Science, Technology, and Public Policy Program

Art and Science of Science and Technology

Proceedings of the Forum and Roundtable

June 5-7, 2013

Sandia National Laboratories,

Albuquerque, New Mexico

HARVARD Kennedy School

Belfer Center for Science and International Affairs

December 2013

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Preface

Sandia National Laboratories (SNL) and its sister national laboratories are among the nation's premier mission-directed research institutions. They invest heavily in research, and their scientists and technologists are widely considered to be state-of-the-art practitioners of the "art" of research.[1] There is no reason to believe, however, that this art, passed down from one generation to the next, could not be improved significantly.

Indeed, over the past decades, a new body of work has emerged in a field that might be called the "science" of research (or of science and technology).[2] The field, while relatively young, is vibrant, as evidenced by the various professional societies that intersect it. For example: the Society for Social Studies of Science (4S), founded in 1975, is devoted to social scientific studies of science and technology; the International Society for the Psychology of Science and Technology (ISPST), founded in 2007, which aims to apply methods and theory from psychology to the analysis of scientific and technological thought and behavior; and finally, the International Society for Scientometrics and Informetrics, founded in 1993, which aims to advance the theory, methods, and explanations associated with quantitative aspects of science and information.

Up until now, however, the two communities above (the "artists" of research and the "scientists" of research[3]) have advanced relatively independently of each other, despite the possibility that they might benefit each other enormously. The practice of science and technology itself remains largely unimproved by the critical examinations that are taking place by the scientists of science and technology, but the mutual benefit clearly exists.[4] Artists (practitioners) of research care deeply about how productive they are: the more productive they are the more they can benefit the nation and humanity. Scientists of research have begun to develop a scientific understanding of various aspects of S&T: what better way to test that understanding than to apply it to improving how S&T is actually done?

The purpose of this Forum and Roundtable was to initiate a dialog between the two communities: distinguished practitioners of the art of research and experts in the emerging science of research. The Forum and Roundtable was held at Sandia National Laboratories with a dual focus: to identify science that can be applied to improving how research is done, and to identify ways in which Sandia could apply such to its own processes. The group was also interested in exploring gaps in the science of the art that, if narrowed, would someday enable improvements in how research is carried out at Sandia. Sandians are willing to be guinea pigs (within reason!) in the noble effort to improve the science of the art.

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[1] The term "Art of Research" is used in this document to refer to the "aesthetic, practice, procedure, and skill of doing science (or technology) acquired by experience, apprenticeship, and/or observation."

[2] G.J. Feist (2006). *The Psychology of Science and the Origins of the Scientific Mind*. New Haven, CT: Yale University Press.

[3] We are aware that using the terms "artist" and "scientist" this way reverses the traditional use of the terms "Arts and Science" where "Arts" refers to the humanities and social sciences. The "artists" in this document are primarily physical scientists and engineers engaged in the practice of research. The scientists are social scientists engaged in studying the research practices of physical scientists and engineers.

[4] Nancy C. Andrews and Venkatesh Narayanamurti, "On Soloists and Symphonies: Orchestrating the Research Culture Shift to Transdisciplinarity". *Issues in Science and Technology*, pp 30-33, Fall (2013).

Initiating such a dialog follows analogous dialogs taking place in other fields, a broad *scientific turn in practice* in which the scientific method is being applied to the arts of practice. In the physical sciences, Sandia itself is expert at bringing together physicists (scientists) with engineers (practitioners) to learn from each other. In the health sciences, a turn toward evidence-based practices in medicine is emerging that questions years of taken-for-granted clinical practices.[5] In the social sciences, the entertainment world is beginning to use "big data" analytics to rethink the process for selecting new TV shows [indeed, Netflix has recently launched two critically acclaimed series ("House of Cards" and" Orange is the New Black")[6] based in large part on data-mining its customer's preferences].

But all of this presupposes that the science of S&T has advanced enough to *enable* a fruitful dialog to take place between the science and the art. Quantum mechanics, in its early days, was not ready to design the transistor; perhaps the science of S&T is in similarly early days. Or perhaps it is not. The aim of the Forum and Roundtable, therefore, was to confront two key questions:

- *Has the emerging "science" of science and technology matured enough to be able to provide scientifically based guidance and tools that would enable significant improvements in the "art" of science and technology (and if so in what ways)?*
- *Furthermore, is there a reciprocal benefit: can Sandia's expert practitioners of the art of science and technology provide a test-bed for accelerating the emerging scientific understanding of the art of science and technology?*

In confronting these two questions, three themes were emphasized – themes intended to narrow and to make more useful the kind of science of S&T that might be applied at Sandia National Laboratories:

> First, an emphasis on improvement of research productivity from the bottom-up (through self-empowered discrete improvements by individual researchers, research teams, and research institutions) rather than from top-down (through recommendations for change in national or international research policy).
>
> Second, an emphasis on mission-driven research, i.e., research that addresses difficult long-term goals of importance to humanity, and goals that, in many cases, require closely interacting interdisciplinary teams.
>
> Third, an emphasis on metrics and quantitative data so that efforts to improve can self-correct as well as provide clear and quantitative tests of the science guiding those efforts.

In summary, the Forum and Roundtable emphasized: scientific measurements and models that can help improve from the bottom-up the productivity, creativity, usefulness, and viability of interdisciplinary mission-driven research teams.

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[5] D. L. Sackett et al., "Evidence Based Medicine: What It Is and What It Isn't.," *BMJ: British Medical Journal* 312, no. 7023 (January 13, 1996): 71–72.

[6] David Carr, "For 'House of Cards,' Using Big Data to Guarantee Its Popularity," *The New York Times*, February 24, 2013, sec. Business Day / Media & Advertising, http://www.nytimes.com/2013/02/25/business/media/for-house-of-cards-using-big-data-to-guarantee-its-popularity.html.

The Forum and Roundtable was organized around three half-day sessions. In Session 1, after some welcoming and introductory remarks by Julie Phillips (Chief Technology Officer at Sandia National Laboratories) and Jeff Tsao (one of the co-organizers of the Forum and Roundtable), three experts on the emerging "science" of science and technology gave tutorial presentations, with extensive post-presentation Q&A moderated by a discussant, also an expert in the particular area. In Session 2, three expert practitioners of the "art" of science and technology moderated roundtable discussions on particular aspects of the art: that of the individual researcher, that of research teams, and that of research institutions. In Session 3, sub-groups of "scientists" and "artists" engaged in focused break-out sessions, again on particular aspects of the art. This Proceedings is a précis of the presentations and discussions, organized chronologically. They do not necessarily represent the views of any one participant, but reflect the give-and-take of vigorous discussion and wealth of experience by the various participants.

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Summary of Conclusions

The conclusion of the discussions at the Forum and Roundtable, reinforced by the process of synthesizing those discussions into this Proceedings, confirmed that our answers to the questions posed in the Preface were clearly "yes": 1) the emerging "science" of science and technology (S&T) has matured enough to provide guidance enabling improvements in the "art" of science and technology; and 2) a test-bed by S&T practitioners could provide reciprocal benefit to the emerging scientific understanding of the art of S&T.

Among the insights and tools from the "science" of science and technology that could be fruitfully applicable to the "art" of science and technology were the following.

- At the individual researcher level, an emerging insight from cognitive science is that idea fixation[7] is the norm for humans, and hence inescapably also the norm for researchers. Idea fixation serves a useful purpose at certain stages of the research process, but at particular key stages, it becomes an impediment. Though researchers are able to de-fixate themselves at those key stages, the state-of-the-art of how they do so is neither codified nor easily taught. There is thus much room for applying strategies based on cognitive science experiments for idea de-fixation. As discussed in sections 1A, 2A, and 3A, these strategies include: surrounding oneself with people from knowledge domains an optimal (not too near but also not too far) "analogical distance" away from one's own knowledge domain; and interacting with them using artifacts which optimally balance abstractness and concreteness.

- At the research team level, an emerging insight from social science is that, just as manufacturing (the production of things) is made more productive by teams, research (the production of knowledge) is also made more productive by teams. The solitary "does it all" research genius has a place, just as the solitary "does it all" craftsman manufacturer has a place. The advantages of specialization and division of labor guarantees and the empirical trend indicates that the future of research increasingly lies in teams. As discussed in sections 1B, 2B, and 3B, there is much room for applying both existing management science and emerging "group innovation" science to the purposeful construction and organization of research teams. For example, research teams have a life cycle during which the relative importance of creativity versus execution efficiency oscillates, and hence during which its optimal composition also oscillates between analogically broad versus socially cohesive.

- At the level of the research institution, the advent of sociometric, informetric, and "big data" analytic tools promise to revolutionize how we measure, diagnose, and improve the internal operations and external impact of virtually every type of institution. Although applying these tools to research institutions will perhaps be more difficult because measuring research impact is more difficult, there is still much to be gained by applying them. The current state-of-the-art of the research institution is highly dependent on the personal characteristics and knowledge bases, difficult to teach and pass on, of top research managers and leaders. Hiring talented researchers, setting broad research directions, managing and leading researchers and research teams, assessing research impact: all of these are at present deeply human

[7] Fixation is defined as "the inability to break out of a particular mind-set in order to think about a problem from a fresh perspective" (Gregory Feist).

tasks. As discussed in sections 2C and 3C, there is much room for providing insights and tools to improve how humans perform these tasks. For example, "big data" integrated from across an institution (human resources, accounting, internal "who is interacting with whom" communications, and external proposals/talks/publications communications) can in principle provide holistic and quantitative information that would enable research managers and leaders to make much more effective and accurate decisions.

We believe that scientific insights and tools, like those described above and in these Proceedings, can be applied with powerful impact to improve the "art" of science and technology. However, we note two major caveats. First, those insights and tools which can in principle be borrowed from the management sciences have not yet been applied to research institutions whose "revenue" and return on investment is not monetary and primarily to the institution, but reputational and primarily to the individual. This inverts the "power" relationship between institution and individual: the institution often has less leverage on the individual researcher than the individual researcher has on the institution! Second, those insights and tools which have newly emerged from the "science" of science and technology have hardly been applied at all. There is much skepticism, particularly amongst artists of physical science and technology, for the social scientists of science and technology.

Thus, there are many challenges to applying scientific insights and tools to the art of science and technology. A test bed for experiments and iterative continuous improvement is clearly needed. Sandia, as an institution with a team rather than a solo research culture, is perhaps ideally suited to be such a test bed. Can Sandia "Bell-ify" itself (see Julie Phillips' welcoming remarks that follow this Summary Conclusions) and use the "science" of science and technology to understand which aspects of Bell Laboratories would be fruitful to adopt and which not to adopt? Bell Laboratories' extraordinary success does not imply that it was optimal. Our hope would be for Sandia to begin with an understanding of what "worked" for Bell Laboratories, and then perhaps go beyond Bell Laboratories by engaging in continuous improvement through the application, empirical testing, and iterative improvement of insights and tools from the "science" of science and technology.

Welcome Address: Julie Phillips

Chief Technology Officer, Sandia National Laboratories

Introduction

It is a pleasure to be able to welcome you this morning to this Art and Science of Science and Technology Forum and Roundtable. From my personal perspective, first as a research scientist and now as a leader of and champion for research, I find that the subject of the science of science and technology fascinating. From my professional perspective, I, as well as the entire Sandia National Laboratories leadership team, have newly embarked on a journey that promises to reshape the Laboratory. We are endeavoring to refocus on our greatest strengths, apply them to the Nation's most pressing problems, and continuously improve our ability to deliver solutions that provide "exceptional service in the national interest." I am thus delighted that Jeff Tsao, Greg Feist, and Venky Narayanamurti have taken the initiative to organize this workshop, and I eagerly await the results of your two days of deliberation.

To help set the stage, I would like to share a bit of my own perspective of science and technology: how both are done, and the environments that nurture them best. My perspective has been formed largely by my experiences at Bell Labs and here at Sandia, so let me speak in turn about these experiences.

My Bell Labs Experience

When I think about my Bell Labs' experience, one of the first things that comes to mind is the way the buildings were laid out. The cafeteria at the Murray Hill location was in the middle of a huge building, and offices and labs were located along long corridors, largely along the one we affectionately called the "infinite corridor." This configuration, basically forcing everyone to walk along the same corridor to get from one point to another, made it inevitable that you would have multiple chance interactions with other scientists throughout the course of the day.

