Envisioning the Future of Ocean Exploration

Statement of

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Chairwoman Fletcher, Ranking Member Lucas, members of the Environment Subcommittee, and members of the House Committee on Science, Space, and Technology, thank you for this opportunity to testify on the importance and future of ocean exploration. I am honored to represent two organizations that have led the world in science, innovation, and exploration for more than 130 years, the Massachusetts Institute of Technology and the National Geographic Society.

Founded to accelerate the nation's industrial revolution, MIT is profoundly American. With ingenuity and drive, MIT graduates have invented fundamental technologies, launched new industries, and created millions of American jobs. At the same time, MIT is profoundly global. The MIT community gains tremendous strength as a magnet for talent from around the world. Through teaching, research, and innovation, MIT's exceptional community pursues its mission of service to the nation and the world.

In 1888, the National Geographic Society was founded to "the increase and diffusion of geographic knowledge"; since then, it has become a US-led global leader in science and exploration. Today, it is an impact-driven global nonprofit organization that pushes the boundaries of exploration, furthering understanding of our world and empowering us all to generate solutions for a healthy, more sustainable future for generations to come.

At the nexus of exploration and technology, and with a 20-year career in deep sea exploration, I founded the MIT Media Lab Open Ocean Initiative to work at the intersection of science, technology, art, and society to design and deploy new ways to understand the ocean and connect people to it, empowering a global community of explorers.

Importance of Ocean Exploration

The deep ocean below 200 m is the single largest ecosystem on our planet (Levin et al., 2019), which supports life for every human on earth. The ocean regulates our climate; provides more than half of the oxygen that we breathe; supplies 20% of the average intake of animal protein to 3.1 billion people; holds numerous sources of living, non-living, and cultural resources; and supports a growing $1.5 trillion global ocean economy. In turn, we are impacting the deep sea at an unprecedented rate with increasing greenhouse gas emissions, pollution, extraction industries, noise, and numerous industries are eyeing the deep sea for further industrial development (Mengerink et al., 2014; Packard & Scholin 2018).

And yet, in more than 150 years, we have mapped the shape of less than 15% of the seafloor and human eyes have observed less than 5%. We have only a rudimentary understanding of the ocean's role in our survival on earth and are at a critical point where we may be irreparably impacting the deep sea without truly understanding what those impacts may be.

How is it possible for us to know how to wisely use and protect our planet if we do not know what resources we have, their interactions with each other, and their interactions with humans? We need to know and fully understand our ocean so that we may thrive in harmony with nature now and in perpetuity. We don't have a Plan B.

