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Food for Thought

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Watching the sunrise on our ocean planet in a new era of marine science

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Food for Thought articles are essays in which the author provides their perspective on a research area, topic, or issue. They are intended to provide contributors with a forum through which to air their own views and experiences, with few of the constraints that govern standard research articles. This Food for Thought article is one in a series solicited from leading figures in the fisheries and aquatic sciences community. The objective is to offer lessons and insights from their careers in an accessible and pedagogical form from which the community, and particularly early career scientists, will benefit. The International Council for the Exploration of the Sea (ICES) and Oxford University Press are pleased to be able to waive the article processing charge for these Food for Thought articles.

Abstract

Over the last 30 years, ocean sciences have been undergoing a technological revolution. Changes include the transition of autonomous platforms from being interesting engineering projects to being critical tools for scientists studying a range of processes at sea. My career has benefitted immensely from these technical innovations, allowing me to be at sea (virtually) 365 days a year and operate ocean networks globally. While these technical innovations have opened many research doors, many aspects of oceanography are unchanged. In my experience, working/talking/scheming with scientists is most effective face-to-face. Despite the growing capabilities of robotic platforms, we will still need to go to sea on ships to conduct critical experiments. As the responsibilities of scientists expand with mandated outreach efforts, I strongly urge young scientists to leverage the expertise of Broader Impact professionals, who are increasingly available to our community, in order to maximize the effectiveness and efficiency of our outreach efforts. Given the increasing observations of change occurring in the ocean, our work is ever-more important while still being fun. I am blessed to have had a career as an oceanographer exploring this planet.

Keywords: ocean observations; marine networks

Reflecting on my science journey is a fun exercise (a BIG surprise given my youthful persona) and has provided me an opportunity to appreciate that I am blessed with having the greatest job in the world. People ask me about what my job is like, and my usual response is that I don't have a job; I have a hobby. What an awesome life! Over the years, my excitement and passion have grown reflecting both an expanding fascination of this amazing, interconnected world and the growing urgency to understand our planet's trajectory given mounting evidence of human impacts on the Earth system. My journey has occurred during a period of fundamental change in how scientists explore the ocean, transition to open data science, and recognition of the importance of translating science knowledge to diverse stakeholders. These changes are altering the definition of what an oceanographer is. I believe that these changes will enable the next generation, armed with novel tools, to meet grand societal challenges. *I must admit to being envious of the new generation of researchers who will be so important in helping society during a critical time. As the sun rises on this new era I am grateful to have been working in the early dawn of the future of oceanography*.

How did I end up as an oceanographer?

I would love to think that my career is a story of committed logical strategic thinking, BUT there has also been much luck that provided me unexpected opportunities, people, and perspectives. Those opportunities started early. I grew up swimming, fishing, diving, and surfing in the Pacific, which dominated any spare time I had. I hope this personal connection to the ocean remains true until I leave this planet. Additionally, my biological father (Max Gumpel) was a driven scientist (Davies and Gumpel 1960) with a full lab in the back of the house and weekends would start with him announcing some projects for us to do. One of my favorites was the weekend we built and installed a Richter scale in the basement. He disappeared when I was young (stories best shared over a beer). My stepfather (Paul Schofield) raised me and even though he was not a scientist, he provided me many career skills. Paul is an amazing storyteller, and early on, he gave me the passion of communicating across diverse communities. My early years hanging out with gifted people in southern California, some going on to become professional surfers, it was clear that my "stork" style of surfing was not going to provide a career path. My love for the ocean expanded to all aspects of the sea (science, history, and art). This led me to my local school (University of California at Santa Barbara), where I was so lucky to join a leading research university with gifted and passionate teachers. At that time, I quickly found myself working with two professors who changed my life. Barbara Prézelin introduced me to the beautiful process of photosynthesis and the physiological ecology of phytoplankton. Raymond (Ray)

Smith introduced me to the strategies and tools for studying processes in a dynamic ocean. Ray's first lecture to me as an undergraduate focused on the importance of understanding spatial and temporal scales in the ocean and that effective sampling would require integrated multiplatform networks. Unknown to me at the time, this concept would become a major focus of my career. Upon graduation, I took a laboratory technician position with ½ of the time focused on mass culturing of algae for a pharmaceutical company in Barbara's laboratory and the other ½ deploying to Antarctica as a krill technician. These experiences convinced me to apply to graduate school working on phytoplankton with Barbara.

