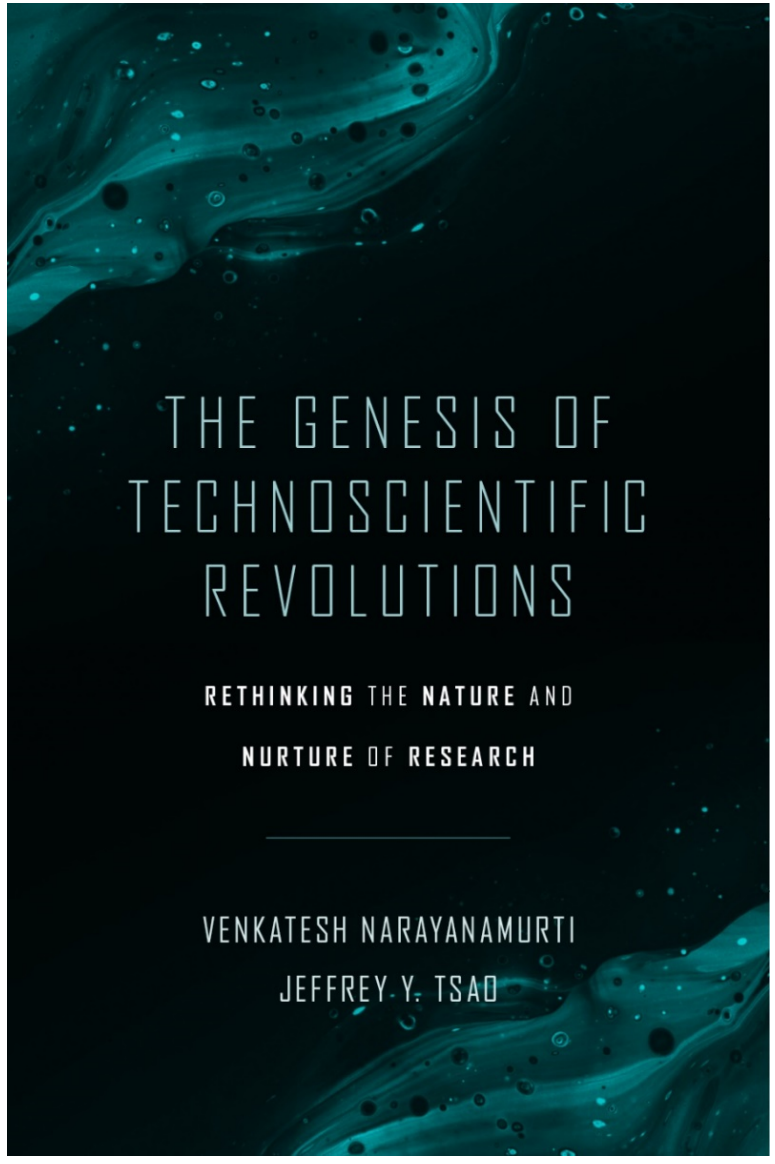
New Research Ideas Forum Sandia National Labs 2021 November 10