Nearly *everyone* went to the cafeteria at lunchtime, whether they bought food there or simply brought their lunch. The best tables were the large round ones, because it was always possible to squeeze in one more person. Sometimes the conversation was rather prosaic – politics, sports, and the antics of kids were familiar topics – but often the conversation turned to science. This was where the Bell Labs "stationery" (also known as a napkin!) came in. It was often used to explore and then capture an idea that germinated during a conversation, which could then be tried out in the lab that same afternoon. Several of my publications resulted from just such interactions.

While there were scientists who were the world's authorities on a wide variety of topics everywhere, scientists weren't allowed to rest on their reputations. The atmosphere was what I'd call irreverent and challenging. Bell Labs was not a polite or comfortable place. Technical debate was expected. If you were giving a talk or just engaging in a technical discussion around a coffee pot or in the hall, you expected that your ideas and data would be challenged. This forced you to think very carefully about your ideas and results *before* presenting them; you simply had to be prepared to defend them at great depth. All levels at the Labs, up to and including the Vice President of Research, regularly engaged in these animated conversations. It was great fun – but

it was not comfortable, and it was certainly not for everyone. There were some visitors who refused to give a talk there or, if they did, fervently hoped that some of the most probing scientists would not be in attendance.

In the days since I left Bell Labs, I have reflected on why it was so special. I think there are several reasons:

- It was big – it had critical mass in many areas, so it was easy to find experts in a wide variety of fields. In several areas, Bell Labs truly defined a technical field for a half-century.
- Collaboration was both easy and required, since no one could build an "empire" of more than perhaps a technician and a postdoc, if that.
- It was part of the phone company, which had a LOT of fascinating technical problems to be solved. While most of us in the research part of Bell Labs did very fundamental research, our choice of problems was strongly influenced by these challenges.
- We had management who had extraordinary "taste" in research. They were technically excellent, performing their own personal research well up into the higher levels of management, and they could and did identify and nurture excellent ideas and sniff out ones that were mediocre or worse.
- Staff had nearly complete autonomy to try things – witness the afternoon experiments after a particularly interesting lunchtime conversation.

What was it that enabled Bell Labs to do what it did? I think that it was because, until divestiture in 1984, when AT&T was broken up by the Justice Department, Bell Labs was essentially a national laboratory. This situation arose because AT&T was a regulated monopoly. Taking the national lab image a little further, Bell Labs was paid for by a tax on everyone's telephone bill! Revenue was guaranteed in exchange for regulation of the businesses in which AT&T could and could not participate. This monopoly situation enabled Bell Labs, through the happy circumstance of highly enlightened leadership, to invest in research that would benefit not only AT&T and its business but society as a whole. I can't help commenting, however, that one thing that differentiated Bell Labs from today's national laboratories was the fact that it never lost sight of the fact that it was part of a company, and a very large one at that. Being part of a private sector entity, even a regulated one, drove efficiencies that the national labs can only hallucinate about.

Upon divestiture, change was inevitable. As AT&T tried to compete in an unregulated marketplace, the tyranny of competition, quarterly balance sheets and the like necessitated choices. The company could no longer justify long-term research that could benefit competitors as much as itself. It took quite a few years, but the fate of Bell Labs was sealed on January 1, 1984.

My Sandia Experience

After leaving Bell Labs, I moved to Sandia, where I immediately experienced a large degree of culture shock. I had left a predominantly physics-based culture and had entered an engineering-based culture. Though Sandia's engineered products are very much rooted in science understanding, Sandia's problem-driven culture is typically self-effacing, polite, and service oriented. That is *very* different from Bell Labs. Frankly, I think Sandia would benefit from a more challenging atmosphere, and I am interested in the thoughts of this Forum and Roundtable on that.

Moreover, Sandia's engineering-based culture was shaped by its mission. That mission spans a wide range of national security areas, but still has as its core the nuclear weapons program. And at the heart of that nuclear weapons enterprise is the requirement that nuclear weapons must never, never, *never* detonate when they are not supposed to – either through an accident or through malfeasance. As you might imagine, this leads to extreme care in the choice of technologies for use in these systems – they must be demonstrated to *always* work as intended and to *never* work in an unintended way. This, of course, means that the technologies must be thoroughly understood and must go through *years* of discovery, development, maturation, and testing. And it also means that new ideas and technologies have an extremely difficult time making it into the nuclear stockpile. In short, the nuclear weapons program must *avoid* risk if humanly possible and, if that is not possible, it must go to extraordinary lengths to mitigate any remaining risk. Taking risk, as must often be done in creative research, is not part of Sandia's culture and DNA.

That said, Sandia has a huge strength: it excels at bringing together a large number of very different disciplines to create one-of-a-kind engineered systems. It is when we do this – bringing a wide range of scientific disciplines together with complex engineering, and integrating fundamental discovery with fielding entire systems – that we are at our best. But while there are many examples of our success in doing just this, we don't manage to do it every time. What we need to do as we move into the future is to "bottle" the best of what we are as a Laboratory. And that means that we must understand what differentiates the times we are successful from those when we are less so. And we need to continually strive to raise the bar for what success means. It's a challenge that we are taking on even as we speak, and I hope that we can learn from the insights at this Forum and Roundtable to become more successful.

1 "Science" Tutorials and Discussions

Session 1 of the Art and Science of Science andTechnology Forum andRoundtable was devoted to tutorials given, and to extended discussion moderated, by "scientists" of science and technology. Three topics were covered: first, Chris Schunn (University of Pittsburgh) discussed the "Psychology of Science and Engineering," with the discussion afterwards led by Greg Feist (San Jose State University); second, Keith Sawyer (Washington University in St Louis) discussed the "Science of Group Innovation," with the discussion afterwards led by Rickson Sun (IDEO); and third, Julia Lane (American Institutes for Research) presented "Measuring Science: Bibliometrics and Beyond," with the discussion afterwards led by Curtis Johnson (Sandia National Laboratories).

1A. Psychology of Science and Engineering: Overcoming Idea Fixation

Presenter: Christian D. Schunn, *University of Pittsburgh*
Discussant: Gregory J. Feist, *San Jose State University*

Synopsis

This presentation focused on one of the most common challenges that faces practitioners of science and engineering: the human cognitive tendency to fixate on ideas and thus to limit creative thinking. Such idea fixation is particularly detrimental in the initial "divergent thinking" phase of framing a problem and its potential solutions. Many examples of the ubiquity of idea fixation, even amongst experts, were presented and discussed. Some strategies for idea de-fixation were also presented and discussed, among them: time away from the problem; adding constraints to the problem; and analogies from other fields. The last strategy, analogies, is perhaps the most powerful, and depends on exposure to other ways of thinking. Thus, interaction with people is vital, but not just any kind of interaction and not just with any kind of person. "With whom" (particularly in terms of "analogical distance" from the problem at hand) and "in what way" (the kind and "degree of specificity or abstractness" of the interaction tool) both matter.[8]

Summary of Main Points

Ubiquity of Idea Fixation. Creative thinking and multiple hypothesis (idea) generation are crucial in any scientific or engineering project, particularly during the early "divergent-thinking" stages of problem definition and solution-development (and perhaps less useful during the more "convergent-thinking" solution-execution stages). However, research on the topic of creativity in idea generation has demonstrated how powerful "idea fixation" can be.[9,10] Fixation is an obsessive preoccupation with a particular idea or potential solution that precludes the consideration of possibly fruitful alternative[11] modes of thinking. For example, given the goal of designing a spill-proof coffee mug along with explicit instructions to avoid a particular problematic design, engineers will "fixate" on the very design they have been shown, and the final product will paradoxically tend to reflect the very problematic design pathways they have been asked to avoid. Moreover, fixation is a universal challenge: from domain amateurs to domain experts.[12]

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[8] Note that in this section the emphasis is on team construction that optimizes analogical distance and on team dynamics that optimize bridging that analogical distance through artifacts. In sections 3A and 3B, we discuss other dimensions of team composition (e.g., personality traits such as introversion or extraversion) and team dynamics (e.g., the balance between time spent as an individual versus in a group). These other dimensions of a team can also influence how effectively the team is able to de-fixate on ideas.

[9] David G. Jansson and Steven M. Smith, "Design Fixation," *Design Studies* 12, no. 1 (January 1991): 3–11, doi:10.1016/0142-694X(91)90003-F.

[10] A.Terry Purcell and John S. Gero, "Design and Other Types of Fixation," *Design Studies* 17, no. 4 (October 1996): 363–383, doi:10.1016/S0142-694X(96)00023-3.

[11] The canonical definition of fixation, from Jansson and Smith (1991): "a blind adherence to a set of ideas or concepts limiting the output of conceptual design." Note the two typical features: 1) sticking to one idea or set of ideas even when they have clear problems, and 2) being unable to generate or consider alternative ideas.

[12] J. S. Linsey et al., "A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty," *Journal of Mechanical Design* 132, no. 4 (April 13, 2010): 041003–041003, doi:10.1115/1.4001110.

Strategies for Idea De-Fixation. During idea generation, it is thus important to avoid idea fixation. Many ways were presented and discussed. For example, simply allowing time away from the problem can "quiet" the fixation.[13] Or, for example, adding a constraint (like a broad mission that one's research must connect to, or a jazz riff that one must improvise to) can help move one away from the fixation. But perhaps the most powerful way of de-fixating is analogies[14] to other knowledge domains. Creating analogies from one domain to another leads to a widening of the possible solution space and is a powerful tool to escape the trap of idea fixation.[15] Given that analogies are a useful antidote to idea fixation, what strategies might help accelerate analogy creation?

De-Fixating through Analogy: the Importance of "With Whom." One strategy is to surround oneself with, or to create a team composed of, people from different knowledge domains. However, studies have shown that if the knowledge domains are too "analogically distant" from each other, then they will be mutually incomprehensible to each other. Thus, there appears to be an optimal analogical distance that a creative team should span. If the analogical distance is too short the team members will have identical or similar experiences and not be able to develop breakthrough analogies.[16,17] If the analogical distance is too long, then the ideas will be incommensurable, mutually incomprehensible, and perhaps even lead to unnecessary conflict.[18] In other words, in idea de-fixation through analogy creation, "with whom" matters. However, choosing the "with whom" is currently art, not science. Thus, we believe there are opportunities for the science of S&T to develop objective measures of analogical distance so as to achieve the team diversity that is optimal for a particular problem.[19]

De-Fixating through Analogy: the Importance of "In What Way." Assuming that a team with optimal (and significant) analogical distance has been created, two questions arise related to "in what way" the team might optimally interact. The first question is how much time to even spend with the team (versus alone). Here a balance must be struck, and that balance may depend on the stage of the project: in the earlier stages of the project, more time together as a team may be needed to harness the interdisciplinary nature of the team. The second question is how to overcome difficulties in intra-team communication, both direct verbal as well as indirect through artifacts (e.g., white board, prototypes). With direct verbal communication, particularly with newly formed teams, face-to-face communication is important: even the best teleconferencing systems are unable to reproduce the subtle but important social cues that accompany face-to-face

[13] See Section 3A "Art and Science of the Individual Researcher" for more discussion of this.

[14] Douglas R. Hofstadter, *Fluid Concepts and Creative Analogies: Computer Models of the Fundamental Mechanisms of Thought* (Basic Books, 2008).

[15] Linsey et al., "A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty."

[16] Kevin Dunbar, "How Scientists Think: On-line Creativity and Conceptual Change in Science," in *Creative Thought: An Investigation of Conceptual Structures and Processes*, ed. T. B. Ward, S. M. Smith, and J. Vaid (Washington, DC, US: American Psychological Association, 1997), 461–493.

[17] K. Dunbar and I. Blanchette, "The in Vivo/in Vitro Approach to Cognition: The Case of Analogy," Trends in Cognitive Sciences 5, no. 8 (August 1, 2001): 334–339.

[18] Susannah B.F. Paletz, Christian D. Schunn, and Kevin H. Kim, "The Interplay of Conflict and Analogy in Multidisciplinary Teams," *Cognition* 126, no. 1 (January 2013): 1–19, doi:10.1016/j.cognition.2012.07.020.