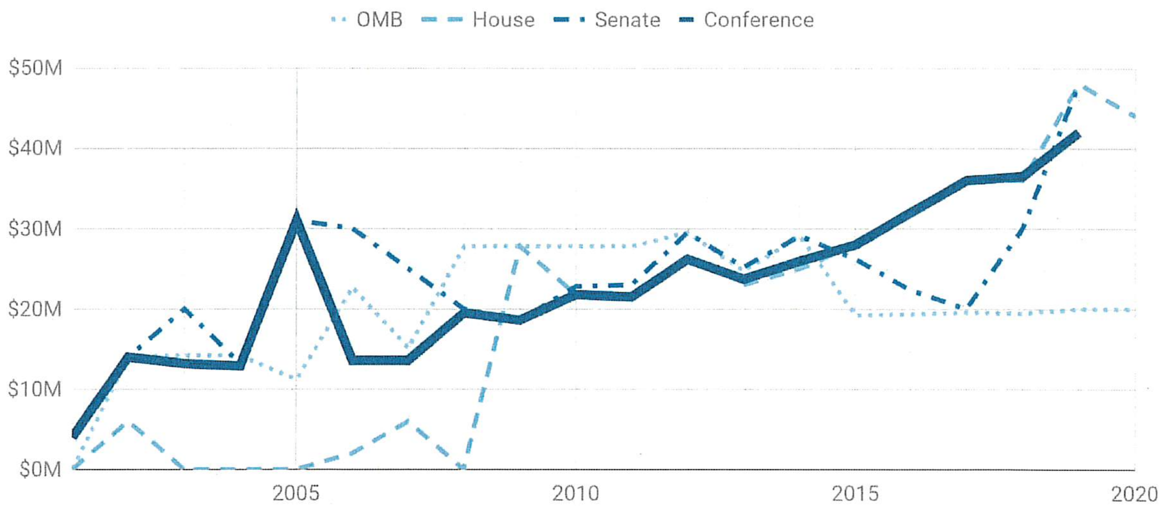
Status of Ocean Exploration

Almost 20 years ago, an expert panel led by Dr. Marcia McNutt was convened on ocean exploration under the Clinton administration. In its Report of the President's Panel for Ocean Exploration the distinguished group of academic, industry, and government leaders called for the establishment of a federal Ocean Exploration Program, funded at $75 million/year with the following objectives (McNutt et al. 2000):

1. Mapping the physical, geological, biological, chemical, and archaeological aspects of the ocean, such that the U.S. knowledge base is capable of supporting the large demand for this information from policy makers, regulators, commercial ventures, researchers, and educators;
2. Exploring ocean dynamics and interactions at new scales, such that our understanding of the complex interactions in the living ocean supports our need for stewardship of this vital component of the planet's life support system;
3. Developing new sensors and systems for ocean exploration, so as to regain U.S. leadership in marine technology; and,
4. Reaching out in new ways to stakeholders, to improve the literacy of learners of all ages with respect to ocean issues.

Such a program was established within NOAA in less than a year, under the administration of President George W. Bush. I was fortunate to have worked in the newly formed NOAA Office of Ocean Exploration in its first year as a John A. Knauss Marine Policy Fellow. In the first year, $4 million was appropriated, and with the exception of 2005, the program has grown linearly since that time but has reached a maximum of only $42 million in 2019 (Figure 1; AIP 2019). This budget history is a far cry from the recommended funding level of $75 million per year recommended in 2001 (roughly equivalent to $108 million in 2019 at level funding).

Figure 1. Budget history of the NOAA Office of Ocean Exploration & Research, 2001-2020 (AIP 2019)



As a result of volatile and insufficient funding, progress in our national program of ocean exploration has been steady, but slow. In a high risk, high reward field like exploration, where we don't know what we might discover when we look in an unexplored region, sufficient, stable funding is necessary to support the enterprise. If, however, funding is meager and unstable, agencies like NOAA will tend to invest in safe bets that will likely result in incremental progress, rather than riskier, but potentially transformative, endeavors that can truly change the future of exploration, enhance our understanding of the ocean, and ensure US leadership in the field.

For example, the technological gold standard of deep sea exploration today is a large vessel equipped with a hull-mounted multibeam echosounder, remotely operated vehicles (ROVs), and satellite telecommunications systems. Assuming a typical exploration vessel spends 800 hours of time per year on the seafloor with an ROV, we will have explored 0.01% of the seabed in one year per ship. At that rate, it will take 10,000+ ship-years to completely view the seafloor, and orders of magnitude longer to characterize the entire volume of the ocean -- once. Even if the fleet of full-time exploration vessels jumped to ten ships, it would still take 1,000+ years to explore the seafloor. In addition, these exploration efforts cost tens of millions of dollars annually and require large ships and equipment, making ocean exploration inaccessible to the vast majority of the population.

While the current operational model plays an important role in current ocean exploration, the vision that is being implemented now is more than 40 years old. Other fields of science have not only kept up with the exponential rate of change of the digital era, but driven it. Ocean science and exploration have, in many ways, been left behind.

Today, deep sea exploration sits at an inflection point. We could continue employing large, expensive assets and making incremental progress in exploration of the deep sea. Or, we could invest in new technologies, research methods, and social systems to transform and accelerate what it means to explore and discover the ocean in the 21st century.