discoveryresearch.org

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- Support from our home institutions
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  - Sandia National Laboratories
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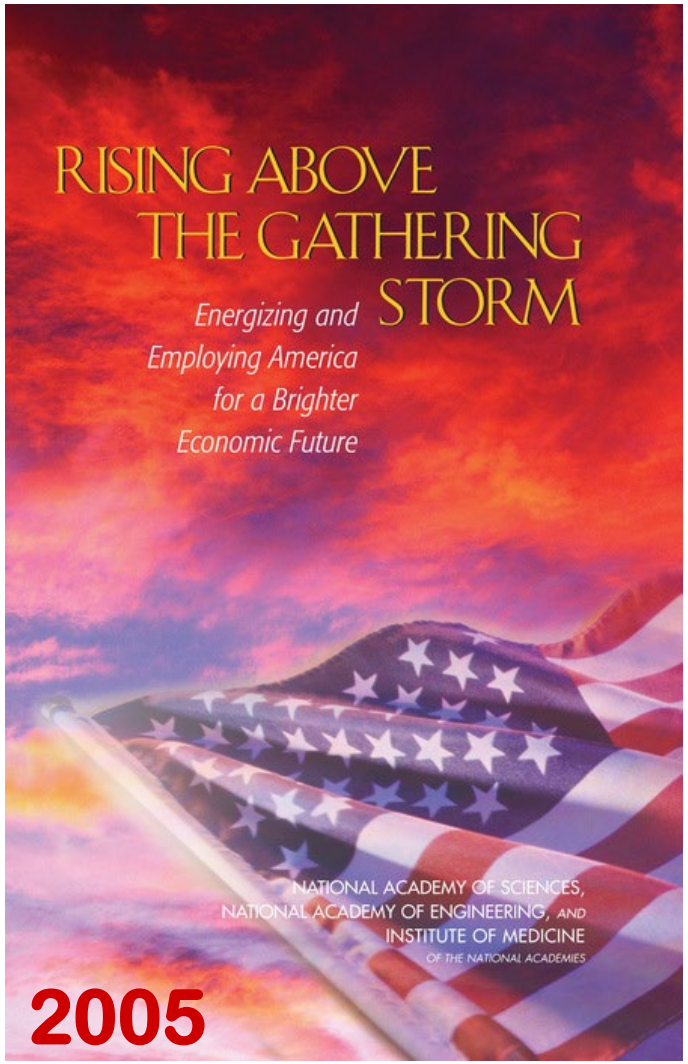
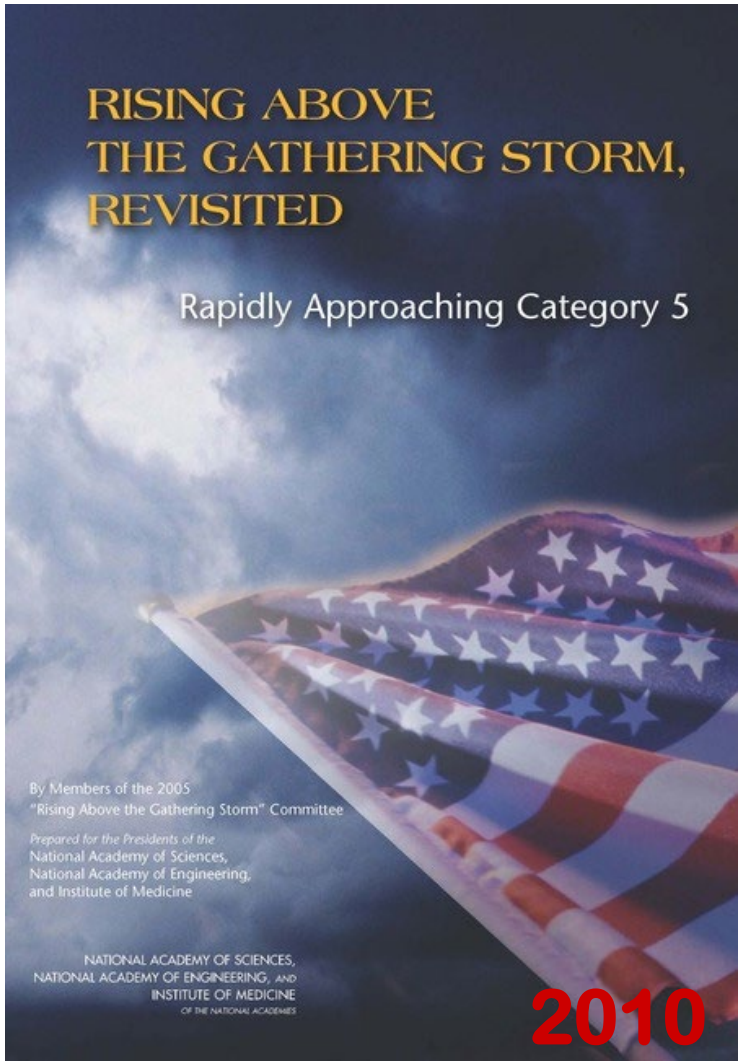
  - History & Philosophy of S&T: Thomas Kuhn, Brian Arthur
  - Evolutionary Sciences: Stephen Jay Gould, Herbert Simon, Philip Anderson, Stuart Kauffman, Joseph Schumpeter
  - Research Leadership & Policy: Ralph Bown, Vannevar Bush, Donald Stokes

