LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

LDRD PROJECT NUMBER: 220394

LDRD PROJECT TITLE: THE STRUCTURE AND EVOLUTION OF SCIENCE AND TECHNOLOGY: A MODERN SYNTHESIS

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ABSTRACT:

This project matured a new understanding (a "modern synthesis") of the structure and evolution of science and technology. It created an understanding and framework for how Sandia National Labs, the Department of Energy, and the nation, might improve their research productivity, with significant ramifications on national security and economic competitiveness.

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Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

INTRODUCTION AND EXECUTIVE SUMMARY OF RESULTS:

Human scientific and technological knowledge has been key to the past, and will likely be key to the future, success of humanity as a species. At a superficial level, the term “research” refers to human society’s formal and purposeful investment in the creation of new scientific and technological knowledge by professional researchers, and we accept this definition. At a deeper level, however, the nature and nurture of research has, in our opinion, remained elusive.

In this project, we matured a modern synthesis of the nature and nurture of research. This modern synthesis is intended to be helpful to any organization, including Sandia, that wishes to do research productively. It made heavy use of an interplay between the “theory” and “practice” of research that had been lacking in the field: many have developed theories of research with little interest in the practice of research; and many have improved the practice of research with little interest in the theory of research. We bridged this gap, and are hopeful that Sandia, DOE, and the nation will build on our work to improve research productivity.

One tangible result that this project contributed to was a major book co-authored with Professor Venkatesh Narayanamurti (Harvard University): V. Narayanamurti and J.Y. Tsao, “The Genesis of Technoscientific Revolutions: Rethinking the Nature and Nurture of Research” (Harvard University Press, 2021, SAND2020-14278 B).

Another tangible result that this project contributed to was a white paper that particularized the insights of the book just mentioned to Sandia. The white paper was co-authored with Jessica Turnley (formerly Sandia research staff, now consultant to Sandia working out of Galisteo Consulting): J.Y. Tsao and J.G. Turnley, “Thought Experiment for a Low-Energy Physical Sciences and Engineering Research Center at Sandia National Laboratories” (OUO White Paper, Sandia National Labs, SAND2022-11072 CTF).

Other tangible results are listed in the references section.

DETAILED DESCRIPTION OF RESEARCH AND DEVELOPMENT AND METHODOLOGY:

This project matured a modern rethinking of the nature and nurturing of research, with the aim of significantly improving the effectiveness of research. Our methodology was to consider the nature and nurturing of research as an integrated whole: focusing on those aspects of the nature of research most germane to its effective nurturing, and likewise focusing on those aspects of the nurturing of research necessary for alignment with its nature.

Importantly, our rethinking of the *nature* of research was both reductionist and integrative. On the one hand, our rethinking broke technoscience and its advance into fundamental categories and mechanisms: science and technology, questions and answers, and surprise (which we identify with and research) and consolidation (which we identify with development). On the other hand, our rethinking emphasized powerful feedbacks between the categories and mechanisms, with technoscience and its overarching advance a unified whole much greater than the sum of its parts. Moreover, although our rethinking of the nature of research was in large part motivated by a desire to better understand how to nurture research, we are cautiously optimistic that it will also be of value beyond that immediate motivation.

Our rethinking of the *nurturing* of research drew lessons from two sources. First, we drew from our own and others' experiences on what it means to "do" research. Our own experiences in research practice and the experiences of research leaders who nurtured spectacularly effective research organizations, including the iconic Bell Laboratories, comprised our "data." Second, we drew from our rethinking of the nature of research: how best to align the nurturing of research so that the various mechanisms of associated with the nature of research are healthy and the feedback loops and internal amplifications between them are not short-circuited.

Throughout, we benefitted from the perspectives of distinguished scholars of research: Thomas Kuhn and Brian Arthur from the history and philosophy of science and technology; Stephen Jay Gould, Herbert Simon, Philip Anderson, Stuart Kauffman, and Joseph Schumpeter from the evolutionary biological, complexity, physical, and economic sciences; and Ralph Bown, Vannevar Bush, and Donald Stokes from the world of research leadership and policy. But, drawing on our experiences within technoscientific research practice, we reframed those perspectives in language that can be followed not only by scholars, but also by practitioners, of research.

