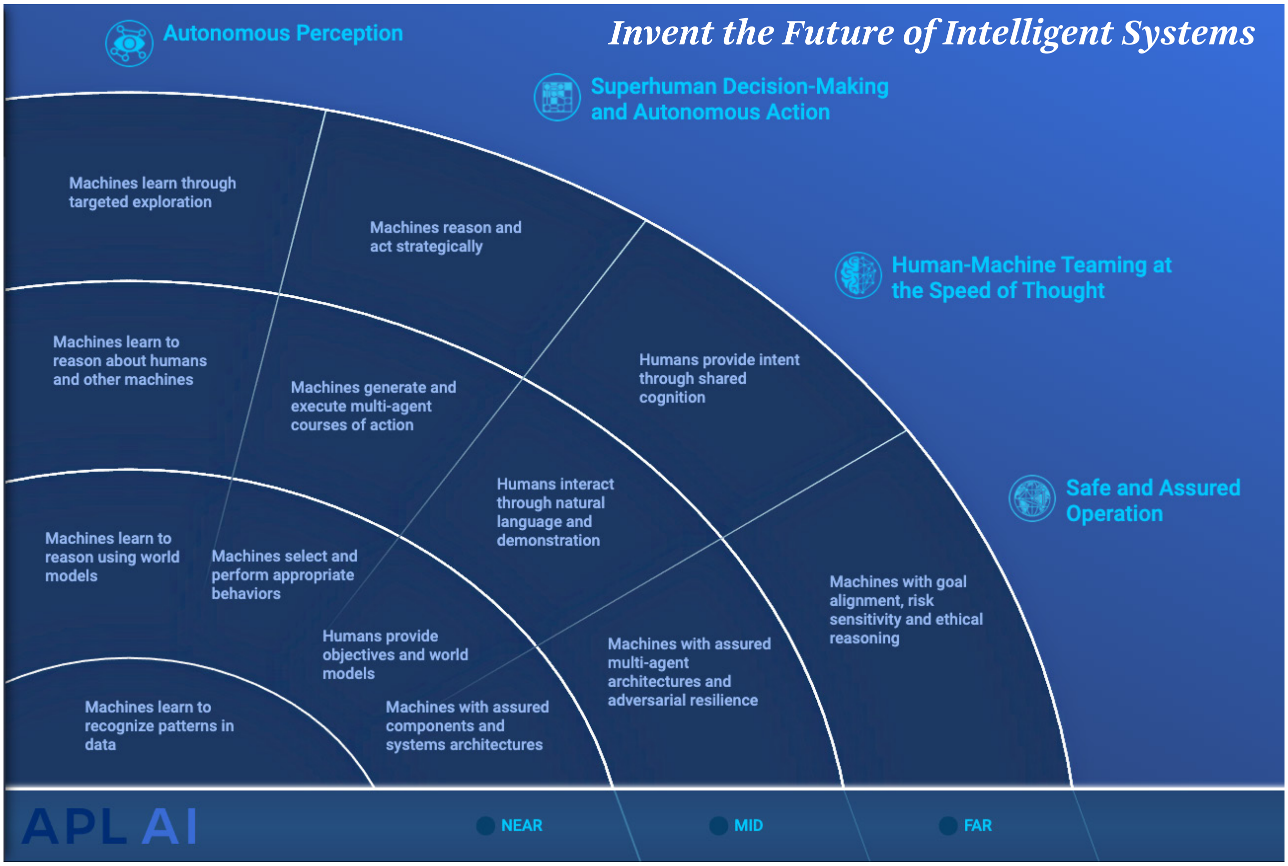

Figure 1. APL AI roadmap. The 20-year roadmap describes four technology vectors that should serve as conceptual guides to the future.