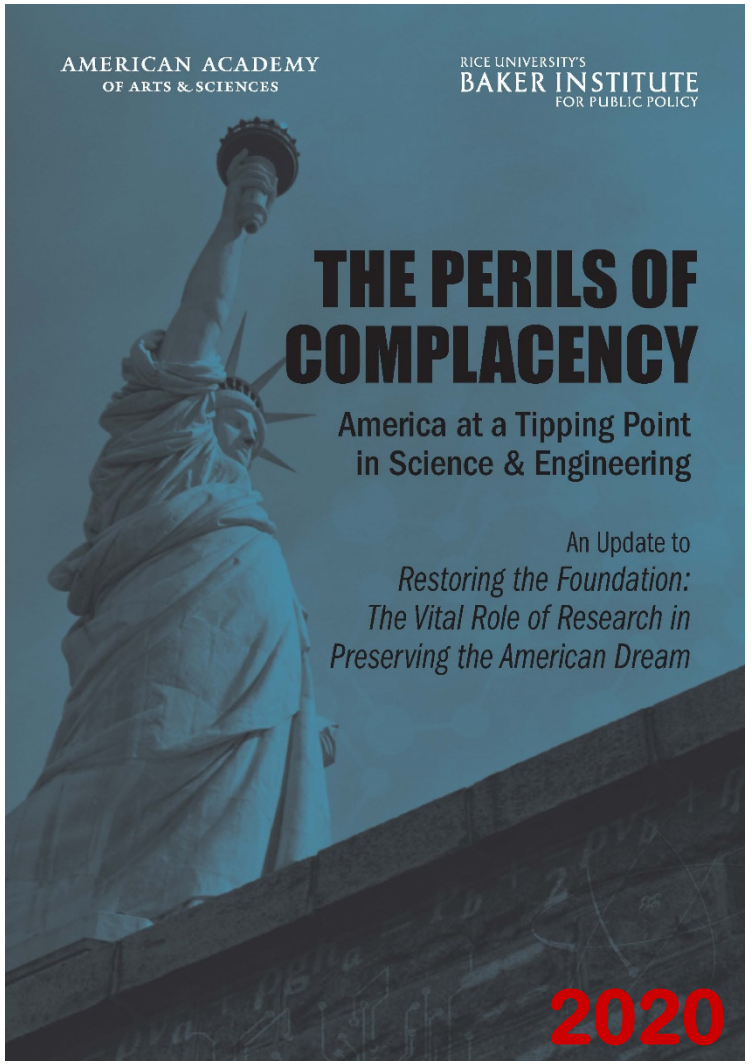
Why Did We Write This Book?

Research is the front end of human society's engine powering innovation and technoscientific advance. We believed it was due for a rethink, one consistent with its **nature** as deeply holistic and its **nurturing** as deeply human.