RESULTS AND DISCUSSION:

Nature of Research

Our rethinking of the nature of research was based on correcting three widespread yet mistaken beliefs associated with the nature of research.

The first widespread yet mistaken belief is that technology is subservient to and follows from science and thus that the advance of science (so-called basic research) is the pacesetter of the advance of technology (so-called applied research). This belief, stemming in part from Vannevar Bush's seminal report "Science, the Endless Frontier," is limiting because it conflates research with science, hence narrowly confines research to the creation of new science and explicitly *not* to the creation of new technology. In fact, scientific and engineering research feed off each other to advance both, in cycles of invention and discovery—exemplified by the deeply interactive and virtually simultaneous engineering invention of the transistor and scientific discovery of the transistor effect at the iconic Bell Labs in 1947. To emphasize the importance of the symbiotic union between science and technology, we call that union *technoscience.*

The second widespread yet mistaken belief is that the goal of research is to answer questions. This belief is limiting because it misses the complementary and equally important finding of new questions. In Albert Einstein's words:

> *The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill. To raise new questions, new possibilities, to regard old questions from a new angle, requires creative imagination and marks real advance in science.*

Finding a new hypothesis (a new question) is just as important as testing that hypothesis (answering that question), but is far less supported in today's research environments. If Albert Einstein were now to propose research into the relationships between space, time, mass, and gravity, he would have difficulty getting funded, but Arthur Eddington, who tested Einstein's theory of general relativity, wouldn't; and Charles Darwin, who came up with the theory of evolution by natural selection, would have difficulty today getting his research funded, but a test of Darwin's theory wouldn't. In fact, *both* question-finding and answer-finding are vital to research and bolster each other in a symbiotic union.

The third widespread but mistaken belief stems from the "Wall Street" perspective that gained strength in the latter half of the twentieth century: the primacy of short-term and private return on invested capital. This belief when applied to research is limiting because it blinds us to the value of long-term and public return on invested capital. Truly path-breaking research seeks surprise. It overturns previous ways of doing and thinking in ways that cannot be anticipated—both in terms of *when* they will occur and *whom* they will benefit. Much of the benefit of research is long-term and public (extending beyond the organization that performed the research) rather than short-term and private (confined to the organization that performed the research). This has been true even for *private* industrial research laboratories, including the iconic ones active in the twentieth century, such as Bell Labs, IBM, Xerox PARC, Dupont, and GE. These laboratories shared common traits such as research cultures that emphasized learning and surprise, and an irreverence for boundaries of all kinds—between disciplines, between science and technology, and between finding questions and finding answers. As a consequence, their contributions had enormous long-term *public* benefit. Examples of their scientific contributions include information theory, the 2.7K cosmic microwave background, electron diffraction, scanning tunneling microscopy, high-temperature superconductivity, laser-atom cooling, and fractional quantization of electronic charge. Examples of their technological contributions include the transistor, the semiconductor laser, solar cells, charge-coupled devices, the UNIX operating system and C programming, the ethernet, the computer mouse, polymer chemistry, and synthetic rubber. When, instead, short-term private benefit crowds out long-term public benefit, R&D becomes weighted away from research, whose outcomes are less certain, toward development, whose outcomes are more certain. Ultimately, such a shift in the 1980s and 1990s caused the demise of research at the great industrial research laboratories.

Nurturing of Research

The corrections to these three widespread but mistaken beliefs just discussed—the coevolution of science and technology, the intricate dance of question-finding and answer-finding, and the punctuated equilibria of surprise and consolidation—are foundational to our rethinking of the *nature* of research. They are also foundational to our subsequent guiding principles for *nurturing* research consistent with that nature.