Defense, Force Projection, Asymmetric Operations, and Space Exploration. The recently completed 20-year roadmap for AI at APL describes four technology vectors that should serve as conceptual guides to the future (see Figure 1):

1. Autonomous perception
2. Superhuman decision-making and autonomous action
3. Human–machine teaming at the speed of thought
4. Safe and assured operation

The AI roadmap goes into detail about research initiatives that will move us forward along each of these vectors, and REDD is actively engaged in many of these exciting projects. For example, in the realm of human–machine teaming at the speed of thought, REDD is currently working on a novel noninvasive brain–computer interface technology. If we can succeed in developing a practical device, it is likely that we will see an interesting array of computations—that is, applications—enabled by such a device, along with new conceptual insights into the inner workings of the human brain.

One final thought on the conceptual foundations of AI mentioned above. You might recall that since the time of Euclid, there has been a dream that a rigorous logical foundation for geometry, and more generally for all of mathematics, could be achieved. If such a system were realized, then, in principle, one could derive mathematical theorems in a mechanical way by following the logical implications of the axioms. In 1931 Kurt Gödel proved that such a rigorous foundation is impossible to achieve. In fact, in any consistent axiom system that allows us to develop the conceptual foundations of the natural numbers, 0, 1, 2, 3, 4, 5, . . ., there are assertions about the natural numbers that cannot be proved or disproved from the axioms. This result of Gödel's work is known as his Incompleteness Theorem.

What might this have to do with AI? Machines perform computations. Can machines ever truly achieve "strong artificial intelligence," in which they are capable of human-level thought? Gödel's theorem tells us that there are true mathematical theorems that cannot be proved true within the system, and this seems to imply that human creativity will continue to be essential as we try to gain new insights into the hardest problems facing humanity. Of course, if the human brain is itself just a Turing machine, we might have a problem here! By the time that APL reaches its centennial celebration, we expect that the current computational work on AI will have led to a much deeper conceptual understanding of these difficult issues.

Figure 2. Human–machine teaming at the speed of thought. In one example of how APL is contributing to advances in this realm, REDD researchers are working on a novel noninvasive brain–computer interface technology.

Currently there is a great deal of research in quantum physics going on across the world in a race to realize the first quantum computer. At APL, REDD physicists are involved in this research and are also pursuing research on quantum sensors. By the time that APL celebrates its centennial, our expectation is that quantum computing will be a reality. A question that the Laboratory needs to focus on in the near future is this: What are the advantages of quantum computing for APL and its sponsors? Researchers in REDD have already developed novel algorithms for quantum computers, and more research needs to be carried out in this area. Quantum computing is another area in which we can expect that computations will drive new concepts.

Here's a quiz question: What is APL's most important secret weapon? My answer is the combined power of materials science and our fabrication capabilities. One of the Laboratory's greatest strengths is that we build advanced prototypes. While many people study hard problems and offer theoretical solutions, APL is one of the few institutions in our country that can actually deliver the entire solution. Which is to say, we can handle both the concepts and the computations. As APL's first director Merle Tuve said in 1942:

> *Our moral responsibility goes all the way to the final battle use of this unit; its failure there is our failure regardless of who is technically responsible for the cause of failure. It is our job to achieve the end result.*

This drive to complete the job and ensure that our work meets the full expectations of our sponsors is an enduring hallmark of APL. For this reason, the mechanical and electrical fabrication capabilities of the Laboratory will continue to be essential to APL's success as it reaches its centennial celebration. Now, needless to say, every object we make has to be made out of something. Most people do not realize the critical role that materials science plays in the realization of APL prototypes. The most obvious recent example is the heat shield for the Parker Solar Probe, which is currently in orbit around the Sun and is providing a great deal of new information for scientists. The heat shield was developed by the materials scientists in REDD, and the same team is now engaged in research on new materials for hypersonic weapons. We expect that the fruitful collaborations that we are now seeing between the REDD materials scientists and our fabrication teams will continue to flourish and yield exciting new solutions to critical APL challenges. Moreover, in the decades ahead we also expect that computational materials science will be a vital tool for the Laboratory as we become better at using the computer to help build and understand new materials from the atomic scale on up. This will be another great example of computations driving concepts and innovations.