Alarm Signals



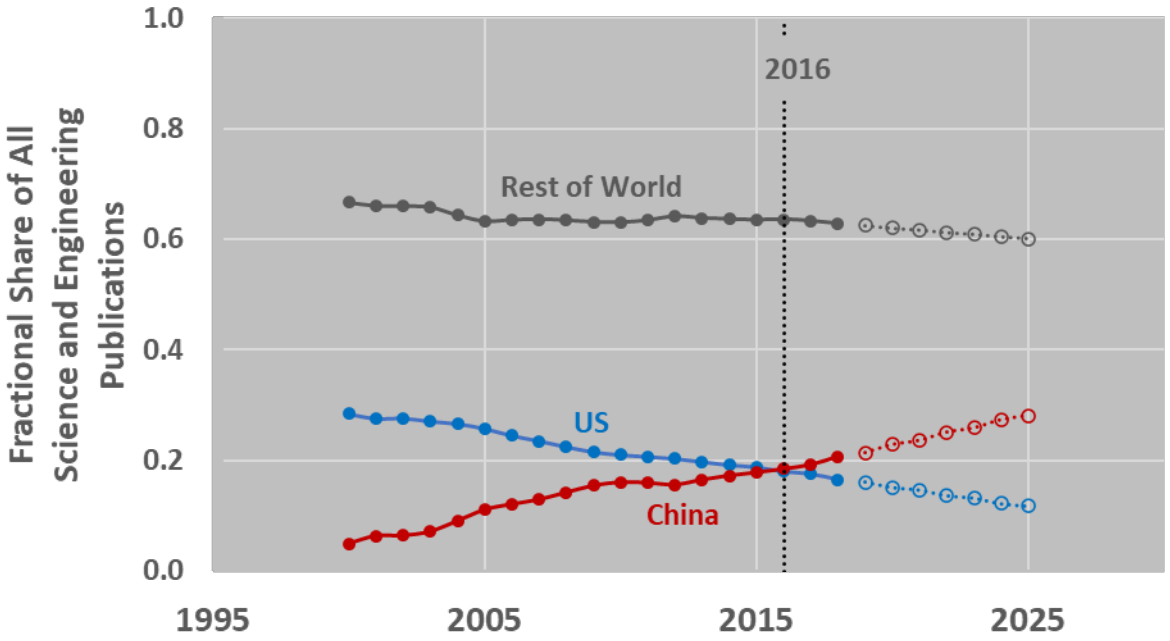


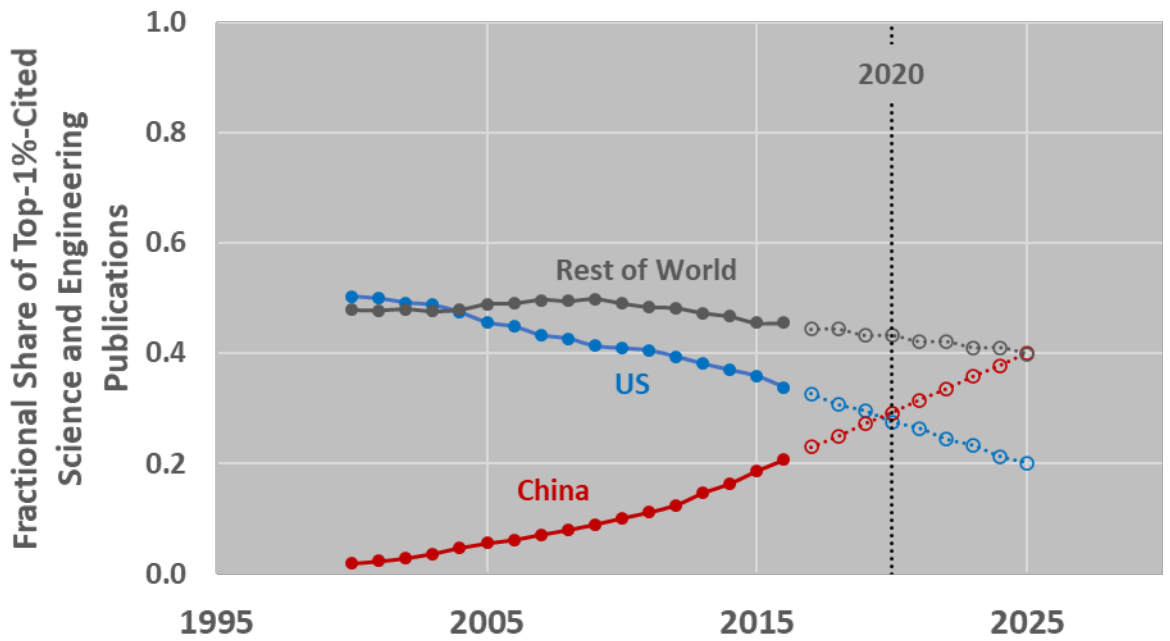


Keen Competition

"Science and technology has become the main battleground of global power rivalry. Competition over cutting-edge technology has intensified to an unprecedented level. We must have a strong sense of urgency and be fully prepared."