Our first guiding principle for nurturing research is *align organization, funding, and governance for research.* Research should not be invested in casually—because research outcomes are highly uncertain and cannot be scheduled or determined in advance, research organizations should invest in research only if they have a purpose that can accommodate the unexpected. Research seeks to surprise and overturn conventional wisdom, while development seeks to consolidate and strengthen conventional wisdom—a deep difference in mindset that requires research to be culturally insulated (though not intellectually isolated) from development. Research must respond flexibly and opportunistically, and this requires resources to be block allocated at the organizational level to research leadership and ultimately to people not projects. And research leadership is critical: research is not simply a matter of gathering researchers for "free range" pursuits; research must be orchestrated and strike a delicate balance between organizational focus and individual freedom.

Our second guiding principle for nurturing research is *embrace a culture of holistic technoscientific exploration.* Asking people to explore the unknown means asking them to take on an uncertain, risky, and exceedingly difficult assignment, and this requires immersion in a culture exquisitely supportive of technoscientific exploration. The full technoscientific method and its science-and-technology symbiosis must be embraced; research must not be compartmentalized by whether it is inspired by curiosity or practical application; the finding of both questions *and* answers must be embraced; hypothesis-finding must be just as valued as hypothesis-testing; and the informed contrariness that facilitates overturning conventional wisdom must be embraced.

Our third guiding principle for nurturing research is *nurture people with care and accountability.* Though not always recognized, research is a deeply human endeavor whose success at a high level requires nurturing people at a high level. There is the loving and empathetic care of creative and sometimes idiosyncratic (even contrarian) researchers who are humans first, intellects second. There is also the selectivity, fairness, and accountability associated with aspiring to the highest standards of excellence in research outcomes.

Particularization to Sandia National Labs

We also particularized some of the insights from the modern synthesis to Sandia. Our motivation: the United States is on a trajectory to be replaced by China as the global leader in the most advanced technoscience, an inferiority that will soon become a serious national security issue. Discovery research, the front end of the research and development (R&D) enterprise that advances technoscience, is essential to reverse this trajectory. Our OUO white paper presented a thought experiment for a new Sandia center for discovery research in low-energy physical sciences and engineering, an area of overarching importance to all of Sandia's strategic missions (nuclear deterrence, national security, global security, and energy/homeland security), and an area that includes advanced microelectronics and quantum-information science and technology.

ANTICIPATED OUTCOMES AND IMPACTS:

Our hope is that this modern synthesis enables a new generation of "Research Labs 2.0" that goes beyond our current generation of "Research Labs 1.0." This new generation of "Research Labs 2.0" could come in very different shapes and sizes. They could have different organizational governance structures, funding models, technoscientific knowledge domain foci, and scales—some at the large scale of CERN (Conseil Européen pour la Recherche Nucléaire), some at the medium scale of a research organization embedded in a larger corporation, and some at the small-scale of a philanthropically supported research institute. But they would all be aware of the timeless and overarching principles associated with nurturing research.

This new generation of labs would be aware that nurturing research must be aligned with what is being nurtured. It must be aligned with the nature of research and all its feedback loops and amplifications—not just the reductionism of physics, though that is important, but also the complexity sciences and the fusion of disciplines with a holistic "more is different" attitude. If the symbiosis between science and technology is not understood, then the full technoscientific cycle and its collective power will not be embraced. If the symbiosis between question-finding and answer-finding is not understood, question-finding especially is fragile and will go unsupported. If the importance of surprise and the overturning of conventional wisdom is not understood, then informed contrarians who are always questioning, always pushing past conventional wisdom's comfort zone, will be weeded out.