While we have made progress in recent decades, if we are to accelerate the pace of deep sea exploration and maintain global leadership in the field, we must create a new paradigm to increase efficiency and access. Only now, with recent technological breakthroughs across numerous sectors, is it possible to take the current linear growth of exploration and make it exponential. To make gains in ocean exploration, we must invest in three areas: (1) **Maximizing** efficiency of discovery; (2) **Exploring** the world's undiscovered places; and, (3) **Leading** a global community of explorers.

Maximizing Efficiency of Discovery

Current best practices focus on ship-based equipment, which afford spectacularly-detailed mapping, exploration, visualization, and sampling, but only on a hyper-focused spatial scale with restricted temporal access. It also defines a very high price point, and caps the area-per-volume-explorable-per-year. In addition, despite the exploration community's growing expertise with setting exploration targets, there are certainly times when hundreds of thousands of dollars could have been more strategically-focused on other areas, since many key questions do not need the fine-grained observations that large ships and ROVs afford. In other words, what if we could maximize the efficiency of discovery by using smaller tools and platforms for preliminary exploration, and then use the larger ships to follow-up on identified targets with the full suite of best-available technology? And beyond the process of data collection, are we truly maximizing use of the data that we collect through advanced analysis techniques?

Toward a Spectrum of Exploration

Exploiting technological developments from outside the field now allows us to tackle many existing and emerging research priorities with low-cost, low-bandwidth, distributed swarms of sensors and platforms. On the one hand, this requires a radical rethink of what data we actually need to extract from the ocean, and on the other, it requires a radical rethink of what a platform looks like, how we deploy them, and how we recover data in an environmentally responsible way. In terms of data needs, high definition video and samples from the entire pelagic and benthic ocean are the ideal, but the reality is that a strategic, focused approach to a suite of standardized metrics would vastly improve our overall understanding, and help to guide future exploration with more fine-grained tools. Some of these metrics could include biomass tallies, environmental DNA (eDNA), CTD, oxygen, visual imagery, and collection of specimens. Platforms must evolve to be efficient and have longevity, but must simultaneously have high retrieval rates, installation-permanence, and/or low environmental impact. New systems must achieve high-tech functionality without compromising environmental integrity.

In many ways, the US is already a leader in marine innovation for ocean exploration. Take for example, the fact that the first autonomous underwater vehicle (AUV) company in the world, Bluefin Robotics, spun out of MIT Sea Grant in 1997; or the winning Shell Ocean Discovery XPRIZE for Advancements in Autonomous Ocean Exploration team, announced last week, was led by a US-based team; or start-up marine tech companies like Saildrone or SofarOcean are beginning to make inroads at making the industry more innovative and nimble.

But in many ways, we are starting to fall behind. Of the 6 leading AUV companies in the world, half are US-owned, and foreign companies are starting to outpace US players in terms of sales growth; in addition, Asia is starting to see increasing results in investment in this space. Furthermore, many marine technology companies primarily support the offshore energy and defense markets, driving up costs for sensors and other systems so high that it is impossible for scientists to explore as efficiently and effectively as we need. Given recent advances made in terms of economies of scale in electronics, robotics, and sensors, the time is right to not only support the invention of new technologies for deep sea exploration, but also nimble, responsive models to support academic-public-private partnerships to operationalize of them.

Big Ocean, Big Data

Ninety percent of the data in the world has been generated in the past two years (Marr 2018), and there is no reason to believe this explosion in data volume will not continue. More than ever, a solid foundation for processing these valuable data is needed so that they can be accessible and usable. There are many platforms for more standard oceanographic metrics, but for the storage, processing, and annotation of computationally expensive visual data that is required for exploration, challenges still remain. As more ocean-going platforms integrate cameras for observation and navigation, platforms such as Seascribe, Squiddle, and the Monterey Bay Aquarium Research Institute's (MBARI) Video Annotation and Reference System have evolved, but still require extensive curation by experts. For example, the recent NOAA CAPSTONE video data was real-time logged by experts on-ship and using telepresence in 2015-2017, but the post-campaign data curation and cross-checking is still underway by a dedicated team of scientists at the University of Hawai'i.