Xi Jinping, South China Post, May 30, 2021

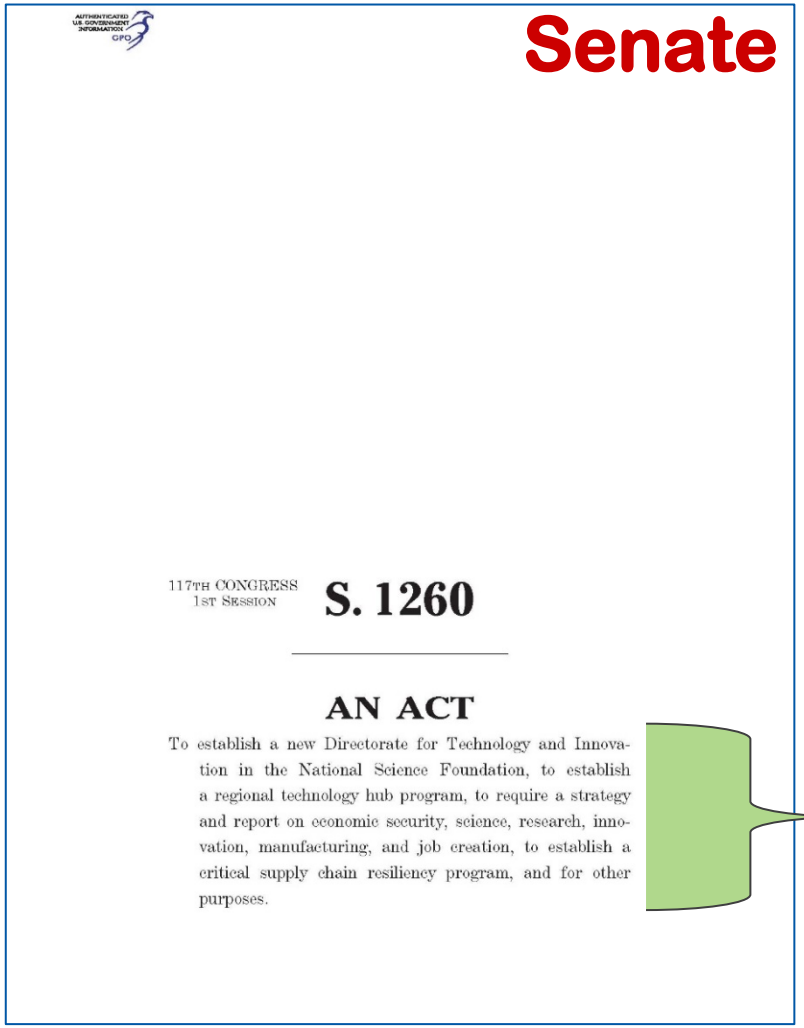




Past and projected future US and China fractional shares of the world's science and engineering (S&E) publications. Data derived from the National Science Board's Science and Engineering Indicators (2018).