[19] For example, new advances in text analytics may enable the quantification of analogical distance.

interaction.[20,21] With indirect communication using artifacts, the degree of specificity (or abstractness) of the artifact is important: not specific enough (too abstract) and the ideas can't be technically evaluated and then built on; too specific (not abstract enough) and the team can become fixated.[22,23,24] Also, with any form of communication, conflict (so long as it is about ideas and does not become "personal") can be productive and should not be avoided.[25] Here it is worth noting that the use of artifacts to communicate can be a way of depersonalizing conflict: the artifact[26] rather than the idea originator becomes the focus of the criticism, which is much less threatening personally.

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[20] Sara Kiesler and Jonathon N. Cummings, "What Do We Know About Proximity and Distance in Work Groups? A Legacy of Research," ed. P. Hinds and S. Kiesler, Distributed Work (2002): 57–80.

[21] Christian Schunn, Kevin Crowley, and Takeshi Okada, "What Makes Collaborations Across a Distance Succeed? The Case of the Cognitive Science Community," ed. P. Hinds and S. Kiesler, Distributed Work (2002): 57–80.

[22] Robert J. Youmans, "The Effects of Physical Prototyping and Group Work on the Reduction of Design Fixation," *Design Studies* 32, no. 2 (March 2011): 115–138, doi:10.1016/j.destud.2010.08.001.

[23] Jooyoung Jang and Christian D. Schunn, "Physical Design Tools Support and Hinder Innovative Engineering Design," Proceedings of the Human Factors and Ergonomics Society Annual Meeting 55, no. 1 (September 1, 2011): 1279–1283, doi:10.1177/1071181311551266.

[24] Christensen, B. T., & Schunn, C. D. (2007). The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design. *Memory & Cognition, 35*(1), 29–38.

[25] Ming-Huei Chen, "Understanding the Benefits and Detriments of Conflict on Team Creativity Process," *Creativity and Innovation Management* 15, no. 1 (2006): 105–116, doi:10.1111/j.1467-8691.2006.00373.x.

[26] Note that one type of artifact is a model.

1B. Science of Group Innovation

Presenter: R. Keith Sawyer, *Washington University*
Discussant: Rickson Sun, *IDEO*

Synopsis

This session focused on the increasingly important phenomenon of group-based intellectual production. For example, in the early days of computer games, a single person could develop a game. Now, twenty years later, broad cross-functional teams are required to develop a game. As games have become more complex and engaging, the intellectual activity required to produce them has quickly eclipsed the capabilities of a single individual. This trend is also visible in the production of research papers. The fraction of papers written by teams with a mean size greater than one has been steadily increasing and, judging by measures like citation counts, such papers are also more influential than those written by single authors. In essence, we have entered an age of extreme specialization and teaming, not just in the production of products, but also in the production of knowledge.

Summary of Main Points

The Myth of the Solitary Genius. There are many examples of the solitary, eccentric, and even renegade genius/inventor/creator who transforms a field of knowledge, particularly in fields such as theoretical physics. One famous example is Claude Shannon, who rode the hallways of Bell Labs on a pogo stick and who also transformed information theory. Such unique temperaments and talents, when they are found, should be protected. However, as historians of science and technology have shown time and time again, even solitary genius is not as isolated as popularly imagined. Even Claude Shannon benefited enormously from his interactions with his many colleagues at Bell Labs and elsewhere. Furthermore, such individuals are special and rare. Much more common are collective breakthroughs, like the discovery of the transistor effect and the invention of the transistor itself, which depended on teams.

Groups and Radical Incrementalism. Indeed, examination of a number of cases from the history of science and technology reinforces the argument that the idea of the singular, solitary inventor is really more myth than reality. It appears that the creativity behind the most important historical innovations is actually situated in groups. The Wright brothers, who famously "invented" the airplane, made much use of many innovations from other inventors all over the world.[27] In essence most work progresses incrementally, building on what others have done, and it is the accumulation of incremental improvements over time that occasionally leads to radical impact. Indeed, whether the improvements lead to incremental or radical impact isn't because the improvement itself is incremental or radical – within the prevailing state of knowledge it could be argued virtually all improvements are incremental – it is more because of the way the improvement happened to be "fit" into the prevailing ecosystem of science, technology, and applications.

[27] Mark A. Lemley, "The Myth of the Sole Inventor," *Michigan Law Review* 110 (2012 2011): 709–720.

Group Genius as Jazz Ensemble. Jazz is a useful metaphor for considering the processes and interactions between team members. In jazz, musicians riff off of each other, cumulatively building on the contributions of other members of the ensemble to create something new and greater than the sum of its individual parts. The jazz ensemble is thus a source of innovative creativity that is well beyond any individual musician. Likewise, research teams benefit from individual researchers building on the contributions of all members of the team. Indeed, it has been found that multi-authored papers tend to have higher number of citations, the larger the team the higher the number of citations. The "solitary genius" is being replaced by "group genius."

Institutionalizing Group Innovation. For consistent creative research, it is thus not a good idea to rely on singular brilliance, but instead on brilliant teams. To institutionalize innovation thus means to institutionalize group-based innovation. How can this be done? One way to institutionalize innovation is from the bottom up: to create free time for researchers, time during which researchers can work and collaborate freely. Gore-Tex is an example of the possibility of creating institutional structures and policies to support group based innovation: its 10% free-time policy has led to some of the company's most successful and innovative products (including improved guitar strings), and almost all of these have been group based innovations. Google's 20% policy is another example of an attempt to institutionalize creative bottom-up innovation. Another way to institutionalize innovation is from the top-down: the visionary company or leader can also drive the kind of innovation that requires extremely large teams (e.g., the development of a new operating system like Windows 8 or a new airplane like the Dreamliner). Whether bottom-up or top-down, though, creativity and innovation are essentially social in nature.

1C. Measuring Science: Bibliometrics and Beyond

Presenter: Julia I. Lane, *American Institutes for Research*
Discussant: Curtis M. Johnson, *Sandia National Laboratories*

Synopsis

Bibliometrics is the one of the ways in which scientific activity is measured. However, the current system of bibliometrics is deeply flawed, resulting in flawed science ("How Science Goes Wrong", The Economist, October 19, 2013. The measurement of scientific activity should be more scientific. It should be based on the appropriate conceptual framework: since science is about the creation, transmission and adoption of ideas, it should focus on scientists, networks of scientists (the doers of science), and their subsequent activities not just the documents created by the scientists. It should be based on the appropriate empirical framework - rather than relying on manual reporting, or on secretively generated, expensive and largely inaccessible datasets on publications - it should make use of new empirical cybertools for automated collection and visualization of data, and for melding data from multiple sources and databases.

Summary of Main Points

Measuring Science. It is increasingly clear that scientific activity and the subsequent results will be measured by managers and stakeholders whether or not the measurement methodologies make deep sense. It behooves scientists to be proactive rather than reactive lest the wrong measures be used.

From Paper- to People-Centric Analytics. Bibliometrics provide deeply flawed sets of measurements. Evaluators often rely on citation shortcuts for "keeping score," shortcuts that have become enormously popular because of their simplicity. For example, Thompson Scientific's Journal Impact Factor (JIF), despite its popularity, is slow;[28] narrow;[29] secretive and irreproducible;[30] open to gaming;[31] and based on journals, not on the articles they contain.[32] The result is that researchers have incentives to game the system. Perhaps most importantly, bibliometrics is paper-centric, while the doing of science and the transmission of knowledge are human activities. While documents can be an important mode of communication and knowledge, the "science" of science and technology should focus on the people and networks who create and transmit knowledge.

A Conceptual Framework for a New Approach. Such a people-centric approach has been developed from the conceptual framework presented by Foster and Lane (2013), in which scientists (who) are funded to do research (what), conduct research within an organization (where), then

[28] Tim Brody, Stevan Harnad, and Leslie Carr, "Earlier Web Usage Statistics as Predictors of Later Citation Impact," *Journal of the American Society for Information Science and Technology* 57, no. 8 (2006): 1060–1072, doi:10.1002/asi.20373.

[29] Anderson, Kent, "The Impact Factor: A Tool from a Bygone Era?," *The Scholarly Kitchen*, accessed September 4, 2013, http://scholarlykitchen.sspnet.org/2009/06/29/is-the-impact-factor-from-a-bygone-era/.

[30] Mike Rossner, Heather Van Epps, and Emma Hill, "Show Me the Data," *The Journal of Cell Biology* 179, no. 6 (December 17, 2007): 1091–1092, doi:10.1083/jcb.200711140.

[31] Msc Falagas, Matthew E. and Vangelis G. Alexiou, "The Top-ten in Journal Impact Factor Manipulation," Archivum Immunologiae et Therapiae Experimentalis 56, no. 4 (August 1, 2008): 223–226, doi:10.1007/s00005-008-0024-5.

[32] Jason Priem and Bradely H. Hemminger, "Scientometrics 2.0: New Metrics of Scholarly Impact on the Social Web," *First Monday* 15, no. 7 (July 2, 2010), doi:10.5210/fm.v15i7.2874.

communicate their output (results).[33] The empirical framework has been shown to be possible through the STAR METRICS program, which is being implemented at over 100 research organizations. Each element can be automatically extracted from information in databases already in widespread use for other purposes. Information on what is funded can be captured from the records of the sponsored research office or funding agency websites. Natural language processing techniques can be used to describe what kind of research is actually done. Data on collaborating institutions and capital inputs can be captured on a flow basis through the vendor and subcontract information in financial accounting systems. Information on who is funded, including graduate students, postdoctoral students, staff scientists and research analysts can be captured through human resource databases. These data form the basis of an infrastructure that can be used to link in, for example, already existing information on the scientific networks manifested in collaborations on grants and projects, the scientific and business networks manifested in coauthorships of publications, working papers, conference proceedings, and in collaborations on patents and startup businesses as well as the critical outcome of the movement of collaborators and coworkers into and out of firms and other research organizations.

[33] Ian Foster and Julia Lane "Building a Better Framework for Research Measurement", University of Chicago working paper, 2013

2 "Art" Moderated Roundtables

Session 2 of the Art & Science of Science and Technology Forum and Roundtable was devoted to roundtables moderated by "artists" of science & technology. Three topics were covered: first, Tom Picraux (Los Alamos National Laboratory) moderated a discussion of the "Art of the Individual Researcher"; second, George Crabtree (Argonne National Laboratory) moderated a discussion of the "Art of the Research Team"; and third, Venkatesh "Venky" Narayanamurti (Harvard University) moderated a discussion of the "Art of the Design of Research Institutions."

2A. Art of the Individual Researcher

Moderator: S. Tom Picraux, *Los Alamos National Laboratory (*retired)

Synopsis

This roundtable discussion centered on insights of highly successful individuals engaged in scientific and engineering research. These insights are based on the vast experience of the moderator during his 40+ years at Sandia National Laboratories, Arizona State University, and Los Alamos National Laboratories. A first insight was that one cannot be taught to be in the top tier of innovative research scientists, any more than one can be taught to be in the top tier of professional basketball players. However, an existing skilled research scientist can be trained, within a wide range of possibilities, to be a better and more innovative research scientist. A second insight was that a problem-rich environment is a spur, not a constraint, on creativity. A third insight was the importance of the research narrative, not only after the research has been done and is being socialized, but while the research is being conceived (the ideation phase) and while it is being performed (the implementation phase).

Summary of Main Points

Training to Be a Scientist. The super-innovative scientist is rare, and it may well be impossible to "train" someone to be such a scientist. Indeed, in the current system of schooling, this characteristic of creativity may be being trained *out* of our scientists via the overwhelming emphasis on grades, SAT scores, and providing only the predetermined answer the teacher wants to hear. That said, within a reasonably broad range, there *should* be means by which someone with an aptitude for research can increase his or her scientific skills. Indeed, an advantage that scientists have over some other professionals (like athletes or musicians) is that scientists train to do science by doing science, as opposed to having to train for many hours before performing their event "for real." In that sense, the most efficient approach in training to be a scientist may just be to do a lot of science under the caring eye of an expert (find a mentor or a coach), while at the same time watching others do science (especially by participating in a team science environment).[34] Mentors especially can provide invaluable advice as decision points arise in the course of conducting research. It is tremendously enabling to see firsthand how to deal with problems, exploit resources, proceed in the most efficient manner, and learn the power of interactions with others in leading teams and solving problems. Such tricks simply can't be learned by reading, even if it were possible to record every possibility. Fully exploiting one's period of mentorship (as a graduate student and postdoctoral scholar) and afterwards continuing to seek out advice is invaluable. In this sense, scientific training has a component of apprenticeship as practiced by master craftsmen throughout human history.