To address the data analysis bottleneck, the MIT Media Lab, MBARI, National Geographic, and CVision AI are using machine learning to develop a new, publicly available, expertly curated, baseline image dataset called FathomNet. We are working together to build and train machine learning algorithms to accelerate the curation and annotation process, such that it will be tractable for large, citizen-science, distributed platforms to collect data that can be made usable in an efficient manner. In short, we are using machine learning to directly accelerate development of modern, intelligent, analysis of underwater visual data that can be used for not only automated tracking and recognition of objects in the deep sea, but also future development of "smart" robots for exploration and science. Given the emergence of high-resolution, cost-effective sensors, platforms, and imaging systems that will be coming online in the immediate future (e.g. Saildrone, 4k, 8k cameras), there is an impending explosion of ocean data. Solutions across a gradient of explorers, platforms, and data types will be required to handle and ultimately understand this deluge of information.

More broadly, there are three areas of opportunity for dealing with big ocean data: using new and emerging data science techniques to explore legacy, current, and future data for better understanding of the ocean across disciplines and industries; using the results of such analysis for the creation of new data-driven tools for exploration, such as curious robots and heads-up data displays to make real-time exploration more efficient; and, visualizing and physicalizing data in new, innovative ways so that we may share results and tell data-driven stories creatively with a broader audience than ever before.

In summary, in terms of technological investments, we must consider:

1. **Leveraging economies of scale** to dramatically decrease the cost of sensors and systems by orders of magnitude to make it possible for us to significantly increase the amount of area and/or volume explored for markedly lower cost than is possible today;
1. **Developing data systems**, standards, archiving, access, and advanced analysis, with consideration for privacy and data rights, to fully understand data being collected so that we may understand ocean dynamics and interactions at new scales in an integrated way;
2. **Innovating across the spectrum of exploration** requires both applying advances from other industries to ocean challenges, and creating a responsive environment in which to deploy and operationalize them to re-establishing the United States as the global leader in marine innovation.

Exploring the world's undiscovered places

The ocean contains 320 million mi^3 of water covering 140 million mi^2 of seafloor across 71% of the planet. Of that, the United States has jurisdiction over 4,382,645 mi^2, the largest Exclusive Economic Zone (EEZ) in the world, and an area larger than that of the terrestrial United States (3,800,000 mi^2). The most robust, comprehensive scientific data from all areas of US waters must be collected, analyzed, and shared to support informed decision-making at all levels of American society for national, economic, homeland, natural resource, and cyber security. To be sure, the mandate to fully explore the entirety of the US EEZ is a significant challenge.

But it is not enough. The ocean does not know boundaries, and it is an incredibly interconnected system, from coastal communities to the high seas; the atmosphere to deep sea trenches. Ocean processes affect every aspect of our lives, and we are now learning that humans in turn affect many aspects of the ocean. Three years after the Fukushima Daiichi nuclear disaster in Japan, radioactive isotopes were found off the west coast of the US (ORO 2019); Atlantic mackerel, which migrate between Canadian and US waters, are in decline, adversely affecting fisheries in the northeast US; and warming waters in the Atlantic are intensifying hurricanes that land on American shores (Witze 2017).

We therefore must view ocean exploration as a global imperative, not a national one. We must come together on an international level, to achieve something greater than we could ever do alone. Other international scientific efforts, like the International Space Station or the Large Hadron Collider at CERN, have achieved amazing results, and we must use these as models for ocean exploration. Furthermore, deep ocean exploration of biological, chemical, geological, archaeological, and physical parameters would greatly benefit numerous international policy-making bodies, initiatives, and agreements that deal with climate, biodiversity, deep seabed mining, fishing, shipping and dumping, and ocean assessment (Levin et al., 2019). These are issues that affect humans around the world, and it would benefit everyone to work together.