Opportunities: The Endless Frontier Act 2021

Senate



117TH CONGRESS
1ST SESSION

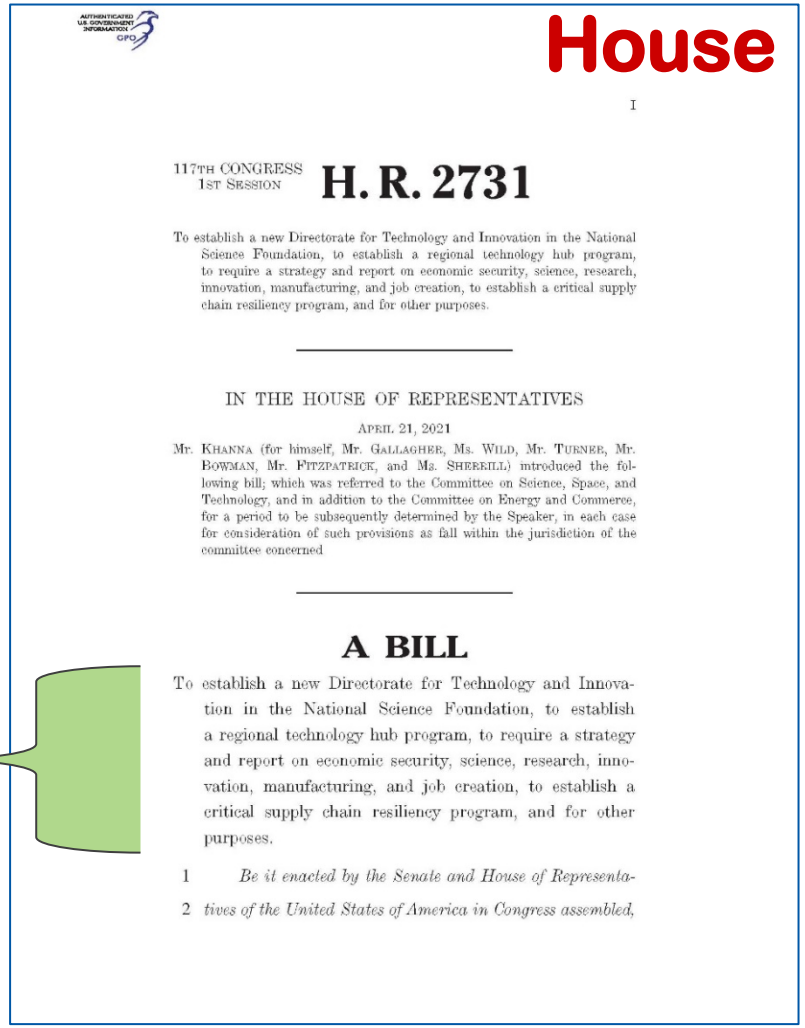
S. 1260

AN ACT

To establish a new Directorate for Technology and Innovation in the National Science Foundation, to establish a regional technology hub program, to require a strategy and report on economic security, science, research, innovation, manufacturing, and job creation, to establish a critical supply chain resiliency program, and for other purposes.

To establish a new Directorate for Technology and Innovation in the National Science Foundation, …

House



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117TH CONGRESS
1ST SESSION

H. R. 2731

To establish a new Directorate for Technology and Innovation in the National Science Foundation, to establish a regional technology hub program, to require a strategy and report on economic security, science, research, innovation, manufacturing, and job creation, to establish a critical supply chain resiliency program, and for other purposes.