[34] Teams are a very big deal. Working in a team, and sharing knowledge and tips, is the easiest way for an individual to increase his or her skills. The ensuing discussion during team activities will sharpen one's critical thinking, encourage efficiency, increase breadth, and spark new ideas. Interestingly, the question is often posed, "How much time should researchers spend on solo thought versus in collective teamwork in order to be maximally productive today?" In fact, it is not just today's productivity that counts, it is tomorrow's productivity: working in a team and engaging in discussions with colleagues is a crucial way of improving oneself so that one can be more productive tomorrow.

Constraints Can Stimulate Creativity. Often, a researcher thinks that constraints (physical, fiscal, time, deadlines, or intellectual) on his or her work will reduce creativity and reduce the quality of his or her research. In fact, constraints can be an enormous stimulus to creativity. When people have a problem with a particular application or technology ("we can't do X"), that problem, which is surely constraining thinking, can be tremendously stimulating. One finds oneself saying, you know, this device won't work because there's no way to make it friction free, and so forth, when in fact on deeper reflection maybe there is a way of making it friction free! So the application is asking what the problem is and what the roadblock is. It serves to focus one's thinking such that coming up with the questions to ask can be very stimulating and lead to new innovation. Being forced to do this thinking within a given timeframe can also stimulate one to rapidly survey a broader set of possibilities in seeking a solution. Thus, it is good to have some boundaries, e.g., a mission or problem space and some deadlines laid out by the executives of the research institution or sponsor. However, when constraints are also placed on the solution space, then in many cases this can kill creativity.[35] The environment that the researcher is within must allow for the support of the researcher to explore a wide solution space.[36] Note, though, that research has become so technique- and specialist-oriented that to succeed researchers often have to stick to the tools they are expert at, and so their solution space is inherently constrained. It is in this context that teams encompassing a wide range of expertise can stimulate more innovative solutions.

Find an Area of Passion. Some scientists are in their particular field to achieve fame rather than to further advance the field and associated research community. They focus their thinking on what will prompt the greatest attention and how to get their papers into the highest profile journals. Don't fall into this trap. Instead, find a topic that can fully engage and excite you day and night. Become fully engrossed in your topic and success will come as well as fame. Indeed, those who have self-selected to go into science generally have a passion for understanding scientific questions and are on a personal quest for knowledge.

Importance of the Research Narrative. The research narrative is extremely important. Of course it is important at the end of a project: one has not done any science until the writing stage is complete and the work is socialized into the scientific community.[37] But it is also important throughout the project: in the ideation phase, in the hypothesis creation and experimental planning[38] phases, in the conducting measurements phase, *and* in the writing-up-the-results phase. If

[35] One often hears innovative people saying: 'Tell me what to solve, but please do not tell me how to solve it'.

[36] Students can even bring a narrow solution space upon themselves. They often get into the mindset that open-ended problems are frustrating and that to succeed they must fall back on textbook examples or suggestions of how to approach the solution. As a community of science, there must be a push to give students the exposure to more freeform problem solving and encouraging intelligent failure to learn the harder-to-teach skills of science.

[37] This is the stage at which one often comes up with the important "n+1 experiment." After the main measurements have been taken, the researcher, in thinking through the logical consequences of their conclusions, tries to predict the outcome of one more measurement to be sure their assumptions of how the system works is correct, and then goes and makes that measurement. Simply giving a plausible explanation for what one has observed is not very deep science, but reaching a set of well-founded conclusions and then predicting the next (n+1) result really advances the science and is immensely rewarding. And this is the stage in which, by engaging colleagues, a researcher is able to iterate over concepts and identify errors in internal logic.

[38] During the experimental planning stage, it is important for the researcher to anticipate how he or she will discuss and justify each measurement he or she conducts, in order to be sure that the most convincing measurements are being done and that the most efficient and powerful tools available are being used. Indeed, some researchers even attempt to visualize their results in a key graph or plot summarizing their major finding, even at the experiment planning and data taking stage.

one is not actively thinking about the research narrative throughout the whole process, there is a risk of not doing the most significant research one can do given one's resources, and of not being able to communicate clearly to the intended audience either the research itself or the intended significance of the research. Research has a large social component to it and successful research requires successfully presenting the results to others.[39] All this said, the organizational, logical, and presentation abilities associated with a research narrative are not native to every researcher. To some extent this can be compensated for through collaboration. However, the research narrative is so fundamental to research that the more a researcher can hone these skills, the greater the quality and impact of their research will be.

[39] Note that a negative reception from the community is not necessarily bad. If, after one has done all the homework, a paper is "virulently rejected," this could be the greatest form of flattery. Generally, the more radical an innovation or scientific advance is, the more it will be challenged and meet with fierce argument and rejection by others.

2B. Art of the Research Team

Moderator: George Crabtree, *Argonne National Laboratory*

Synopsis

Research problems have different scales, and require teams with different scales to tackle them. Problems that are small are the natural domain of single-investigators at universities. As a nation, though, we also have bigger and more complex problems to tackle, and this has led to new modalities for funding bigger and more coordinated team research. Examples are the new Department of Energy (DOE) Energy Frontier Research Centers (~$4M/year), the new DOE Energy Innovation Hubs (~$25M/year), and the Advanced Research Projects Agency – Energy (ARPA-E; ~$27M/year). Both of these are still small in scale compared to, say, the Manhattan Project of the 1940's, but nonetheless go well beyond small single-investigator projects. How to improve the research productivity of these bigger and more coordinated teams is of major importance as these new modalities become increasingly important.

Summary of Main Points

Joint Center for Energy Storage Research (JCESR). This research program is one of DOE's Energy Innovation Hubs, and has as its stretch goal a new type of battery with five times greater energy density, at one fifth of the cost, within a five year period. To achieve this goal, JCESR is coordinating efforts across five different universities, five national laboratories, and four companies. In a sense, JCESR is a microcosm all of the issues associated with a coordinated research team and of how to "make the whole greater than the sum of its parts."

Communication, communication, communication. Perhaps the most difficult issue is communication, in many different ways. Large teams are inherently geographically dispersed teams, making face-to-face communications important – even amongst research staff who are already acquainted – difficult. To some extent, formal communication can be pre-arranged through voice or video calls, but informal communication (serendipitous hallway interactions) is difficult to pre-arrange. And, even for formal communications, teleconferencing is just not as useful as face-to-face communication.[40] Large teams are also inherently hierarchically organized into sub-teams, so one must be concerned not only about intra-team, but *inter*-team, communication. Here, sub-team reviews with participation from other sub-teams can be helpful, especially when sub-teams are competing against each other and might otherwise be reluctant to share information. Finally, large teams inherently harness various kinds of expertise and skill sets, and communicating across these different expertises, skill sets, and motivations (research, development, demonstration, and deployment) can be difficult even when the communication is face-to-face. In sum, communication requires a lot of attention. On every team or sub-team, there should be someone who can play a communication-facilitating role: be T-shaped in technical depth and breadth and be well-versed in the *process* of communications (able, e.g., to draw out introverts).

[40] The experience of the JCESR team has been that face to face communication is essential for developing rapport even at the highest level of the hierarchy, i.e., between the four directors.

Collaboration versus Competition. In teams, large or small, balancing collaboration and competition is tricky. Friendly *technical* competition between individual researchers or between sub-teams for research outcomes can be healthy to the overall team. Unfriendly *non-technical* competition for funding or not to be "fired" from the project can be unhealthy to the overall team. JCESR thus is organized to "fund outcomes rather than people": if the outcome is accomplished, the team moves onto something else; if the outcome proves too difficult, there are 150 other things for the individual researcher or the research sub-team to work on. In other words, allow people to move into and out of teams fluidly as outcomes come and go.

The Coordination Cost of Teams. Though teams give benefit, obviously, teams also come at a cost, particularly time spent coordinating and communicating. For the productivity of the team this cost is necessary; however, for the productivity of the individual researcher it may or may not be viewed as necessary.[41] Especially for senior, well-established researchers with other funding resources available, the restrictions and requirements associated with team projects may not be "worth it," and they may simply drop out to avoid the hassle. One has to develop a way of keeping one's best researchers.

[41] Note that there is a difference between a team and collaboration. In collaboration, it is the interests of the various parties to the collaboration that are primary; only if those interests are served will there be voluntary collaboration. In a team, it is the goal of the team that is primary; even over the interest of any particular member of the team.

2C. Design of Research Institutions

Moderator: Venkatesh Narayanamurti, *Harvard University*

Synopsis

This discussion is focused on the key elements, based on personal experience of experienced practitioners, and associated with highly successful research institutions. Much of that experience is drawn from AT&T Bell Laboratories, the famously productive research laboratory from which the transistor and many other civilization-scale innovations emerged. The elements posted were a clear but not overly confining mission; technically excellent people; stable funding; a balance between research freedom and focus; a push not to engage in everything but to choose a few selected items and support them amply; and long-term research that integrates science and technology.

Summary of Main Points

Elements of Successful Research Institutions. On the basis of personal experience in corporate and national laboratories, we posit a small number of elements that are essential to a successful research institution.[42] These elements, as discussed below, are a clear but not overly confining mission; technically excellent people; stable funding; a balance between research freedom and focus; and long-term research that integrates science and technology.[43]

Purpose. A broad purpose and mission for the institution is essential, both to provide focus as well as to inspire and attract quality researchers. The purpose cannot be too narrow, and, as discussed in section 2A, must not specify both the goals and the approaches to that goal; otherwise there will not be enough room for creative solutions. But having purpose and just-right constraints are healthy and indeed important for research creativity. For publicly funded research institutions, one criterion for choosing purpose and mission is that the social benefit should be much larger than the private benefit.

Technically Excellent People. Particularly in a research institution whose aim is the creation of innovative ideas and knowledge, technical excellence throughout the research institution is vital. In a culture in which technically excellent people challenge and debate each other all ideas will get better.[44] Technical excellence is vital in the research staff, but perhaps even more vital in management. Management sets the tone that technical excellence is what is most valued and respected; management is where recruiting and hiring of "the best and brightest" takes (or

[42] A more detailed discussion of these elements, in the context of research institutions for energy innovation, is given in: Narayanamurti, Venkatesh, Anadon, Laura D., and Sagar, Ambuj D., "Institutions for Energy Innovation: A Transformational Challenge," Science, Technology, and Public Policy Program, Belfer Center for Science and International Affairs, Harvard Kennedy School (Fall 2009).

[43] A few other elements thought to be important and that characterized the famously productive Bell Laboratories are: outstanding infrastructure and technical support; open "doors" between staff and management; a healthy regard for the "doers," "growers," and "tool makers;" and always asking (as did Mervin Kelly, for many years the Director of Research at Bell Laboratories) "not what you know but what you don't know."

[44] The challenges and debates must of course be technical and not personal. This line is easy to cross, so management must be alert to be sure it is not crossed.

should take) place;[45] management is where performance review and accountability (which should be serious) for technical excellence takes place; and management is the source of much coaching and mentoring.

Stable Funding. Funding of people and projects must be stable and predictable. Regarding people, when staff spend a significant fraction of their time seeking (and worrying about) funding, their research productivity will suffer. A funding model that relies on a project-based, contract-oriented work model can make it terribly difficult for young scholars to find their trajectory. If researchers are constantly being pulled from one project to another in order to adequately fill out one's timecard, it becomes very difficult to build an integrated research domain and respectable publication record. This is an especially critical issue for an early career researcher. Research projects, particularly at publicly-funded institutions, should be long-term and should be given the funds and the time to produce enough information to enable managers to make decisions about the future of each project and to accommodate unexpected twists and turns. Block funding at each appropriate management level is also important. That said, once it is clear that a particular person is not performing adequately on a particular project, or that a particular research direction does not adequately support the institution purpose and mission, management must make clear, technically-based, redirection decisions. In other words, along with insulation from funding instability must come accountability.

Balance between Freedom and Focus. The research institution, and its researchers, must balance freedom with focus. On the one hand, ideas can emerge anywhere and anytime (and must be encouraged to do so through "planned" serendipitous interactions), and researchers must have the freedom to have an idea over lunch then be able to spend the afternoon confirming or disconfirming experiment (see Julie Phillips' welcome address). The psychosocial as well as the physical environment of the research space should be conducive for focused attention and a great number of "natural" interactions.[46] At the same time, metaphorically, a thousand flowers should not be allowed to bloom with uncontrolled random variation; leaders are needed who embody the purpose and mission of the institution, who allow many flowers to flourish and bloom but simultaneously kill the weeds.[47] In other words, research must be insulated but not isolated from the purpose and mission of the research institution.