The 21st century is the century of biology. Of course, the discovery of DNA was one of the greatest conceptual achievements of the 20th century, but the computations had to wait until the technological developments of the current century. Now that computing DNA sequences is routine, a vast amount of information is being generated and the century of biology is charging ahead. The discovery of the CRISPR-Cas9 genome editing capability is heralded as one of the greatest discoveries in the history of the biological sciences. While there is controversy surrounding some potential applications of genome editing, it seems likely that in the years ahead this powerful technique will provide profound examples of computations driving new concepts. At the time of this writing, researchers in REDD, together with professors at the Whiting School of Engineering and doctors at Johns Hopkins Hospital, are on the front lines of the fight to understand the virus COVID-19 through genome sequencing. This is just one of many projects that the biologists of REDD are engaged in now, and we fully expect that biological research at APL will expand greatly in depth and breadth as we approach the Laboratory's centennial celebration. We have even gone so far as to suggest that APL might change its name to the Applied Biology Laboratory, but prospects for that appear dim at the moment! Our final topic will likely involve a great deal of new biological research opportunities for APL.

As an example of a major new area of technical work for APL that we expect will flourish in the decades ahead, we highlight mitigating fundamental changes to Earth systems due to climate change and the depletion of our planet's natural resources. In recent years REDD began an effort called Save the World based on the following vision:

> *Reimagine, redesign, and reengineer human culture and the planet Earth as a system of systems that provides for basic human needs, critical infrastructure, education, a viable economic system, civil order, human rights, life, liberty, and the pursuit of happiness, within a stable, sustainable, and healthy natural environment.*

As it turns out, we have not quite realized this vision yet! There's a lot more work to do. However, the real point of this grandiose vision is that we need to think of the world as a system of systems, and collectively we must stop optimizing one system at the expense of others. The fundamental changes to planetary systems that we are seeing every day, whether they are part of a natural cycle or the result of human activity, along with competition for natural resources, will be among the major challenges confronting humanity in the 21st century. The national security implications of this emerging reality will transform the nature of conflict and require a range of new technologies for the Department of Defense, the Department of Energy, the Department of Homeland Security, and other government organizations. Here are some specific ideas where APL might have a role to play.

Earth sensors and AI: Knowledge is power. To make sound decisions on how to address the major challenges facing our planet, we need continuous access to trusted sources of data on the evolving conditions in each essential domain: land, sea, air, and space. APL has a long history of creating remote sensor systems, and it should be very feasible to use this expertise to develop novel and highly accurate sensors to monitor the environment. The need for continuous analysis of sensor data opens up a vast array of opportunities to build new AI systems that can predict crisis situations before it is too late to act. Examples of current APL expertise that can be engaged in this area include hyperspectral imaging systems, Internet of Things knowledge and capabilities, and research on plants as sensors. The unique relationship between APL and the US Navy provides opportunities to develop and deploy a variety of new sensors to monitor the ocean environments of the world to track temperature changes, fish populations, pollution, bacterial growth, and other threats. Space-based sensors and robotic systems provide another great opportunity to leverage the existing APL expertise base and sponsor relationships.

Water on Earth: Vast areas of the world are now experiencing drought and its devastating consequences for agriculture and the increased probability of wildfires and civil strife. At the same time, sea levels are rising and threatening islands and coastal communities in many parts of the globe. One of the major threats of the 21st century is that there will be too little fresh water and too much salt water. The melting of the Arctic ice poses a range of critical challenges and national security threats as new transportation routes will become open year-round. Competition for natural resources in the Arctic will be a potential source of conflict and a threat to the fragile Arctic ecosystem. How can APL help? APL systems engineering expertise can be used to study the large-scale systems that provide fresh water across the globe to understand how we might capture fresh water from areas where it is abundant and redistribute it to arid regions for food production and reforestation. Our military requires access to clean water in remote parts of the world, and APL work on water filtration systems to meet this need can be applied to community water systems as well. Improving water purification and desalinization systems and exploring their potential value to the United States is another area where APL can make significant contributions, along with systems that harvest water from air. We need to understand the role that these systems can play in addressing water shortages in arid regions and in supporting reforestation projects. Work in these areas will also involve modeling capabilities that help us understand the system-of-systems relationships among water supplies, populations, and energy generation.