Graduate school, remaining with Barbara and Ray, was a joy full of great teachers–friends, and much time at sea studying aquatic bio-optical properties, the impact of the Antarctic ozone hole on plankton, and phytoplankton physiology. When in graduate school I was lucky to be embedded in a culture of open intellectual flexibility that was not averse to students diving into entirely new endeavors. My graduate experience went quickly but much life happened. My first child was born during my Ph.D. After the birth of my daughter, I began to experience physical issues that eventually was diagnosed as Stage 4B Hodgkin's lymphoma. The oncologists put me on a very aggressive chemotherapy and radiation regime but with the support of my wider academic community and family I was able to beat the disease with 8 months of weekly treatments. Seven months after being cleared I deployed to Antarctica to study the impact of the ozone hole on phytoplankton. My cancer experience impacted me as I had gained an appreciation in my early 20's that life is fleeting and for *me* the best remedy was to charge at full speed while able.

During graduate school, I was very lucky to have time interacting with John Kirk. He, while working in the United Kingdom, was one of the first to isolate plant plastids (Kirk 1970, 1971), but then relocated to Australia to start a new career and helped create the field of hydrological optics (Morel 1977, Smith 1978, Kirk 1994, Zaneveld 1995, Morel 2008). His advice to graduate students was to conduct a major shift in research focus about every 5–10 years to keep yourself a hungry novice. I see this reflected in my career with an initial focus on phytoplankton photosynthesis, to the cellular physiology of stress, to autonomous ocean observing networks, to evolution of phytoplankton taxa, to climate-driven changes in ocean systems, and now moving to integrated terrestrial–marine food security strategies. Some of these changes grew organically out of the work being conducted, but often it was the incorporation of new methodologies/technologies that got me invited into large interdisciplinary expeditions. These opportunities early in my career were enabled through the strong advocacy of my graduate student advisors.

As I had been at UC Santa Barbara as an undergraduate and graduate student, my thought when finishing my Ph.D. was that it was time to do something different to expand my horizons and try to differentiate myself from my biological oceanography peers to better compete for a permanent job. Through a friend, I met David Millie at an ASLO Ocean Sciences meeting and our discussion resulted in a postdoctoral position in the Department of Agriculture in New Orleans, as a food flavor quality biologist. The project was to develop methods to discriminate specific taxa of algae using optical approaches and, if possible, provide insight into the physiological state of the algae. This work was motivated by the commercial aquaculture industry, specifically catfish, where a major economic bottleneck for the industry was the production of off-flavor metabolites by cyanobacteria in the farm ponds that made the product unpalatable. I figured the title food flavor quality biologist would catch people's attention, but my Ph.D. advisors were not stoked thinking that I was going to fall out of the oceanography community.

Our first effort focused on identifying specific algal taxa using bio-optical techniques. For those efforts, David and I collaborated frequently with Gary and Barbara Kirkpatrick from Mote Marine Laboratory, where for decades we developed signal processing approaches to discriminate different algal taxa based on their cellular absorption properties (Millie et al. 1997, Kirkpatrick et al. 2000). These efforts resulted in a decades-long partnership with the Kirkpatrick's, focusing not only on the discrimination of harmful algal bloom species but also on the development of new tools to make measurements over sustained periods of time (Kirkpatrick et al. 2003, Schofield et al. 2008). David was an active mentor and within a week of joining his group, he required that I apply to a job at Rutgers University (he said he had a hunch it would be good for me, but I thought I had already pissed him off and he was trying to get rid of me), and I was fortunate to get the job during my first year as a post-doctoral researcher. That said, I applied for many positions in that year (I used to keep a binder of rejection letters for graduate students to see and know that we all go through uncertain periods), but compared to many, I had a relatively short wait. I credit my graduate and postdoctoral advisers, who were always pushing me to be completing manuscripts and finishing projects.