Today's hearing is particularly timely because two weeks ago, the International Oceanographic Commission of UNESCO held the first Global Planning Meeting of the UN Decade of Ocean Science for Sustainable Development. The Decade will take place from 2021 to 2030, and is now defining the goals and approaches that a collaborative, international community of scientists, engineers, policymakers, and citizens can undertake over the next ten years to ensure ocean science and technology can support countries around the world "in creating improved conditions for sustainable development of the ocean." The United States is already involved, with four out of nineteen members of the Executive Planning Group representing US organizations, as well as numerous American scientists and policymakers participating in the first meeting. We should The Decade of Ocean Science is a tremendous opportunity to work with an international team that is already working on a strategy for long-term exploration and understanding of the ocean.

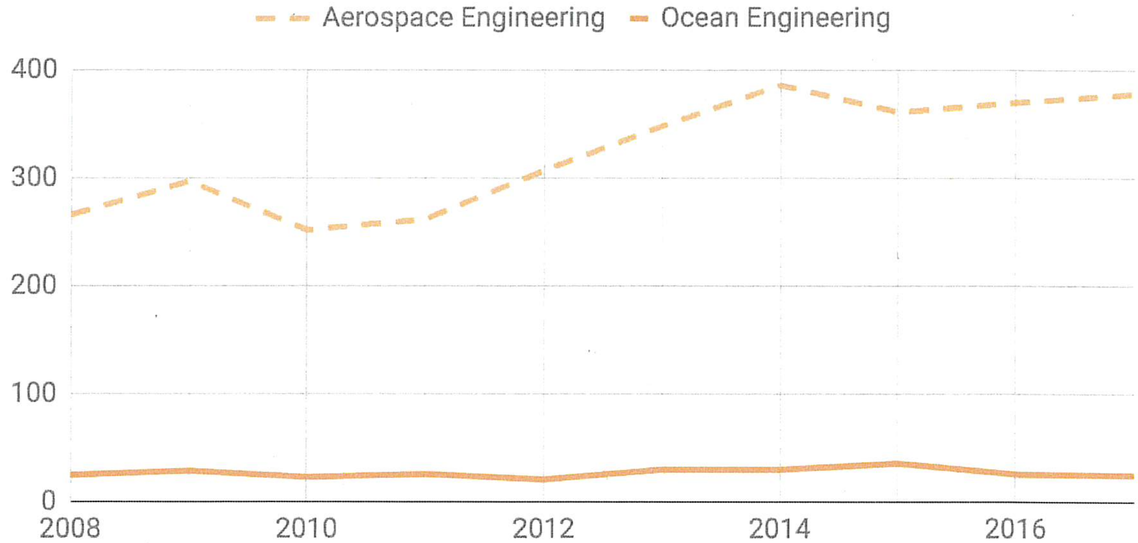
Leading a global community of explorers

Traditionally, exploration is conducted by those with advanced degrees and access to costly equipment. In order to fully explore and understand our vast oceans, however, we need to work outside of the traditional academic structures of science and innovation. One strategy for thinking beyond our current model is to build new bridges with communities who have not yet been invited into oceanographic exploration, including underrepresented communities within the United States, as well as developing countries around the world. Instead of only an elite cadre of academics participating in ocean exploration — which limits the types and amount work we are able to do — we need to nurture new communities, build greater global capacity for exploration, and look for ideas and expertise in unexpected places.

First, however, we must determine whether or not the United States is positioned to lead such a community. To do so, consider the number of students graduating with doctoral degrees as a metric for investing in future leaders as well as diversity in the field (NSF 2018). When considering technical capacity, we see that the number of Ocean Engineers graduating with

PhDs from 2008-2017, the number has not significantly changed (average 27/year); this is in stark contrast to the number of Aerospace, Aeronautical, and Astronautical doctoral recipients, which averages 323/year, more than ten times the number of Ocean Engineers (Figure 2).