Power the planet: Clean energy is, of course, one of the driving goals of many researchers and companies across the globe right now. APL can contribute in this area through innovative materials science and potentially through large-scale systems engineering. Recent APL research on thermoelectric materials offers a path to create new energy-harvesting technologies. Research on battery safety and flexible batteries can open the doors for more expansive program in battery technology. At the macro scale, APL engineers are well equipped to make two types of contributions. First, our engineers can develop new systems to harvest tidal energy, wind energy, and solar energy. Second, we can carry out analysis to understand the return on investment in these methods.

Geoengineering: What is geoengineering? According to the University of Oxford, "Geoengineering is the deliberate large-scale intervention in the Earth's natural systems to counteract climate change." There are two major activities within this area. The first area is solar radiation management, or solar engineering. The goal here is to develop technologies like space reflectors and stratospheric aerosols to reflect sunlight away from Earth to counteract global warming. The second area is greenhouse gas removal, carbon capture, and negative carbon emission, also known as carbon geoengineering. The goals here include reducing the carbon emissions of the world and developing new approaches to sequester carbon. China is reportedly already deeply engaged in geoengineering. A great deal of research needs to be done on modeling the impact of geoengineering proposals to ensure that we understand their potential benefits while also anticipating their potential unintended consequences. Our nation needs a trusted source of ground truth in this area. APL's expertise in atmospheric and environmental science puts it in a great position to assess geoengineering technologies and approaches as well as possibly offer some new ideas in this area.

Geopolitical impact of the changing physical world: Dramatic changes to Earth's systems and the depletion of our planet's natural resources are vital national security issues. At the midpoint of the 21st century, it is highly likely that excessive carbon emissions, competition for natural resources, shortages of food and water, extreme weather events, floods, waste disposal, wildfires, pandemics, and many other environmental problems will be at the center of conflicts across the globe. These problems have the potential to drive human migration on a scale that the world has never seen, and we are already well aware of the tragedy that could result when people fleeing a desperate situation reach a national border. As climate change threatens the stability of geopolitical and economic systems across the world, conflicts become inevitable. Additionally, as transportation across the Arctic becomes available throughout the year, control of shipping lanes emerges as a new international issue. As nations search for new sources of energy and minerals, the ocean floors of our planet become battlegrounds in which unregulated seabed mining operations threaten to unleash a new array of unforeseen environmental disasters. This looming state of dystopia is poised to be the most critical national security issue of this century. APL is in a unique position to provide analysis grounded in science, and this will be essential to our nation's leaders.

The areas above are not meant to be an exhaustive list of the areas that APL could or should pursue in responding to the challenges of climate change. It is clear, however, that fundamental changes in Earth systems and the depletion of natural resources will present problems of national importance that touch every mission area at APL.

In addition to all the topics discussed above, there is an exciting set of problems that REDD is working on right now that will certainly be active areas of research in 2042 and beyond. These areas include:

- Research and development of hypersonic weapons
- Innovative systems for personalized health care
- Novel uses of plants and animals as sensors
- Human performance and biomechanics
- New materials and applications for additive manufacturing
- A general mathematical theory of emergent phenomena
- Design and fabrication in support of Space Exploration Sector missions

REDD support for a wide array of APL sector projects will be constant in the decades ahead. There will also be a wealth of additional research on artificial intelligence and autonomous systems beyond what we have mentioned above, and additional articles in this issue cover some of those areas.

Finally, we would like to mention something that we fully expect to stay the same for many years into the future. APL has succeeded for almost 80 years now because its most important core value is *unquestionable integrity*. The world today is experiencing a crisis of trust in public information and a lack of confidence in national-level leadership. APL will always have a vital role to play in establishing, preserving, and communicating scientific truth. At its centennial APL will be more important than ever as a trusted national treasure that helps our nation's leaders arrive at the best possible decisions in an increasingly complex world.

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