The diverse experiences and collaborations prepared me to thrive when I joined Rutgers in 1995, where I was hired by Frederick Grassle, who was tasked with building a new oceanography program in New Jersey. It was during my job interview that I met Scott Glenn and we started a conversation on ocean dynamics, biophysical coupling, ocean observation, and modeling. That conversation has continued for 30 years. It has been an unparalleled gift to work with a great friend. We come from disparate science backgrounds. He was a physical oceanographer with a background in waves and sediment resuspension processes and I was a biological oceanographer interested in physiological ecology of phytoplankton. Our respective mentoring committees discouraged this partnership often saying it would distract us from our fundamental research, which was important to us achieving tenure. I find this humorous now looking at the numerous current grant calls for transdisciplinary research across disciplines while back then having a physical and biological oceanographer merging groups was considered risky. Both Scott and I are happy that we ignored the well-meaning advice provided at the time.

As a team, we developed the Coastal Ocean Observation Lab (COOL), which grew quickly, hosting many diverse interdisciplinary programs spanning from forecasting coastal upwelling and its biogeochemical consequences to the fate of river plumes and their potential transport of urban contaminants across continental shelves and associated impacts on water quality. Our other focus was on developing tools (instruments and models) to resolve the time and space scales required to address the questions at hand. We hosted the Office Naval Research Hyperspectral Coastal Ocean Dynamics Experiment (HyCODE) off New Jersey, where over 4 years every summer, over 200 researchers, up to 11 ships, and 3 aircraft joined us. Many of the groups that participated in the experiments were not funded by the actual HyCODE project but came through their funding to conduct focused experiments in a well-sampled 3D ocean with a range of forecasting products guiding adaptive sampling of their processes of interest. Some groups arrived unannounced. We had Navy SEALS show up, which was awesome, and my favorite memory was when a science group (who shall go nameless) showed up by accident a year early. Around the 24:7 sampling, a large community of scientists connected as we had rented almost a block of summer rental houses and it became the equivalent of a giant nerd block party with dinner debates ranging from turbulence closure schemes, optical inversion techniques, and who was the best cook in the group. This was much fun, but I was still going through the tenure process, which was stressful. I wish I had more training in management skills/tools and cooking for large groups (I signed up to be our head cook for the group, and quickly found a need to diversify meals outside of my comfort zone).

The success of HyCODE convinced many organizations of the value of these novel data streams. For example, the state of New Jersey has anchored its coastal water quality sampling with COOL gliders for over a decade; hundreds of fishermen throughout the mid-Atlantic use the open-access satellite data on a daily basis; and US Coast Guard Search and Rescue tools now include high-frequency surface current radar data. This was a challenge for us, as COOL was/is funded one project at a time with no sustained funding to maintain the operational data streams that are critically important to numerous external communities. We therefore suggested-forced-coerced the University to transition us into a University Center, which provided a means to garner support to maintain a large portfolio of projects and better utilize resources of the larger University. As we had built the COOL "brand" globally, we also wanted to maintain our existing name recognition and came up with the name Center of Ocean Observing Leadership so that we could keep our acronym. Developing a funding base to maintain a large group is difficult. My advice is to keep an open mind of potential funders and diversifying (federal agencies, foundations, and local stakeholders) the funding pot, which is an effective strategy to survive the shifting priorities of any specific agency. This strategy takes time to develop and working with a cohort collaborators is required to navigate diverse funding streams and to stay sane when funding is tight.

With the autobiographical story out of the way, I want to focus on how much oceanography has been changing. For this, it is important to review where the world was then, and how much it has fundamentally changed to provide context of what I believe are exciting opportunities moving forward.