Figure 2. Ocean vs Aerospace, Aeronautical, and Astronautical Engineering PhD graduates 2008-2017 (NSF 2018)



As has been demonstrated in numerous studies, as well as recent hearings hosted by this committee, the diversity of a nation's workforce is a key indicator of innovation and success (NASEM 2019). First, I will note that it was challenging to determine how well the US is training graduate level students -- the future leaders of exploration -- due to a lack of data on ocean science, which is often aggregated with other earth sciences. I did find, however, a few notable trends. First, that, on the whole, the gap between male and female earth scientists has narrowed by 8% from 2008 to 2017, with 2017 seeing 45% of graduating earth science PhD being female (Figure 3). From the data available, it is not possible to know what percent is ocean scientists, but this is a positive trend overall for earth sciences generally.

In terms of racial and ethnic diversity, we are also seeing a positive trend. In 2009, doctoral graduates in ocean, marine, and fisheries sciences were 14% non-white, and in 2017, 24% of doctoral graduates were non-white US citizens (Figure 4). While these trends are headed toward seeing a workforce that represents the US population as a whole (USCB 2019), we still have work to do. Female engineering PhDs, for example, are still outnumbered by men in a 3:1 ratio. And while it is encouraging to see that 24% of ocean science PhDs are not white today, we are still lagging behind today's composition of US population, which is 35% non-white. Examining projections of the size and composition of the US population in 2060 shows that we should be aiming for nearly 60% non-white ocean scientists in the next 40 years (Colby & Ortman 2015). The only way to do that is to start investing in the children that are in school, and those who are being born, today.

Figure 3. Female vs Male PhD Graduates in Geosciences, Atmospheric Sciences, and Ocean Sciences (2008-2017) (NSF 2018)