This new generation of labs would also be aware that nurturing research requires an appreciation of research as a deeply human, collaborative, and social endeavor. Like all social endeavors, it requires active social construction: organization, funding, and governance that is aligned with research; a human culture that supports holistic technoscientific exploration; and the nurturing of people with care and accountability. Like all collaborative endeavors, it benefits from the full diversity and inclusiveness of the society in which it is embedded and to which it will contribute. Like all human endeavors, particularly those that require extraordinary performance, it requires nurturing the whole human being and spirit. We paraphrase here one particularly important insight from Ralph Bown, vice president of research at Bell Labs from 1951 to 1955:

> *[R]esearch environments reflect human relationships and group spirit. In short, successful research institutions should never forget that they are human institutions, and they should place people above structure.*

Our hope is also that in the more distant future, an increasingly effective generation of research laboratories, Research Labs 3.0, will emerge. This new generation would be based on improved principles that go beyond, and perhaps even overturn or displace, the ones articulated in this book. To reach beyond where we find ourselves today, we must continue to "learn how to learn." We recognize two sources of learning: First, real experiments. As we become more deliberate in designing research organizations and watching them operate, we must use these same organizations as experiments from which to learn more about the nature and nurturing of research. The nurturing of research is a body-contact sport that requires direct human experience. Second, artificial experiments. As artificial intelligence advances and begins to learn how to learn, we look forward to mapping the nature of artificial learning onto the nature of human learning. Much has changed in the social enterprise of research in the seventy-five years since Vannevar Bush's seminal report to President Roosevelt and the creation of the National Science Foundation. We believe at least as much change is possible in the coming seventy-five years. As articulated by President Joseph R. Biden Jr.:

> *I believe it is essential that we refresh and reinvigorate our national science and technology strategy to set us on a strong course for the next 75 years, so that our children and grandchildren may inhabit a healthier, safer, more just, peaceful, and prosperous world. This effort will require us to bring together our brightest minds across academia, medicine, industry, and government—breaking down the barriers that too often limit our vision and our progress, and prioritizing the needs, interests, fears, and aspirations of the American people.*

Finally, our hope is that we have stimulated thinking on ways in which Sandia National Labs might play a role in discovery research in Low Energy Physical Sciences and Engineering on behalf of the nation.

CONCLUSION:

It takes only a moment of reflection to be astonished by the technoscientific revolutions that have remade human society just during this past century and a half. A few examples from the physical sciences and engineering: special relativity, the transistor effect, the light bulb, the transistor, the laser, the blue LED, and the iPhone. Some examples from the life and information sciences: DNA, the polymerase chain reaction method, CRISPR-Cas9 gene-editing tools, and deep learning. Who knows what technoscientific revolutions might remake human society in the future, at any level of the "more is different" seamless web of knowledge: physical science and engineering, life science and medicine, and social science and human affairs? We are certainly mindful of the positive and negative consequences of technoscientific advance, and thus of humanity's collective responsibility for managing those consequences. As articulated by science and technology studies scholar Sheila Jasanoff:

> *If engineering has emerged as the powerhouse of progress in the 21st century, with [that] power comes responsibility.*

But we are confident in the limitlessness of the transformative and ultimately beneficial technoscience waiting to be created.

Just as technoscience shapes society, society also shapes, and must shape, research—the front end of the research-and-development cycle that is the genesis of technoscientific revolutions. How does society shape research? It does so through the social enterprises within which research is done. The first formal research organization, Thomas Edison's Menlo Park Laboratory, formed in 1876, was a social enterprise. The great industrial research laboratories of the twentieth century—including Bell Labs, IBM, Xerox PARC, Dupont, and GE—were social enterprises. Today's research universities, research institutes, and national and international laboratories are social enterprises.

As society and its values have evolved, these social enterprises have evolved and in turn, research has evolved. In the latter half of the twentieth century, following World War II, modern society's support for research was accelerated by its belief in the power of technoscience as a public and collective good, particularly for national defense, economic prosperity, and human health. Subsequently, in the latter quarter of the twentieth century continuing into the first quarter of the twenty-first century, modern society began to shift its emphasis to short-term and narrower measures of return on capital invested and to a transactional "what's in it for me" approach to research. The consequence was that the great industrial research laboratories shifted their emphasis from research to development and, in some cases, eliminated research entirely. As we approach the second quarter of the twenty-first century, our hope is that modern society will move away from viewing research as a transactional creator of short-term private benefit and toward a view of research as a creator of long-term public and *collective* benefit, addressing today's societal grand challenges and enabling society-transforming advances we can now only dimly imagine.

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