Long-Term Research that Integrates Science and Technology. The boundary, nearly universally delineated, between "basic" research aimed at advancing science and "applied" research aimed at advancing technology, must be blurred. Science does not so much "lead" to technology as it co-evolves with it: science has at least as much to learn from engineering as engineering from

[45] As is often said: "grade A managers hire grade A+ staff, grade B managers hire grade B- staff."

[46] Austin Silva and Glory Emmanuel, researchers at Sandia, currently have a project, entitled "Connecting Physical and Psychosocial Space to Mission" that addresses this.

[47] With the degree of alignment depending on size and time-scale: for research institutions that are larger and have a longer term time horizon the alignment can be broader; for research institutions that are smaller and have a shorter term time horizon the alignment must be narrower.

science,[48] and recent case studies[49] reveal the mutually beneficial linkages between discovery (science) and invention (engineering and technology). Thus, the research institution must encourage integration across science and technology, both at the highest levels (between "science" and "engineering" organizations) as well as at the lowest levels (project teams).[50] That said, there is an important distinction to be made between long-term versus short-term research, no matter how well the S&T is integrated. Publically-funded research institutions must focus on the long-term, as it is long-term research whose social (public) benefit is greatest and whose private benefit is least captured by private enterprise.

[48] This applies to the topic of this Forum and Roundtable as well. There is no reason to wait for the "science" of S&T to be fully developed before beginning to apply it to the "art" of S&T. The science will learn from its mistakes as it is applied.

[49] Narayanamurti, Venkatesh, Odumosu, Tolu, and Vinsel, Lee, "RIP: The Basic/Applied Research Dichotomy," *Issues in Science and Technology* XXIX, no. 2 (Winter 2013).

[50] It goes without saying that the research institution must also encourage integration across technical disciplines.

3 "Art and Science" Breakout Sessions and Offline Discussions

Session 3 of the Art and Science of Science and Technology Forum and Roundtable was devoted to breakout sessions bringing together the "scientists" and "artists" of science and technology. Three breakout sessions were held: first was on the "Art and Science of the Individual Researcher"; second was on the "Art and Science of Research Teams"; third was on the "Art and Science of the Research Institution."

In addition, a number of offline[51] email discussions relevant to the breakout sessions took place before and after the Forum and Roundtable among subsets of the invited participants.

This section summarizes ideas both from the breakout sessions as well as from the email discussions.

[51] This includes pre- and post-Forum and Roundtable email conversations, phone call discussions, and in person meetings.

3A. Art and Science of the Individual Researcher

Synopsis

The following section is based on discussions from a breakout session in which the participants with special interest in the art or science of the individual researcher formed a small group to discuss the individual researcher's practice in greater depth, reflecting on the ideas discussed in sections 1A and 2A. Many ideas were generated on how the individual researcher can achieve greater skill in the practice of his or her art through purposeful engagement in various activities. The themes of this section include: how to train and measure the abilities of an individual researcher, strategies to enhance creativity, the importance of research narratives, and the power of collaborations.

Summary of Main Points

Continuous Self-Improvement

The key questions here were: how can young researchers be best brought to a high level of research performance, and how can mature researchers continue to improve their research performance? In other words, can continuous self- or coached-improvement be fruitfully applied to the skills and knowledge of individual researchers throughout their careers?

Skills, which blend natural talents and temperaments with training, have a life cycle of youthful improvement, mature peak performance, and then post-maturity decline.[52] Within the broad contours of this life cycle, there should be considerable room for skill improvement. Even such basic skills as personality and IQ have genetic heritability of only 50-60%; less basic skills such as creativity, even accounting for decreased brain plasticity and epigenetic influence in post-adolescents, should have significant room for improvement by training. Creativity in individuals, in particular, is often "anti-trained" by early childhood peer pressure toward social and idea conformity. The resulting "creative anxiety"[53] prevents many from achieving their creative potential, just as "math anxiety" prevents many from achieving their math potential, and could perhaps be overcome through training.[54]

Knowledge also has a life cycle. People accumulate knowledge over their careers, so older researchers will have more accumulated knowledge; but knowledge gradually becomes outdated, and accumulates more slowly as one ages. Thus, the life cycle of *useful* knowledge mimics that of the life cycle of skills: a youthful increase, a mature peak, and a post-maturity decrease.

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[52] Feist, Gregory J., "Scientific Talent: Nature Shaped by Nurture," in *The Complexity of Greatness: Beyond Talent or Practice*, by S. B. Kaufman (New York, NY: Oxford University Press, 2013), 257–273.

[53] Kelley, Tom and Kelley, David, "Reclaim Your Creative Confidence," *Harvard Business Review*, December 2012, http://hbr.org/2012/12/reclaim-your-creative-confidence.and David Kelley, "How to build your creative confidence," TED Talk (March, 2012) http://on.ted.com/Kelley.

[54] There is a tremendous benefit to discussing with colleagues a question with which one is wrestling. This may involve simply walking down the hall to find an expert, contacting an expert one knows by email, and/or meeting with them at a conference or visiting their lab. Often the result is the generation of new ideas, the rapid rejection of false concepts, and the opening up of new directions in a project. Young researchers often are extremely reluctant to engage in discussions with others at times of uncertainty for fear of exposing their lack of knowledge, to their great detriment. Mentoring which encourages aggressively seeking input and discussions about their research and engineering work at an early stage can provide great benefits.

Again, though, within the broad contours of this cycle, there should be considerable room for an increase in useful knowledge, likely much more than for an increase in skills. The rate of accumulation of disciplinary (technical) knowledge can be enhanced through practices such as skim reading,[55] social networking with experts, and the use of modern bibliometric search tools. The rate of accumulation of process (strategic and tactical) knowledge can be enhanced through copying and social networking, coaching, and receptiveness to new tools.

That the skills and knowledge associated with successful researchers can both be improved and increased is perhaps obvious. Every serious athlete practices to improve his or her basic skills (e.g., passing or handing off a football); and every serious athlete learns the disciplinary and process knowledge associated with his or her sport (e.g., the strengths and weakness of opposing teams). Less obvious, however, is how to *measure* research skills and knowledge so that they can be quantified and improved. Athletes have stopwatches to measure skill development, and have their win-loss record to measure the adequacy of their knowledge of the opposing team or of their tactical decisions on when to pass and when to hand off. The skills and knowledge of the individual researcher are largely hidden from view, unmeasured, and therefore unavailable to either self or coached improvement.

An important challenge for the science of research is understanding and devising tools for measuring the skills and knowledge that enable researchers to be successful. Much as the "quantified self"[56] movement aims to use newly developed technologies for sensing and data collection/analysis to provide feedback on the daily aspects of our lives, is there the possibility of a similar "quantified researcher" movement? Some aspects of the two movements might be similar (e.g., time management); but others might be different and more sophisticated (e.g., degree of risk diversification across projects or degree of exposure to cutting edge ideas).

Importantly, the development of such "in vivo" tools for measuring the "psychological" or individual aspects of scientific productivity would enable both self-improvement as well as coached improvement. The latter, in particular, is noticeably missing from the research profession, despite the fact that it is taken for granted in virtually all other professions (sports, music, acting) in which individual performance is important.[57]

In three following sections, we describe three particular pieces of "process" knowledge (or strategies) for enhancing the productivity of individual researchers.

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[55] William Ian Beardmore Beveridge, "The Art of Scientific Investigation," *The Art of Scientific Investigation.* (1950), http://www.cabdirect.org/abstracts/19522203234.html.

[56] Gary Wolf, "The Data-Driven Life," *The New York Times*, April 28, 2010, sec. Magazine, http://www.nytimes.com/2010/05/02/magazine/02self-measurement-t.html.

[57] In sports or music, formal coaching occurs throughout one's career and is based on evidence-based "best practices" that can be taught. In research, formal coaching mostly occurs just for a brief period in graduate school, and its nature is mostly implicit "best practices" absorbed through "osmosis."

Strategies for Creativity Enhancement

Creativity is at the heart of many of the process steps associated with research: asking questions, coming up with approaches to answer those questions, and understanding how those questions and answers can impact the prevailing socio-scientific context of knowledge. Not every successful researcher needs to have outstanding individual creativity. As discussed later, many individual weaknesses can be compensated for by collaborations. However, there are known methods for improving, if one chooses to improve, one's individual creativity.

A first method, mentioned above, is to overcome whatever "creative anxiety" one feels due to early childhood social training.

A second method is to create an oasis of space, time, and environment for individual creativity to "happen." A space that is free from interruptions can facilitate the relaxed mind-wandering associated with creative thought. Time spent focusing on the domain details of the problem space,[58] followed by time thinking persistently about possible solutions ("stick-to-itness")[59] can also facilitate creativity. An environment in which mistakes are tolerated and in which play and humor are encouraged can also facilitate creativity.

The incubation time (time spent *away* from a complex problem) just mentioned is particularly important. It was first discovered by German psychologists in the 1930s, and is now well documented, with at least two mechanisms at play. First, while immersed in the details of the problem space, a particular solution becomes a fixation point, inhibiting memory retrieval of alternative solutions; time away from the problem allows that solution to de-activate, allowing competing ideas to become more retrievable.[60] Second, while away from the details of the problem one is now prepared to benefit from relevant hints/cues found in the environment, whereas before starting the problem these hints/cues were ignored.[61] In other words, in the language of idea fixation and de-fixation discussed in section 1A, there are both "reduce fixation" and "see alternatives" aspects to incubation effects. One possible way the brain might support such effects is through an emerging concept in neurobiology such as "default networks," which become active in the absence of external stimuli and which act on the brain's own repository of ideas and thoughts.

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[58] As said by W.I. Beveridge: "The most characteristic circumstances of an intuition are a period of intense work on the problem accompanied by a desire for its solution, abandonment of the work perhaps with attention to something else, then the appearance of the idea with dramatic suddenness and often a sense of certainty. Often there is a feeling of exhilaration and perhaps surprise that the idea had not been thought of previously." Quoted from W.I. Beveridge, "The Art of Scientific Investigation, 2nd Ed" p. 73.

[59] Popova, Maria, "John Cleese on the 5 Factors to Make Your Life More Creative," *Brain Pickings*, n.d., http://www.brainpickings.org/index.php/2012/04/12/john-cleese-on-creativity-1991/.

[60] Steven M. Smith and Steven E. Blankenship, "Incubation and the Persistence of Fixation in Problem Solving," *The American Journal of Psychology* (1991): 61–87.

[61] Bo T. Christensen and Christian D. Schunn, "Spontaneous Access and Analogical Incubation Effects," *Creativity Research Journal* 17, no. 2–3 (2005): 207–220, doi:10.1207/s15326934crj1702&3_7.

Andrea L. Patalano and Colleen M. Seifert, "Opportunistic Planning: Being Reminded of Pending Goals," *Cognitive Psychology* 34, no. 1 (October 1997): 1–36, doi:10.1006/cogp.1997.0655.

Jarrod Moss, Kenneth Kotovsky, and Jonathan Cagan, "The Influence of Open Goals on the Acquisition of Problem-relevant Information," *Journal of Experimental Psychology. Learning, Memory, and Cognition* 33, no. 5 (September 2007): 876–891, doi:10.1037/0278-7393.33.5.876.

Strategies for Impact: Centrality of Research Narratives

As mentioned above, critical aspects of the research process are understanding and writing up[62] both how one's research questions, approaches, and answers are internally self-consistent as well as how they fit into and impact[63] the prevailing socio-scientific context of knowledge. This means developing a research narrative, a "meta story," about the research itself. As discussed above in the context of creativity, not every successful researcher needs to be able to develop compelling research narratives. As discussed later, many individual weaknesses can be compensated for by collaborations. However, if one chooses to do so, there are known strategies associated with improving one's ability to develop such narratives.