Where were we in the 1980's and early 1990's?

As I was entering graduate school, it was well known that the ocean was spatially/temporally complex and that the available tools were not up to the task to address many of the critical questions. This was especially true for the coastal ocean characterized by compact turbulent layers and boundaries (land, ocean, and atmosphere). Grand challenges at the time included balancing the planet's carbon budget anchored by understanding the fluxes of carbon and nutrients in the ocean (see Oceanography 2001), uncovering picoplankton communities in the open ocean (Waterbury et al. 1979, Chisholm et al. 1988), and understanding carbon export to the deep sea (Boyd and Trull 2007, Iverson 2023, Siegel et al. 2023). Meanwhile, fundamental ocean features such as marine viruses, one of the most abundant and rapidly evolving forms of life on Earth, were not discovered until the early 1990's (Bergh et al. 1989, Proctor and Fuhrman 1990, Hara et al. 1996). Walter Munk and Carl Wunsch (1982) highlighted that many of the knowledge gaps reflected limitations in our ability to observe the ocean over the relevant time and space scales.

The gaps in ocean-observing capabilities were significant. The ability to transmit and share information remotely was limited. "Live" communication was limited to expensive satellite phones and custom mail messaging services of miniscule bandwidth in the late 1980's and often text messages from land to ships were satellite transmitted and then printed on paper. The "world wide web" was still in its infancy and collaborations relied on "slow" mail. As but one example, I found out where I was going to graduate school via a global community of HAM radio operators while working as a krill technician in Antarctica in 1988. At sea, we relied on fax machines over which we could receive low-resolution maps of satellite imagery. Satellite oceanography had fundamentally transformed oceanography and provided scientists with amazing imagery of warm and cold core rings, major currents, enhanced phytoplankton biomass trailing ocean storms, and ocean weather (Halpern 2000). *In situ* data was collected by ship-based systems for limited windows of space/time or with moorings providing Eulerian time series. Moorings, despite their great value, could never provide a realistic dynamic view of the ocean spatially but drove home the importance of episodic events in structuring marine systems (Dickey et al. 1998, Toole et al. 2000), which was poorly resolved by traditional ship sampling. Autonomous underwater vehicles were still in early development and the few field deployments of robotic platforms were conducted by teams of engineers to learn about feasibility of the technology, not by scientists using the technology to address fundamental questions (Straton 1969, Manley 2003, Wynn et al. 2014). The promise of autonomous sampling was still a dream. A great example of this was the science fiction vision provided by Henry Stommel, who described graduate students at Woods Hole Oceanographic Institute (WHOI) remotely navigating an underwater robot on an ocean circumnavigation (Stommel 1989). Since then, AUVs as well as sea floor cables (Schofield et al. 2002, Favali and Beranzoli 2006), drifters (Lumpkin et al. 2017), profiling floats (Riser et al. 2016, Claustre et al. 2020), animal-borne sensors (Costa et al. 2012, Watanabe and Papastamatiou 2023), and air-borne drones (Johnston 2019) have all matured to become science tools. Ocean modeling, data assimilation, and prediction have rapidly evolved with growing skill, inclusion of increasingly complex chemical–biological processes, and improving temporal and spatial resolution capable of resolving the mesoscale (Peloquin 1992, Smith 1993). These evolving technical capabilities are altering how scientists maintain a sustained presence at sea, which is allowing us to quantify in space and time the importance of episodic events (storms, river plumes, and subsurface jets). As bio-optical and chemical sensors were developed, it revealed the spatial complexity in the subsurface ocean not visible to satellites.