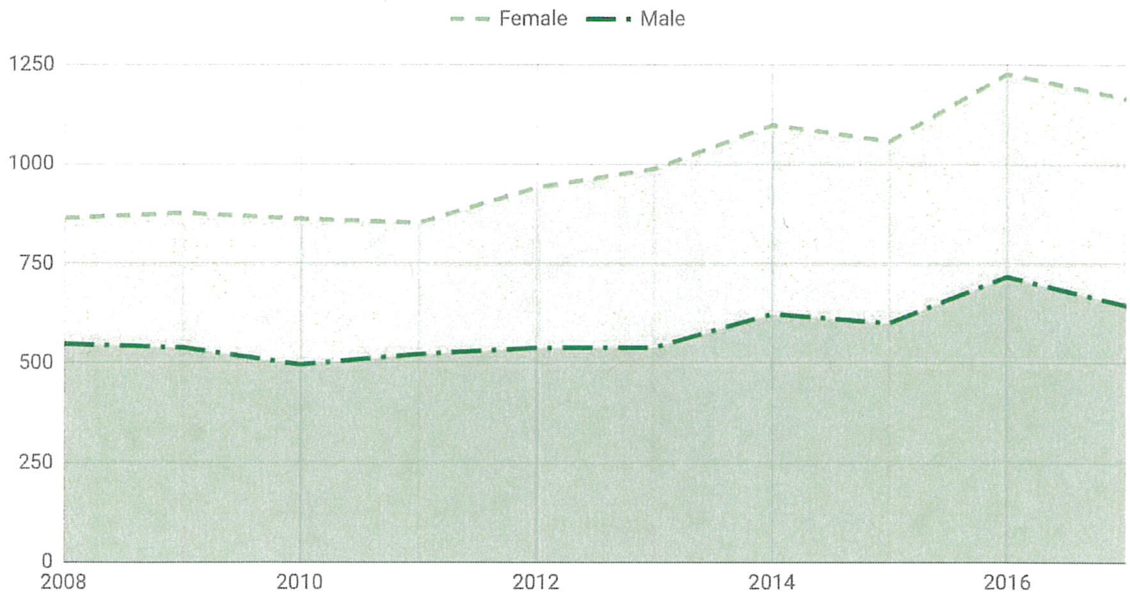
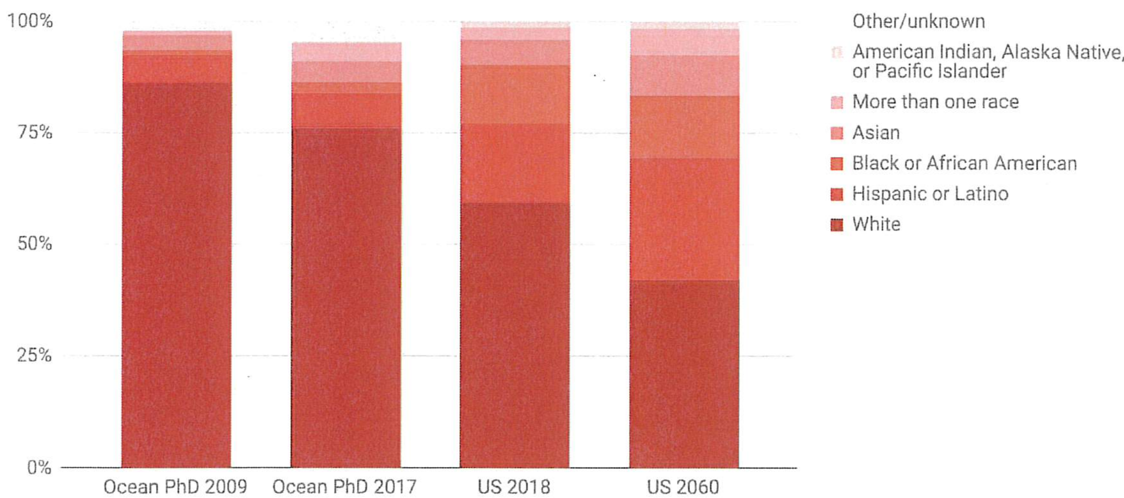


Figure 4. PhD Grads in Ocean, Marine, and Fisheries Sciences 2009-2017 vs US Population 2016-2060 by Race/Ethnicity (NSF 2018, USCB 2019, Colby & Ortman 2015)



To address ocean exploration as a global imperative, we also must consider global capacity. Only ~5% of coastal nations operate 10 or more research vessels, and the United States is the only country in the world that operates vessels of exploration. Academic deep submergence capacity is similarly small. That leaves approximately 95% of coastal nations with little to no ability to explore their own deep waters. This is problematic, not only for those nations to be able to understand and manage their own resources, but also for understanding global connectivity of deep sea systems.

Building an informed appreciation by the global population for ocean discovery is critical. Knowledgeable, responsible citizens purchase, work, and behave differently when rationally-made choices reaffirm beliefs established during early childhood (Kahneman 2011). Continued exposure to ocean discovery will strengthen stewardship and inform decision making – making discovery visible and mainstream will pave the way for a long-term cultural commitment to exploration. In the last 10 years, ocean exploration has entered the public eye through the power of telepresence, and reaches an audience of tens of millions people annually (Raineault et al. 2019). This figure is less than 1% of the global population – more of a niche following than a mainstream one. To create a foundational culture of ocean exploration, we should reach at least 10% of the global population, with a goal of reaching 100%. That is a long way to go.

Early education, continued engagement, and mainstream entertainment can work together to reinforce a connection to the ocean that could result in a global network of individuals, institutions, and industries more responsibly using the bounty of the seas. A populace raised on, near, or deeply invested in the ocean would create a larger pool of knowledgeable employees for the blue economy, and citizens engaging as responsible ocean stewards. To that end, leveraging the tools of mass media such as film and television with ocean-based themes and stories will create beloved characters and fond memories, as well as profit for entertainment industry. Disney's *Moana* is the first animated ocean exploration hero to hit the mainstream, grossing more than $600M worldwide, and the 12th-most profitable release of 2016; *Aquaman* grossed $1.148B worldwide, becoming the highest-grossing film based on DC comics characters, and 21st highest of all time. The time is right to add more ocean characters and role models to the scene.