First and foremost is to recognize that the research narrative must be done continuously from the beginning to the end of a research project. Forcing oneself to think through a plausible research narrative at the beginning of a research project can save one from launching into a research project that, even if successful, might not be particularly impactful. Having some idea of what to expect even before one executes the first laboratory experiment or computer simulation, even if one's idea turns out to require heavy revision later, can save one from exploring approaches less likely to succeed. Many young scientists suppose that research narratives developed early will wrongly predispose them to expect particular results and to fall prey to positive confirmation bias. In fact, in the early stages of a research project, positive confirmation bias is healthy: it enables persistence in the face of the many ways that experiments are fallible to human error in set up and execution.[64]

Second is to recognize that the research narrative shares many of the characteristics of good writing and good storytelling. And here is where there appears to be much room for improvement in the art. Here is where all the elements that we know make a difference in ordinary story-telling (character, setting, plot, conflict, theme, clarity) could make a difference in scientific story-telling, but rarely do. And, just as in ordinary story-telling, writing can be part of the puzzle-solving process itself.[65] The process is analogous to the way movies are storyboarded early and throughout the movie production process the research narrative is itself the object of a rapid and iterative prototyping process.[66]

Third is to recognize that construction of the research narrative is difficult and not easily done solo. Individual scientists, like individual humans, are susceptible to making all sorts of errors of logic, both the internal logic of the research work itself and the external logic of the fit of the research work to the prevailing socio-scientific context of knowledge. In order to see and to fix these errors of logic, it is important to engage in continuous discussion with colleagues. A researcher embedded in a social network associated with the projects he or she is working on will benefit from checks and balances on his or her research narrative.

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[62] As put by Michael Faraday: "Work, Finish, Publish." Quoted from W.I. Beveridge, "The Art of Scientific Investigation, 2nd Ed," p. 121.

[63] As Wilfred Trotter put it: "In science the primary duty of ideas is to be useful and interesting even more than to be 'true'." Quoted from W.I. Beveridge, "The Art of Scientific Investigation, 2nd Ed," p. 41.

[64] See, e.g., Alan Francis Chalmers, *What Is This Thing Called Science?* (Univ. of Queensland Press, 1999).

[65] As said by Flannery O'Connor: "I write because I don't know what I think until I read what I say."

[66] A process that enables it, as said at IDEO, "to fail early to succeed sooner." After Tim Brown, *Change by Design* (HarperCollins, 2009).

Strategies for Weakness Compensation: Collaborations!

No researcher is universally skilled or universally knowledgeable. Even the most successful researcher is emphatically not "Renaissance" like. Individual researchers possess no more than a tiny fraction of any field's disciplinary knowledge, and do not possess in equal measure the full range of skills necessary for the full range of research steps (the divergent thinking associated with creativity, the convergent thinking associated with getting the project done, the narration skills associated with writing up and presenting the work, etc.).

In other words, every researcher is riddled with weaknesses and, to be successful, *must* compensate for these weaknesses with collaborations. Three important kinds of collaborations can be envisioned: the first is commonly recognized and practiced; the second is controversial and only sometimes practiced; the third is less commonly recognized and less commonly practiced.

The first kind of collaboration is across knowledge disciplines. The materials physicist must, e.g., collaborate with the microscopist to ascertain the basic properties of nanostructured materials. Moreover, as human societal knowledge continues to accumulate, finite human cognitive capacity ensures that division of labor and domain knowledge specialization will only become more pronounced, and the importance of collaboration across disciplines will also only become more pronounced.

The second kind of collaboration is across science, technology, and applications. This kind of collaboration recognizes that even though a knowledge domain may span the full range of science, technology, and applications, researchers rarely do. The frames of mind and motivations common for research in these different "categories" of knowledge are sufficiently different to coincide only rarely in the same person. Nevertheless, cross-fertilization associated with collaborations across these frames of mind can be powerful. In ideal cases, extremely productive virtuous spirals[67] emerge in which science feeds technology (discovery feeds invention) and technology in turn feeds science (inventions feed discovery). Despite this, strong incentives currently exist in many organizations to "protect" science from technology and applications: if science is constrained to be relevant to technology improvement, then surely the quality of the science must suffer. In fact, this may be so if the technology is narrowly considered and immediate improvement is desired. The key is to take the long-term view: the quality of science benefits from considerations of benefit to technology provided those benefits are broad and long-term.

The third kind of collaboration is across skill set. Proposal writing, skim-reading, back-of-the-envelope calculations, conference organizing, team organizing, social networking, writing up and marketing results, generating creative questions and answers, constructing research narratives, all of these require different skills. Two researchers with overlapping domain knowledge, who might not think to collaborate, could easily have a very different set of research skills and might collaborate extremely productively.

[67] J.Y. Tsao, K.W. Boyack, M.E. Coltrin, J.G. Turnley, W.B. Gauster, "Galileo's Stream: A Framework for understanding knowledge production," *Research Policy* 37, 330-352 (2008).

Finally, we note that whether to collaborate to compensate for a weakness or whether to invest effort to strengthen the weakness so as to avoid the inefficiencies associated with collaboration, is a difficult question. It probably depends both on the nature of the weakness as well as on the nature of the problem at hand. Perhaps there is an opportunity for the science of S&T to categorize the nature of the skills necessary to tackle various kinds of scientific problems, and the responsiveness of those skills to training, so as to enable better understanding of the trade-off between training and collaboration.

3B. Art and Science of Research Teams

Synopsis

Teams are critical to research, and will only become more critical. In constructing a team, it is important to consider: the disciplines the team must span for the problem at hand; the beneficial impact of integration of science, technology and applications; temperaments and skill sets; and stage within the divergent-convergent thinking life cycle that the team is in. In enhancing the productivity of a team, three important aspects are: how inspiring and "big" the challenge that the team faces is; the technical and social leadership of the team; and communications internal and external to the team. Going forward, it will be important to develop more sophisticated process (proximate) and outcome (ultimate) metrics for team dynamics and success than exist today, and to make causal correlations between the two. Team science could someday be a differentiating capability for Sandia National Laboratories, making use of its existing culture of teaming and its desire to be of broad service to the nation. However, teaming in science faces some fundamental challenges due to the reputational-rewards-to-the-individual culture of science.

Summary of Main Points

Team Composition

It is universally acknowledged that teams are critical to research. As discussed in section 3A, all individual researchers have weaknesses. To accomplish virtually anything except for the smallest research project requires teams, and to accomplish something significant requires large teams.

What, however, is the optimal team for a given research project? The current art of research team construction is typically one in which the designated team lead invites those he or she knows and trusts to be part of the team, mostly with an aim to cover the knowledge domains thought necessary. Indeed, deep, hard-won domain knowledge is undoubtedly the most important aspect of team building. A team can only do top-notch research – asking the most important questions, knowing when answers are right/wrong, new/old, creative/not-creative – if it has deep underlying disciplinary knowledge. A key question for the science of S&T is then to quantify, for a given problem space, a research team's optimal mix of disciplines (perhaps through quantifying via computational linguistics their spread in some analogical distance space). [68]

But more than just deep multi-disciplinary knowledge can benefit a top-notch research team. As discussed in section 3A, independent of knowledge domain, representation from and integration of the different frames of mind associated with science, technology and applications can enhance considerably research impact. Also as discussed in section 3A, and again independent of domain knowledge, representation from different temperament and skill sets can be valuable to a team.[69]

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[68] See, e.g. Andy Dong, "The Latent Semantic Approach to Studying Design Team Communication," *Design Studies* 26, no. 5 (September 2005): 445–461, doi:10.1016/j.destud.2004.10.003; Clive L. Dym, *Learning and Engineering Design* (TEMPUS Publications, 2006); Jang and Schunn, "Physical Design Tools Support and Hinder Innovative Engineering Design."

[69] Note, though, that the absence of some (but not all) individual skills can be compensated for by the team. For example, one might anticipate the need for at least one "creative guy" on a research team. However, groups can be creative even when populated by individuals with seemingly very little individual creativity or spontaneity just by the forced integration of different knowledge domains.

Perhaps most importantly, research projects have life cycles and the optimal composition of the team will vary with that life cycle. At some stages divergent thinking is relatively more important: at the beginning of the project, certainly, and periodically throughout the project as new information is uncovered with relevance to potential approaches going forward. During this stage, larger and more cognitively dissonant teams are desirable. At other stages convergent thinking is relatively more important: during the execution phase, certainly, when relatively clear tasks must be coordinated. During this stage, smaller, more homogeneous and socially cohesive teams are desirable.

As the research project progresses through its life cycle, then, its optimal team composition will change, requiring periodic team expansion and contraction. A key question then is: how can one know what stage in its life cycle a project and a team is in? One might imagine that most teams (as well as individuals) shift too early to, and then get stuck in, convergent thinking mode when they might benefit from lingering longer in, and then moving earlier back to, divergent thinking mode. There is a discomfort associated with divergent thinking and "not having an answer," and there is always time pressure which favors convergent thinking. Thus, a challenge for the science is to come up with ways of understanding where a research project is in its life cycle, so that it doesn't shift at the wrong time from one mode of thinking to another, and at the wrong time from one team composition to another.

Team Productivity

Assume now that the team has been formed, and that its composition is optimal in terms of its coverage of: knowledge domains; the science, technology, and applications frames of mind; and mixes of temperaments and skills. What other aspects of the team are important to its productivity? Here we discuss three: the challenge that the team faces; the team leader; and communications within the team.

Importance of the "Challenge"

A first, and perhaps most important, aspect of a productive team is the "challenge" that the team faces. A big challenge is energizing and powerful. As popularized by Daniel Pink, people want to be a part of something big and meaningful. What precisely the challenge is people are often pretty open to letting a leader define (and then finding their own space and definition within that), but however it is defined, it must be big and meaningful.

Indeed, being part of such a challenge is a reward in and of itself, one that can trump (but not totally replace) others such as money, promotions, individual reputation, or even on-site cappuccino bars. And big challenges tend to attract top-notch people ("stunning colleagues"), which

is itself energizing to the team. Indeed, these elements are interdependent – the big challenge attracts "stunning" people who enable even bigger challenges to be taken on which attracts still more "stunning" people, and so on.[70]

Importance of Leadership

A second aspect of a productive team is its leadership. Teams need fostering, the mission or big "challenge" needs communication and tweaking along the way, and these are not wholly bottom-up activities. There is an art to creating an environment where people do not feel over-managed,"[71] and where people have freedom but without losing focus. A well-functioning team is like an organism, adaptive and creative and problem solving, but still in need of a leader who sets the ground rules for its internal functioning.

That said, there are two aspects to team leadership, and they do not both need to reside in a single individual. One aspect is technical – there must be top-down technical pull that meshes with bottom-up technical push, and there must be technical curatorship that organizes the technical knowledge produced by the team. Another aspect is social – there must be top-down setting and enforcement of the rules by which the team interacts, and top-down nurturing of the individuals on the team.

In an integrated model, the team lead performs both functions. In hybrid models, the team lead performs one of the functions, and is augmented by someone who performs the other function. The team lead could be technical, and augmented by a "team process ombudsman" who watches and suggests social enhancements to the team lead. Or, the team lead could be social, and augmented by a "technical curator" who provides technical vision and organizes the team's technical knowledge.

In all these models, the common denominator is that team leadership is active, not passive. There must be a give-and-take between the team and its leadership. However, we note that this is new to research. Unlike in other kinds of teams, say, in industry, where there is a lot of active management intervention to tweak and improve teams, in research there is typically very little such intervention.

Of course, great leaders (whether born or trained or both) have an instinct about how to organize teams. The key for the science of S&T is: how to develop tools and/or measurements that can help a good leader becomes a great one.

[70] From Hastings, Reed, "Culture," June 11, 2013, http://www.slideshare.net/reed2001/culture-1798664. Facebook's Sheryl Sandberg recently said that this slide deck "may well be the most important document ever to come out of the Valley."

[71] As said by Curtis Johnson: "People like to be actively managed. They like clarity of roles and goals. They just don't want bosses making decisions they themselves are more qualified to make."

Importance of Communications

A third aspect of a productive team is communications, both internal and external to the team.

Regarding communications external to the team, teams that have such communications, and are continuously comparing their performance to others' and also to what will be useful to the community, are generally more productive. Even Pixar, a famously closed company, interacts closely with the community, even if they end up sharing stuff that could have become patents.