Beyond technical limitations, the dissemination of marine science was different then. It was the era of proprietary data, where all information was formally embargoed by grant specifications for up to 3–5 years. In addition, the timeline to open up the data was rarely enforced. The early years of transitioning to open-access data were an adventure. As part of the COOL group, we started by posting raw real-time satellite data to the web, which resulted in our group being sued by commercial entities that were selling imagery to the general public. These conflicts resulted in clarification of the Federal Open Sky policy, where everyone had the right to share raw tax-payer-sponsored satellite imagery publicly but value-enhanced imagery could be a protected product that could be sold. We as a group decided that we would share data as rapidly as available to facilitate adaptive sampling during large experimental efforts. In the late 90s, our efforts included large community experiments focused on developing ocean forecasting approaches for coastal regions in the mid-Atlantic Bight to coordinate science sampling of the biogeochemical dynamics (Glenn et al. 2004). While managing these field campaigns was a significant time sink, it provided datasets that could serve the wider community simultaneously but did present some frustrations. Despite still being in the tenure stream, some researchers published data that I had worked hard to collect without offering me authorship. My anger was constructively tempered by talking to my colleagues who gently pointed out that I had many more ideas than I had time to publish so don't waste energy and focus on getting my stories out. This did not "right the wrong" but it shifted my frustration into constructive energy. I also saw that the "bad players" were often marginalized over time reflecting their recurring bad behavior. These experiences were rare and more often than not the community were excited to collaborate and work as a team.

The transition to open data has not diminished the importance of peer-reviewed manuscripts but now provides another metric for demonstrating science impact. The fact that the datasets are now published and often required by science journals is a great sign of cultural progress (Pendelton et al. 2019, Fredston and Stewart Londes 2024)! There is still much more progress to be made on this front by increasing open access data (along with the critical metadata) without burdening the scientists that often are not adequately resourced to do so. Many different data systems exist; however, they are often scattered among different disconnected repositories, and so, while publicly available, many data sets are still difficult to find. *Despite the need for more progress, this new era of open data and collaborations, facilitated by the internet, is broadening our oceanographic community. Oceanography is no longer dominated by those lucky few who had access to ship time. Anyone with internet access and desire can now ask fundamental science questions. In my opinion, this will ultimately help democratize oceanography across large and small research-teaching-outreach institutions*.

Finally, it was predicted that science productivity (the rate of getting science manuscripts published) would accelerate if data were delivered in real-time back to the researchers on shore. If data were streaming directly to computers worldwide then the historical lag between data collection and synthesis would be minimized. This idea has been tested by comparing the publication rates from large programs that collected data using either traditional oceanographic approaches vs. those experiments that used real-time data streaming (Schofield and Glenn 2004). The lag between data collection and eventual publication were similar often taking 3 years between data collection and publication. Quality science capable of surviving peer review still requires time for critical thinking and synthesis. Thus, while new technologies do provide us an unprecedented amount of data, science is more than a data report, and our work will still require significant creative and rigorous work to turn data into new science knowledge.

Where are we heading?

The technologies now available to the oceanographic community will enable us to address a wide range of science questions needing information on mesoscale processes with temporal/spatial resolutions that cannot be resolved using traditional approaches (Godø et al. 2014). Future graduate students will conduct studies using autonomous networks of remote sensing and mobile platforms. The platforms will be diverse consisting of airborne, surface, and subsurface vehicles. These systems will provide spatial data over time in which traditional sampling from ships to moorings will be embedded. The networks will allow both ship- and shore-bound scientists to adaptively sample the chemical, physical, and biological properties in a sustained manner over time. Sampling will be aided with model forecasts. This 4-dimensional view will be open access and much of the data will be available and visualized in near real-time (as example see https://www.hubocean.earth/platform). Scientists will know when and where to conduct shipboard experimental manipulations and the observational data will provide context to interpret/extrapolate the experimental results. The open data will allow large communities of scientists to work together despite being distributed across the globe. As the networks grow, they will increasingly rely on machine-to-machine-to-model networks capable of automated optimization of the network in the field to study specific processes of interest (Schofield et al. 2010, Ramp et al. 2009). Like many numerical models, these networks will be nested within each other to provide varying degrees of spatial and temporal resolution. For example, the global ARGO-Global Ocean Biogeochemistry Floats-model arrays will provide basin-scale integrated datasets in which continental-shelf networks will sample more compact space and time scales required to understand these systems. Scientists from around the world will work together using real-time data collected in the ocean and the barriers that prevent groups from working together will continue to be minimized. The exponential growth of machine learning and artificial intelligence will be a new revolution helping synthesize and use diverse, complex, and large data streams. I believe these approaches will complement but not replace analytical modeling built upon fundamental first principles.