2018 National Ocean Exploration Forum: All Hands on Deck

In November 2018, I chaired the 2018 National Ocean Exploration Forum at the MIT Media Lab in collaboration with OER to imagine creative new ways to make the ocean so pervasive in modern culture that everyone has a positive association with, and understanding of, the sea. The Media Lab and OER brought together leaders in ocean exploration, industry, entertainment, recreation, art, and design to empower an open, inclusive global community of ocean explorers. Throughout the course of the Forum, we addressed: sparking curiosity in the ocean through play; imagining a bright, optimistic future for the ocean; immersing people in the ocean and bringing the ocean to people; engaging the heart and soul through the creative arts; empowering a global community of ocean explorers; and, connecting people to the ocean and to each other.

Given how poorly the oceanographic community has historically tackled diversity, we knew we needed a new approach to planning of the 2018 Forum. We intentionally structured the event to enhance diversity and equity, including investing in travel funding for 40 people from around the world who could not otherwise attend the Forum, particularly students, early career scientists, and those from developing countries; demonstrating that representation matters by inviting 57% female and 35% non-white speakers. Finally, we included representatives from mass media and toy industries, such as Disney, LEGO, and the World Surf League, that reach billions of people in a fun and entertaining way; a myriad of opportunities abound with innovative collaborations such as these because it is clear that the oceanographic community cannot reach the global population alone.

My Deep Sea, My Backyard

In parallel, to address the capacity gap between developed and developing countries, the MIT Media Lab is working with colleagues from Boston University, National Geographic Society, Natural History Museum (UK), University of Rhode Island, Inter-American Development Bank, and others to empower citizen explorers in developing island states to explore their own deep-sea backyards using low-cost technologies, while building lasting capacity. This pilot project, called *My Deep Sea, My Backyard* aims to help realize UN Sustainable Development Goal 14 in Kiribati and Trinidad and Tobago; There is interest from colleagues around the world to expand the project to dozens of other countries. Our goal is to enable access to emerging deep-ocean technology that can be used from any platform; and train new scientists, students, and communicators to enable use and dissemination of findings to all stakeholder groups in both underrepresented communities in the U.S. and developing countries around the world.

Working across lines of difference — culture, gender, geography, and industry — requires trust and respect built through a commitment to a shared set of values. We are also doing research on participatory design approaches, and we have been developing this set of Principles for Value-Driven Design, which are being applied to these and other projects focused on enhancing equity, diversity, and innovation in ocean exploration. Participatory approaches to data collection and analysis as well as participatory approaches to technology development, are nascent in the oceanographic community (Glazer 2019). These approaches will allow us to collect and analyze broader datasets, expand the definition of who is considered an explorer, open up future STEM careers for underrepresented people, and help create technologies that have yet to be imagined.

Toward a new Paradigm for Ocean Exploration

Creating a global program of ocean exploration is ambitious, but imperative. Investing in innovative, strategic exploration of our own planet will have a significant return on investment and will result in innumerable benefits to the United States and the world. Most importantly, we must find a balance between ensuring a thriving blue economy with understanding deep sea systems, thus giving us the opportunity to protect the systems on which we rely before they are destroyed. Our very survival on Earth is at stake and there is no time to waste.

The MIT Media Lab Open Ocean Initiative stands ready to serve the nation and the world. We look forward to the opportunity to work with the House Committee on Science, Space, and Technology to create an innovative spectrum of platforms, technology, and people to maximize discovery and under. By undertaking an ambitious, long-term global strategy for ocean exploration, we will leverage all that we already know, and all that we will discover.

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