Regarding communications internal to the team, this is even more crucial, no less so as teams get larger, and spread geographically with emerging new modalities of research funding for "virtual centers" such as the Department of Energy's Energy Innovation Hubs and Energy Frontier Research Centers. For these virtual centers "the biggest challenge is not collecting the raw brain power, it's getting the communications between the brains right, and getting the whole to be more than the sum of its parts."[72]

- Here the evidence is overwhelming that face-to-face communications is much more effective than other modalities (voice, email). In part face-to-face communications is important because of the subtleties of social cues from facial and body language, which are impossible to reproduce with even the most advanced video-conferencing technology. Such social cues ("meta communications") are crucial, particularly in the early stages of team formation when social cohesiveness is not yet formed. But also in part face-to-face communications is more effective because it allows for more vehicles for communication of complex ideas (white board, gesturing, rapid prototyping). Communicating complex ideas is fraught with potential for error, particularly when communication is between knowledge domains separated by large analogical distances.
- The evidence is also overwhelming that serendipitous encounters are crucial to the functioning of creative teams. They cannot take the place of formal communication through planned meetings, but they are a powerful enabler of new idea generation as well as social cohesion. Thus, as Yahoo recently and famously declared: engineering serendipitous encounters through geographical proximity is important. And, as Google and other companies practice, even when geographical proximity has been achieved, serendipitous encounters can be further engineered through physical layouts, open office areas, lunch rooms, water coolers, etc.[73]

Interestingly, communications is one area where much scientific progress *is* being made, through real-time measurements (for example, the MIT Media Lab's sociometric badges[74]) as well as collection and analysis of communications (like emails) that leave electronic fingerprints. Indeed, much can apparently be learned simply by analyzing the communication pattern of a team,[75] without paying any attention to the semantic content of the communications. There appear to be

[72] Quote from George Crabtree.

[73] Note, though, that not all Silicon Valley companies have fancy lunch rooms or espresso cafes. Nurturing creative interactions may not require Google-like extravagances, assuming colleagues have a natural affinity and respect for one another (dialogue just happens), and some minimal effort is made to show appreciation and encourage interaction/bonding (providing coffee, catering lunches for meetings that run over the lunch hour, throwing the occasional afternoon happy hour, etc.).

[74] Olguin, D.O., and Pentland, A. 'Sociometric Badges: State of the Art and Future Applications.' IEEE 11th International Symposium on Wearable Computers. Boston, MA October 2007.

[75] Alex (Sandy) Pentland, *Honest Signals* (MIT Press, 2010).

opportunities here, both in terms of correlating communications patterns (and modalities) with the success of teams (e.g., throughout their divergent-convergent-thinking life cycles) as well as in analyzing not just communication patterns but semantic content.

Metrics: Process and Outcome

Building on the above, metrics are an important opportunity for both the art and the science of S&T. We would like to understand how communication patterns (possibly including the semantic content of those communications) correlate with the productivity of ultra-creative research teams. Applying sociometric badges and the commercial analysis tools currently available would be an interesting first step. We note here that correlation is one thing; deducing causal links will be another, more difficult, but extremely important, thing.

Perhaps most difficult, however, will be separately measuring the productivity of ultra-creative research teams, so that correlations can be made. In other words, it is one thing to have "proximal" metrics (useful on the time scale appropriate for behavior and organizational change); it is another thing to have "ultimate" metrics (having to do with impact on the larger science and technology community). These ultimate metrics are currently bibliometric, but the time lag is too long to be used for feedback into the team. Novel metrics are needed, for sure, perhaps along the lines of Yelp or Wikipedia plus peer review. And one thing to keep in mind also is that not everything that is important is yet measurable, but this shouldn't keep us from trying to measure.

Team Science: an Emerging Differentiating Capability for Sandia?

Team science is not just a fad, it's a long-term trend. The exponential growth of knowledge will continue to drive increasing domain knowledge specialization and division of labor, and the increasing need to team across those knowledge domains. Indeed, the importance of team science is highlighted by the recent National Research Council project on "The Science of Team Science," a study aimed at recommending opportunities to enhance the effectiveness of collaborative research in science teams, research centers, and institutes.[76]

In this area, can Sandia perhaps play a cutting edge role? For two reasons, maybe.

A first reason: Sandia is already a highly multidisciplinary place, and a science-technology-applications cross-cutting place. Sandia normally only proposes to do work that *requires* a multidisciplinary approach. So Sandia has the raw material and the incentive for unleashing the power of multidisciplinary teams. That said, Sandia is good at this kind of teaming, but it isn't *very* good at this. Typically, Sandia builds teams if it thinks it is necessary to get the job done. But it doesn't necessarily build teams so that it can do an even better job than is required. Indeed, Sandia, at least in the basic research area, does not have incentives built into its performance review system to encourage teamwork.

A second reason: Sandia is well into transitioning from solving just weapons technology problems, to finding broader horizons for service to the nation. If Sandia learns how to make team research work better, this could transform not only Sandia itself, but the nation as a whole, "lifting all ships." In some sense, Sandia would then be following in the footsteps of IDEO. From

[76] The project began in October, 2012, with a report expected to be issued in late 2014. See: http://sites.nationalacademies.org/DBASSE/BBCSS/CurrentProjects/DBASSE_080231.

purely technical teams, IDEO began adding human factors, social stuff, then narrative people, so that it can add increasingly higher value for its customers, sometimes even teaching its customers *how* to team. This has been very successful, to the point that the social "stuff" now dominates the company, and their most innovative work is at the intersection of human, technological and business factors. Perhaps someday, Sandia could be an exporter of the human and social centered aspects of how science is done (and in what direction it is heading), rather than just being a doer of science. It would still *do* science, but now with a powerful human factors side added.

That said, there are clearly some hurdles to overcome. Perhaps foremost among these is that physical scientists have an inherent distrust of social science, so the "artists" of physical science are going to be slow to apply what the social "scientists" of science know, even if they have known it for a long time. The physical science community would need to recognize that Management Science is not all bunkum. There is a lot to be gained from learning about existing professional knowledge about teams, e.g., how their compositions should depend on desired outcomes (production versus innovation), how they should operate and be evaluated, etc.

Changing the Culture of Science to Better Reward Team-based Research

Science is increasingly thought of as a "team" enterprise. Through collaborations between individual scientists with unique skills and disciplinary specialization, teams of scientists can ask and answer questions that individual scientists working alone could not hope to ask and answer. However, the prevailing culture of science is actually not conducive to teams: its rewards are largely reputational and allocated to individuals not teams. A scientist steeped in the prevailing culture of science is concerned first and foremost with his or her scientific reputation, and that reputation depends on receiving credit for his or her scientific contributions, undiluted and not overshadowed by contributions made by other members of his or her team.[77]

There is thus a tension, not always present in other enterprises, which limits the degree of teaming. On the one hand, scientific productivity demands teams, the larger the better (until, as mentioned later, diseconomies of scale enter in). On the other hand, the culture of science limits the degree of teaming so that individual scientists can maximize reputational reward.

Note that, in the past, when team science was not as common as it is now, this aspect of the culture of science served an obvious useful purpose. It lit in many individual scientists a "fire in their belly" to publish so that their newfound knowledge could be spread. In other words, to advance science means to publish, and the competition for reputation provides a critical incentive to publish. Individual scientists who were whip smart and enjoyed problem solving, but who gave little thought to their external reputation or to publishing, didn't advance science much because the scientific community didn't know what they had done.

[77] Indeed, a junior scientist takes on particular risk when teaming with an eminent scientist. R. K. Merton's "Matthew effect" describes how eminent scientists will often get more credit than less eminent scientists, even if their work is similar. This also means that more credit will typically be given to the more famous of the researchers on the team. See, e.g., Merton, Robert K. (1968). "The Matthew Effect in Science." *Science* 159 (3810), 56–63.

Going forward, with team science becoming more common, the disadvantage of this aspect of the culture of science begins to emerge. Teams must work *around* this aspect of the culture of science in order to harness scientists who crave reputational reward even though credit for their research contributions may be diffused across the team.

But perhaps the culture of science is changing somewhat. In the past, a sole person has often been awarded the ultimate reward in science, the Nobel Prize. More recently, it is routine for two and in some cases the maximum of three people, to share the Nobel Prize. For example, Peter W. Higgs and François Englert shared the 2013 Nobel Prize in Physics for the discovery of the Higgs boson. Moreover, *The New York Times*, as well as many other media sources, not only praised their work but also highlighted the critical contributions made by many others over the past 4 decades that led to this discovery.[78] These are important steps towards exposing "The Myth of the Solitary Genius" discussed in section 1B.

[78] Dennis Overbye, "For Nobel, They Can Thank the 'God Particle'," *The New York Times*, October 29, 2013, sec. Science, http://www.nytimes.com/2013/10/09/science/englert-and-higgs-win-nobel-physics-prize.html.

3C. Art and Science of the Research Institution

Synopsis

The research institution is all about people and how they are organized. Thus, hiring "the best" people is critical. At the research staff level, exactly what "the best" means is not easy to quantify, though, especially as institutions shift emphasis from individual work to teamwork. At the management level, "the best" must mean both top-notch technical talent *and* high social EQ so as to be able to build, diagnose, and nurture successful teams. Once hired, researchers must be given freedom to ask and answer what they consider to be the most fruitful questions within a broad mission space; but they must also be accountable for producing great research. Finally, research institutions must gather data about themselves and use that data to make informed decisions about how they are organized. There are many sources of data (project, financial and human resource) that could be tapped into and integrated (big data analytics) to create a fuller view of the institution and its people, and to enhance the productivity of research teams and of the larger research institution.

Summary of Main Points

Hiring

Hiring for research is extremely important. As is sometimes said from an "artist's" point of view: hire the best, not the second best, because: in procedural work, the best are 2x better than the average, but in creative/inventive work, the best are 10x better than the average.[79] Moreover, hire for the highest performance, not for the hardest work ethic, and hire for technical excellence but not beyond the boundary of "jerks."

This seems like a no-brainer, but one might legitimately ask whether a money-ball-like hiring strategy might also work. That is, perhaps there is a balance between hiring high-profile but expensive researchers versus low-profile and less expensive researchers? And perhaps this balance depends on the field and on where Sandia is (leader, new entrant, etc.) in the field itself.

Assuming, though, that it is the best that is required, one can ask what it *means* to be "the best," particularly in the new era of team science. Is it: technical depth (I-shaped people), technical breadth (hyphen-shaped people), or a combination of technical depth and breadth (T shaped people)? Is it ability: to write and come up with compelling research narratives, to focus and execute, to collaborate selflessly, to outcompete competitors, to be immune to social pressure and therefore to be able to come up with the most innovative but sometimes the craziest ideas, or to become famous through self-promotion and marketing? And what are the symptoms in a young PhD graduate of any of these qualities: graduation from a prestigious university, a high GPA, an Eagle Scout badge, fluency in multiple languages, or ten papers published as a graduate student?

And at what level or levels within a research institution should recruiting and hiring be done? Should it be done at all levels? Should it be concentrated at the first management level, since this is the level that is still highly technical and yet has a broad view of the requisite disciplinary and non-disciplinary knowledge and skills needed?

[79] Hastings, Reed, "Culture."

Finally, how about hiring managers, especially first-level managers? These managers occupy arguably the most important positions in a research institution: they must be top-notch technically so that they can inspire and recruit the best staff, but they must also have high social EQ so as to be able to build and diagnose and nurture successful teams.

Balancing Freedom and Accountability

It goes without saying that freedom for a researcher or research team to ask and answer what they consider to be the most fruitful questions within a broad mission space (i.e., in a "problem-rich environment") is important. Only at the researcher level is there sufficient technical knowledge of capabilities and of the field to enable such decisions to be made effectively. And only at the researcher (or first-level manager) level can such decisions be made quickly to respond opportunistically to new developments. It thus also goes without saying that line managers, particularly first-level line managers, must have broad discretion in funding research. Within the mission space of the researcher, a very large fraction of time should be "exploratory time," not just the 20% that some companies (like Google, 3M, etc.) set aside for such. Or, if it must be only some percentage of time, the research institution must create an environment that incentivizes such exploratory activities. Doing this would create a lifestyle and culture of discovery and invention.

In exchange for this freedom, though, must come accountability. If a researcher or research team, over time, does not produce great research, he or she or they must be accountable. Ways must be found to measure the outcomes of exploratory time, i.e., research output. And if those outcomes are insufficient compared to that of other teams, then the individuals in those teams must either leave the organization or move into a new role (or new team) in the organization. Importantly, though, this accountability must not come in the form of a competition between researchers for credit for their individual contributions and thus to destroy the fabric of teamwork. The accountability must be the team's success convolved with a competition between researchers *to contribute to the team*, and thus to enhance teamwork.