Beyond the development of infrastructure enabling science to maintain a sustained presence in the ocean, we are in the midst of an ocean sensor/measurement revolution. A vast array of new tools now allow us to measure the ocean physics, chemistry, and biology with unprecedented detail. This is especially true for the biological sciences, where, e.g. the "omic" revolution provides the first potential synthetic view of overall systems biology that will allow biologists to characterize community diversity, gene expression profiling, transcriptional regulation, protein and lipid identification/modification, metabolism, elemental profiles, morphological, and physical traits. Combinations of these measurements will provide insights into a range of physiological/ecological processes, including particle sinking–flocculation processes, grazing, and animal movements (diel behavior, migrations, and population transport and connectivity). New fluorometers offer the potential to measure photosynthetic activity through measurements of electron transport. These approaches will be important to providing insights into fundamental rate processes (Packard 2018). These new capabilities will benefit from the data/forecasts provided by the ocean observing networks, which will inform when and where data will need to be collected. Discrete ocean sampling will transition from fixed grid sampling to adaptive sampling grids that incorporate the evolving structure of the ocean. As a community, we will need to learn how best to use these new multi-platform approaches. The success of these networks will depend on optimizing measurements to resolve specific processes that will require specific temporal/spatial sampling. Given this, the systems will need to be flexible in their use and open to evolving as the questions change based on our increasing knowledge of the ocean. I am an optimist and believe the combination of sustained high-resolution sampling combined with experimental efforts will provide novel insights into a range of critical transdisciplinary questions facing society.

With these new capabilities, the questions I am increasingly thinking about are broad and, despite my best efforts, will be a focus of our science community well after I retire. A major interest for me is mean state transitions in ocean ecosystems and the adaptive capacity of ecosystems to respond to change. This is critical given a changing climate and a rapidly increasing industrialization/urbanization of the ocean. Additionally, I am thinking about how these changes will influence the overall carrying capacity of the ocean for providing food and energy. This is a question of increasing importance as ocean and inland waters provide >20% of the protein supply for a growing human population. My interest in these questions has grown over the last few decades as I have personally observed the ocean exhibiting significant change. One of my major study sites, for over 30 years, is the West Antarctic Peninsula, which is one of most rapidly warming regions on the planet and I have witnessed declining sea ice and the corresponding changes rippling throughout the food web from the plankton to the penguins. Watching these changes has been eye opening-scary-concerning and has spurred me to think about the potential trajectory of marine food webs in the near future (years to decades). Beyond potential climate-driven changes, the activity of humans on the ocean has been increasing. For example, in my backyard in the mid-Atlantic Bight construction has started on building the world's largest offshore wind network with >3000 turbines to be deployed over the next decade. This development is arguably the deployment of the world's largest artificial reef. How will this construction alter the food web? How will these man-made changes interact with climate-driven changes? All these potential changes increase the importance of marine science to help society navigate potentially dramatic shifts in the ocean.

Over my career, there has been a growing appreciation that there is a critical need to bring science and its processes directly to stakeholders-society. In the past, this was not a scientist's responsibility as it was often assumed our "brilliant" insights would be spontaneously and enthusiastically devoured by the public. This assumption is not grounded in reality. This responsibility has become a formal responsibility for the scientist with many funding agencies now requiring a dedicated focus on outreach. For example, the National Science Foundation in the USA began considering broader impacts in proposal reviews in the 1960s. However, it only became a separate and distinct criterion in 1997. What outreach should be conducted is generally not prescribed and it can span from communicating the process of basic research and the scientific method to the general public, training teachers, or educating local-state-federal regulators. Each of these audiences requires a distinctly different set of communication strategies. Many institutions have dedicated professionals who can help in deciding and connecting with potential stakeholders. Finding these broader impact (BI) professionals to collaborate with is a key to maximizing the effectiveness of the time dedicated to the effort.

I have been uniquely lucky in my career to have collaborated with BI professionals during my entire time at Rutgers. Janice McDonnell has been a partner for broader impacts spanning from student–teacher–scientist training and public engagement efforts. Working with her has been critical for me to learn a totally distinct skill set from my science training and evolve my Broader Impact identity (Risien and Stoeksdieck 2018). Developing a Broader Impact identity is focused on blending science interests to the potential impacts of a specific community of interests. This identity is likely to change over the course of one's career as perspectives/interests evolve. My initial efforts were focused on conducting elementary through high school teacher training and over time expanded to general public outreach associated with feature-length documentary movies (*Atlantic Crossing: A Robot's Daring Mission* and *Antarctic Edge: 70° South*) and national radio (*You're the Expert*, https://podcast.app/youre-the-expert-p8942). What I have learned is that the time commitment and the resources required vary dramatically with the audience. What does not vary is that none of these efforts would have been possible without Janice helping me to navigate the effort and help hone my message. These efforts have generated some of the most rewarding moments of my career. She has been critical to keep me growing as a public outreach communicator, including pushing me out of my comfort zone. My most recent event was a public story reading of a piece I had written in a New York City bar with professional short story tellers. That event was truly humbling. Compared to those experienced and talented speakers, I felt like a novice. I know where my efforts to practice will be focused over the next few years. *Working with BI professionals is critical to maximizing our outreach to stakeholders-society, which is amazing as this growing class of professionals did not exist when I began my career*.

What has not changed?

The importance of curiosity driven science

Ever since Vannevar Bush's groundbreaking report (Science, the Endless Frontier, https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm) advocated for fresh thinking to unleash the intellectual capacity of civil society, basic research has been fundamental to the modern science enterprise. The value of this vision was not only that curiosity-driven science was fundamental to making novel discoveries but also that these advancements would meet the needs of society. To do this well (I am still learning), it is critical to focus on taking the time to develop good science questions. I have found that good questions, whether fundamental research or applied science, can find funding with dogged persistence. Unclear and unfocused questions will often not find a funding home. I warn all new graduate students that the hardest, but most rewarding, part of a thesis is formulating good questions. This is hard work. Make sure that you *take the time* to develop these questions, and continuously bounce them off all your science colleagues. For me, my clarity usually comes at sunrise, when it is quiet, or when I am weeding on the organic farm that my wife and I have. What works is different for each person, so find your creative space and use it! Where to get the good questions funded is another challenge but cast a wide net between local-state-federal-international agencies, foundations, and philanthropies.

Don't forget that science is fun!

Despite the stress of competing for grants and the many commitments associated with a science job, after 35 years, I still find science creative-frustrating-exhilarating-fun-consuming and full of twists and turns associated with each new insight. Too often, with life chaos, it is easy to lose track of the gift of having a career focused on exploration. My curiosity has grown as I am continually learning through field expeditions, laboratory experiments, and the continuous stream of discoveries published in the primary literature. Reading/listening about the science being conducted at this time leaves me stunned by the exciting and audacious work of our community. Given the many demands on our time, what is my advice to keep science fun?