Metrics: Institutional "Big Data"

In other sections of these Proceedings, data and metrics have been discussed: "process" metrics associated with, say the communication patterns of a team, and "outcome" metrics associated with the impact of a team's research on the external community of science and technology.

There is another kind of data that isn't associated so much with a research team, but with the research institution as a whole. For example, in 2010, NSF, NIH, and OSTP launched the STAR METRICS initiative. This initiative taps into an institution's project, financial, and human resource information systems to capture in precise detail the identity and level of participation of individual researchers on federally funded research projects. In particular, we know that knowledge that is produced by researchers is embodied in multiple forms: publications, patents and the training and placement of students. We also know that the knowledge is generated by a combination of inputs: different types of team members, different types of collaborations within and across institutions, different combinations of equipment expenditures and differential access to facilities and services.

Sandia has an opportunity to participate in and leverage the STAR METRICS initiative and its researcher community to answer similar questions for its own purposes. This data would provide much needed ground truth about Sandia's staff and research: What are the active competencies of Sandia's staff (e.g., how many active research FTE's does Sandia have in a given discipline or problem domain)? Which of Sandia's staff are collaborating externally or publishing prolifically, and in which research areas? Such information could be deployed on Sandia's internal network to catalyze collaboration and enable Sandians to locate desired information, expertise, and other resources. With its own data, Sandia could improve the quality and defensibility of its LDRD assessments, increase the benefit from future LDRD investments, map past and current technical collaborations and their relation to programmatic and organizational structure, and gain insight into the effects of research participation on an individual's career trajectory. Multidisciplinary efforts are a hallmark of Sandia. This data could be used to understand and improve multi-disciplinary research outcomes, using computational techniques to define researcher specialization areas in much finer detail than is currently possible with conventional disciplinary taxonomies.

In other words, there is an opportunity to do "big data" analytics on Sandia with the aim of assessing who is doing what, what kind of impact they are having, and helping construct teams with optimal analogical spread. One could even imagine someday a Google-Now-like "push" to internal management and staff with meta-information that would be helpful for whatever task they are currently trying to perform.

3D. Art and Science of Science Metrics and Rewards

Synopsis

Although the focus of the Forum and Roundtable was on issues that were internal to the Research Institution, some of the discussions (both at the Forum and Roundtable and in pre- and post-Forum-and-Roundtable emails) inevitably spilled over into issues that intersect the global research community as a whole. For completeness, we summarize those discussions here. The discussions centered on deficiencies in the system by which research impact is measured and by which reputational rewards are given.

Summary of Main Points

Measuring Research Impact on the Global Economy

The impact of research is of course extremely broad. At a macro-economic level, research in all of its forms, both formal and informal, is widely acknowledged to be a key engine for economic growth.[80,81,82] At a micro-economic level, however, connecting particular research projects to economic growth has been more difficult. This is true not just for informal research, but for formal funded research, the kind discussed throughout this Forum and Roundtable. Ideally, one would like to trace the microscopic paths by which individual research breakthroughs in a laboratory influence the larger economy: on technology, on products, on quality of life, on GDP, on human capital. Only then could one gain a full view of the economic impact[83] of a researcher or a research team or a research institution.

We are in the early stages of asking how one might do this. One emerging idea is to think of knowledge production as not just ideas (embodied in artifacts such as publications or patents) but the people who give birth to, transmit, and serve as a critical repository for, those ideas. As an example, the success of Silicon Valley is often attributed to Stanford, but that success couldn't just be due to the papers that Stanford published (which are globally accessible), it must also be due to the people (e.g., students) Stanford produced. As another example, industry has benefited enormously from people (i.e., students, post-docs, research staff) who have worked and developed expertise at Sandia and then moved to industry.

In other words, one must shift from an idea-centric view of research and its impact to a people-centric view[84] (or at least to a balanced people/idea view). To do that, one needs to know who is working on what and how the "who" and the "what" are connected. As discussed in section 3C, this is just beginning to be done with the STAR METRICS initiative begun in 2010 by NSF,

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[80] Charles Jones, "Introduction to Economic Growth (2nd Edition)" (1998), http://class.povertylectures.com/JonesChapter2C.pdf.

[81] Shiping Tang, "Knowledge as a Production Factor: Toward a Unified Theory of Economic Growth," *Unpublished. Available: Http://www. Iapscass. Cn* (2005).

[82] Paul M Romer, "The Origins of Endogenous Growth," *Journal of Economic Perspectives* 8, no. 1 (February 1994): 3–22, doi:10.1257/jep.8.1.3.

[83] We recognize that global macro-economics and GDP are not the only ways in which science makes impact. Knowledge is also important for its own sake or for the overall benefit of mankind.

[84] Julia Lane, "Let's Make Science Metrics More Scientific," *Nature* 464, no. 7288 (2010): 488–489.

NIH, and OSTP.[85] Once one has the core data patterns, statistical "big data analytics" can be used to test theories of research and research impact, and to make inferences about what works and what doesn't on the basis of evidence.

Again, we are in the early stages of developing these new measures of research and research impact. We won't be able to measure everything, but we do need to advance the ball forward as best we can. And though Sandia is only obliged to use standard publications data in the research metrics it reports to DOE, it could certainly augment those metrics with these emerging ones, as well as use those metrics internally to drive behavior.

Measuring Research Impact on Research Itself

The "home run" of measuring research impact would be that discussed above: impact on the global economy. The "double" of measuring research impact might be: the narrower impact on the research community itself. And the "single" of measuring research impact might be: the even narrower impact just of publications on the research community (in other words, moving towards more sophisticated bibliometrics).

We emphasize that, as discussed above, measuring research impact *must* eventually be much more than bibliometrics: one can argue that bibliometrics, at least in its current form, has skewed the research enterprise to its detriment. The key mechanisms for the creation, transmission, and adoption of ideas across the research community are people-centric: teaching (from senior researchers to junior researchers and students), seminars, conference presentations, workshops, keynote speeches and publications. Publications are only one of these many mechanisms.

But this should not deter us, in the meantime, from also trying to improve idea-centric publication-based bibliometrics. Publications and bibliometrics dominate the current metrics landscape: citations to an article have become nearly synonymous with the impact of research on research, and are now embodied in a researcher's H-Index or a journal's Journal Impact Factor. There is much room for improvement in these metrics, however, with the research community even beginning to rebel against over-reliance on bibliometrics.[86]

At the heart of the weakness of bibliometrics is the difference between semantic knowledge (that $E = mc^2$) and meta-knowledge (that everyone *accepts* that $E = mc^2$ is true whether it is actually true or not). Ultimately, it is semantic knowledge that really counts – it's the knowledge that allows us to get to the moon, to improve solar cell efficiency, or to sequence the human genome. But because semantic knowledge is nearly all specialist knowledge, unverifiable by anyone but specialists, meta-knowledge *about* semantic knowledge is necessary, otherwise researchers would not know what semantic knowledge outside (and sometimes even within!) their own specialty to trust.

It is thus impossible *not* to rely on meta-knowledge to make sense of semantic knowledge. The question is how to correct for the deficiencies associated with the current dominant form, citations, of meta-knowledge. In fact, citations can be thought of as information aggregation, one of

[85] Julia Lane and Stefano Bertuzzi, "Measuring the Results of Science Investments," *Science* 331, no. 6018 (2011): 678–680.

[86] See, e.g., *San Francisco Declaration on Research Assessment (DORA)* (Initiated by the American Society for Cell Biology (ASCB), December 2012), http://am.ascb.org/dora/.initiated by the American Society for Cell Biology (ASCB, which cautions against glib use of journal impact factors.

the key functions of a social group.[67] Citations, however, are highly imperfect in the way they aggregate information: they are often just a way of making sure possible referees are appeased; they tend to favor review over original articles; and they are increasingly "gamed."[87]

Perhaps most importantly, citations are subject to "gossip": when a person's opinion (or tendency to cite) isn't based on his or her own unique analysis or information, but on another person's social influence. Thus, citations often preferentially accrue to more socially influential older scientists, even though many just-as-important ideas come from younger junior scientists. This is perhaps at the heart of the DORA[76] criticism: current bibliometrics are simply popularity contests with gossip heavily built in. As discussed by Sandy Pentland, at a small (team of people) scale, there are ways to discount gossip through knowledge of the structure of their social network (who talks to whom). At a large (citations across the entire research landscape) scale, however, there aren't yet ways of doing this. A key challenge, if one is to live with the current citation metric, is thus to come up with ways of correcting for gossip at a large scale.

Alternatively, one could develop alternatives to the citation metric. The most promising would be to borrow from emerging social-network-based metrics such as Yelp or Wikipedia, via which knowledgeable people's opinions might be aggregated to give a balanced view of a research publication. As has been noted by Michael Eisen, [88] we don't currently now capture the opinions of the readers of journal articles, and thus are not capturing a rich source of meta-knowledge that overwhelms other sources in both quantity and quality. Moreover, as has also been noted by Michael Eisen, a large fraction (perhaps as much as half) of what is published even in the most prestigious journals (Nature or Science) is refuted within a few years of publication and yet this valuable meta-knowledge doesn't "attach" to the paper. Note also that one could go beyond a Yelp/Wiki-like system by taking the credibility of the reviewers into account through a recursive Google-like PageRank algorithm. In other words, one would like to transmit meta-knowledge not only about what strangers think about a publication but about who (and how reliable) those strangers are.

The world of meta-knowledge is a rich one, and one that is relatively untapped. Ultimately, it should be possible to use it to facilitate and speed up all the fundamental aspects of knowledge creation, aggregation, and consolidation: highlighting the important contradictions in semantic knowledge, highlighting significant new results and theories for resolution, and providing guideposts for non-experts from related fields as to what is likely to be important, stimulating, or true. In this way, there can be a metrics-facilitated interplay between semantic and meta-knowledge that advances both.

Assigning Reputational Credit to Teams not Individuals

Finally, we note here that one of the difficulties in measuring research impact on research via publications is that the "currency" of research impact isn't monetary, but reputational. This has consequences that go beyond how research is impact is measured and extends, as also discussed in section 3B, to how the process of doing research is organized.

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[87] Richard Van Noorden, "Brazilian Citation Scheme Outed," *Nature* 500, no. 7464 (August 27, 2013): 510–511, doi:10.1038/500510a.

[88] Michael Eisen, University of California - Berkeley. He talks about this in:*Responsible Authorship and Publication*, 2012, http://www.youtube.com/watch?v=XOi1ZWf63hM&feature=youtube_gdata_player.

In particular, a universal observation is that engineering projects are more conducive to teaming than research projects are. Often in~~n~~ engineering, the goal is a product, the customer judges whether he or she likes the product, and the reward is $ to the company. The company has nearly complete control over how to reward (presumably fairly) the team and the individuals on the team for their contributions to the team and to the product. In research, in contrast, the goal is often impact on the research community. But the research community doesn't reward with $, it rewards with "reputational currency." And, most importantly, reputational currency goes largely to individuals, not to teams. Without a massive culture change in science, it would be hard to imagine a scientific paper with simply the author byline "Sandia National Laboratories" the way a product might simply have "Intel" on it.

The consequence of this "reputational reward to individuals" system of research is that companies (like Sandia) do not control one of the most fundamental rewards of a researcher: the researcher's reputation in the research community.[89] That reputation is the product of external perception of the quality of work associated with the researcher and external perception of the degree to which the researcher contributed to the work. It is thus to every researcher's advantage to publish the best possible work with the fewest possible co-authors. And it is to every researcher's disadvantage to contribute to a work that they will not be a co-author on.

Researchers thus have an incentive to team (so they can be part of the best possible work) as well as an incentive not to team (so they can gain as much external reputational credit as possible for that work). Engineers, in contrast, have the same incentive to team but much less incentive not to team. Thus, a key challenge to the community of research, if it wishes to encourage teamwork, is to figure out a mechanism by which reputational credit can be given to teams and not just individuals.

[89] We do not mean to imply that this is a researcher's only reward for his or her research. There are many other rewards (satisfaction of personal curiosity, love of problem solving, impact on engineered products and customers, salary, etc.). However, it is the main reward that is controlled by and originates in the external research community.

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