- Increasingly in a virtual world, there are fewer contiguous time windows to focus and just think about the science. Therefore, it is important early on to take control of your calendar and formally block time to think-discuss-do science. In the modern world, everything has deadlines (grants, classes, meetings, and committees) except for the actual science, which does not have a formal deadline, which leads it to be the task too often postponed until tomorrow. Great advice I continually receive from my father-in-law, a successful scientist (Syukuro Manabe), is don't mistake busy work for science thinking. Deep thinking requires time. *Make science deadlines/goals and block the time do it. Treat this time religiously, turn off email and phones, but if needed turn on the music that helps you escape into the work. Close the door or hide in the library but revel in your explorations*.
- Choose a meeting-webinar-lecture series outside your expertise at least once a year. Block out the time to truly attend. When I mean truly attend, keep your computer shut, phone off, with at most a notebook to take notes. As stated in a James Bond movie, "Sometimes the old ways are the best." Stay nimble to learn the questions and languages of different disciplines. Science has transitioned from interdisciplinary to transdisciplinary discussions. This is relatively new. Today I see scientists successfully working with others in engineering, medicine, oceanography, art, public policy, and supply chain economics. What a wonderful evolution and my only response is "amen." This evolution is recent and I believe that the new generation of scientists will need to be trained differently in order to better to conduct transdisciplinary science. What that training is I am still working on. While a broad supporter of these efforts, I often struggle on how to design/conduct this transdisciplinary research, probably a symptom of a small brain. I am still learning the language and communities in completely separate disciplines. *My best advice, given I still learning how to do this, is to go collaborate with creative people who push you into uncomfortable areas you might have never considered*.

Science is important and worth the effort

As our climate changes, humanity is facing many critical issues. Mine and future generations will need to figure out how humanity should respond to changes in the Earth system, how human activity might become sustainable, and how we might develop a science community that reflects humanity's rich diversity. These are not theoretical challenges, but are urgent and require plans, a strategy, and action. Science and technology will be central to meeting these challenges and in an increasingly polarized global political environment decisions will need to be based on science and not ideology. I do not accept the premise that science has become an ideology and believe these verbal attacks are a deliberate strategy to delay and obfuscate what we have learned and delay or prevent societal actions that should flow from fact-based knowledge. Our science is critical to this planet, and in my mind, this is a noble and grand task i.e. worth the energy I invest.

The people in our community are the life gold mine

Above, I identified a handful of people who were critical to my journey. For every person I mention (Barbara, Ray, John, David, Gary, Barbara, Fred, Scott, Janice, Deborah, and Syukuro), there are another dozen who I could/should have highlighted. The take-home message is that our community is blessed with amazing, funny, passionate, and wonderful people. What a blessing that I have an extended "nerd" family. This is a community that provides life-long friends. A great example in my career is my decades-long collaboration with Deborah Steinberg. I met her as an undergraduate freshman in basic biology and we now co-manage large programs together. What a gift to work with your best friends.

While there are occasional bad apples, I have been lucky to not have encountered many. I learned when working on ships that it is critical to make sure everyone feels secure, safe, and valued. I believe it is critically important for science leaders to publicly and formally communicate expectations and be clear that certain behaviors will not tolerated. While issues remain, I have seen improvement. When I was an undergraduate going to sea, my advisor was often the first woman chief scientist in the ship's history, and I witnessed many instances of a toxic male culture. One example was that Barbara often had to insist that the public rooms should not broadcast pornographic movies. This is unfathomable now, but back then, her insistence was met with outrage from the often all-male crew. While we are evolving for the better, much more work is required to ensure at sea and on land, our culture is open, accepting, and supportive.

One piece of advice is to make sure that you work to develop collaborations as much as possible face-to-face. While this web-world allows for global and distributed collaboration, the value of human–human interactions cannot be overemphasized. This was recently highlighted in an article in Nature (Adams 2023) that expounded upon how remote collaboration allows for an expanded pool of knowledge. The cost is that distributed teams often don't integrate fully and thus are less vested in the conceptual debates that can lead to "disruptive" breakthroughs. Given that our community is full of great people, take advantage of this and maximize your time to work with them face-to-face. It leads to great science.

I have had the pleasure of working with Doug Webb for several decades and he has provided me and my students sage advice maybe we should all follow. *"Work hard, have fun and change the world."*

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