IN THE HOUSE OF REPRESENTATIVES

APRIL 21, 2021

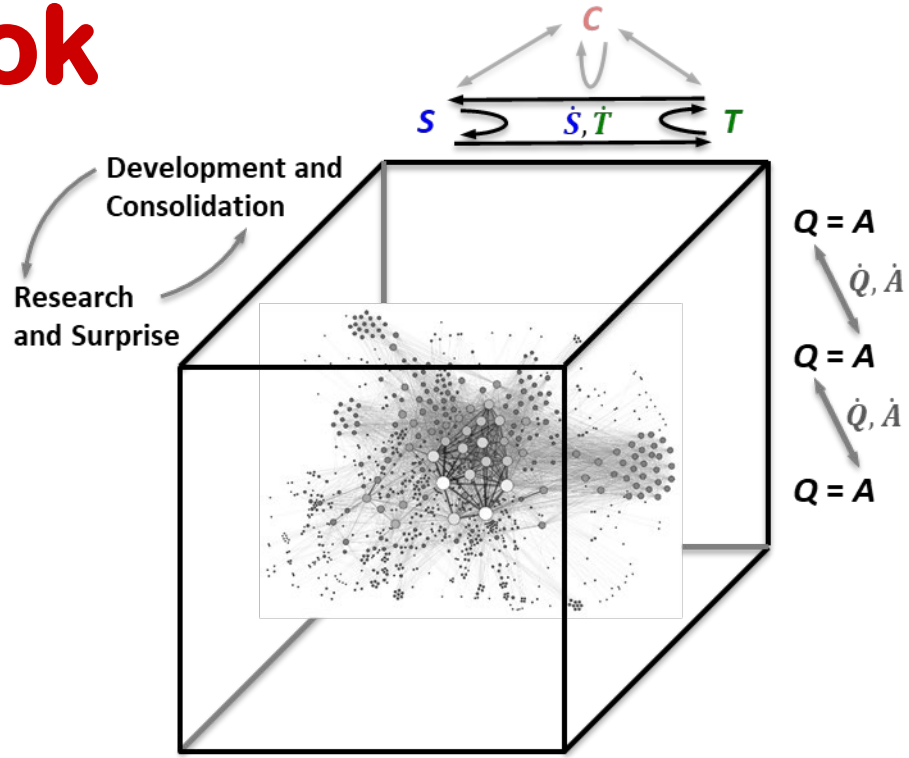
Mr. KHANNA (for himself, Mr. GALLAGHER, Ms. WILD, Mr. TURNER, Mr. BOWMAN, Mr. FITZPATRICK, and Ms. SHERRILL) introduced the following bill; which was referred to the Committee on Science, Space, and Technology, and in addition to the Committee on Energy and Commerce, for a period to be subsequently determined by the Speaker, in each case for consideration of such provisions as fall within the jurisdiction of the committee concerned

A BILL

To establish a new Directorate for Technology and Innovation in the National Science Foundation, to establish a regional technology hub program, to require a strategy and report on economic security, science, research, innovation, manufacturing, and job creation, to establish a critical supply chain resiliency program, and for other purposes.

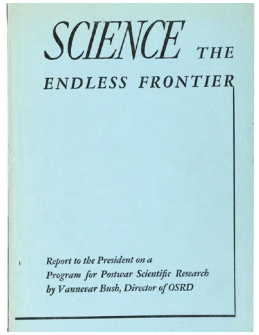
Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

Core Reflections of the Book



1. Beyond Bush:
   - $\dot{S}$ is not synonymous with Research
   - $\dot{T}$ is not synonymous with Development
2. Beyond Popper and Heilmeier:
   - Finding Questions is just as important as Finding Answers
   - Constructivism is just as important as Reductionism
   - Questions and Answers are Networked into a Seamless Web of Knowledge
3. Beyond Development and Gradualism:
   - Punctuated Equilibria require both Surprise and Consolidation
   - Exploring the frontier of knowledge means seeking Surprise, which cannot be scheduled or "projectized"
   - Consolidating the frontier of knowledge strengthens and extends what *was* Surprising
   - The Metagoal of Research, Surprise, is not the same as the Metagoal of Development
4. Beyond Bell Labs: Guiding Principles for Nurturing Research
   - Bell Labs 2.0: Building ecosystems that support research with intentionality
   - Bell Labs 3.0: Learning how to learn

1: The Relationship Between *S* and *T*



THE MISTAKEN "LINEAR" VIEW: SCIENCE IS THE PACEMAKER OF TECHNOLOGICAL PROGRESS

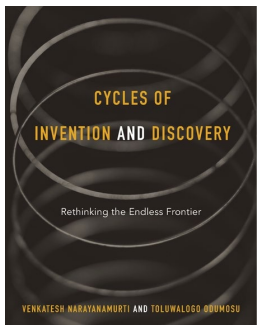
"Today, it is truer than ever that basic research is the pacemaker of technological progress."

Vannevar Bush, 1945

BUT TECHNOLOGY CAN ALSO BE THE PACEMAKER OF SCIENTIFIC PROGRESS

"The deepest flaw in the dynamic form of the postwar paradigm is the premise that such flows as there may be between science and technology are uniformly one way, from scientific discovery to technological innovation. . . . The annals of science suggest that this premise has always been false to the history of science and technology."

Donald Stokes, 1997

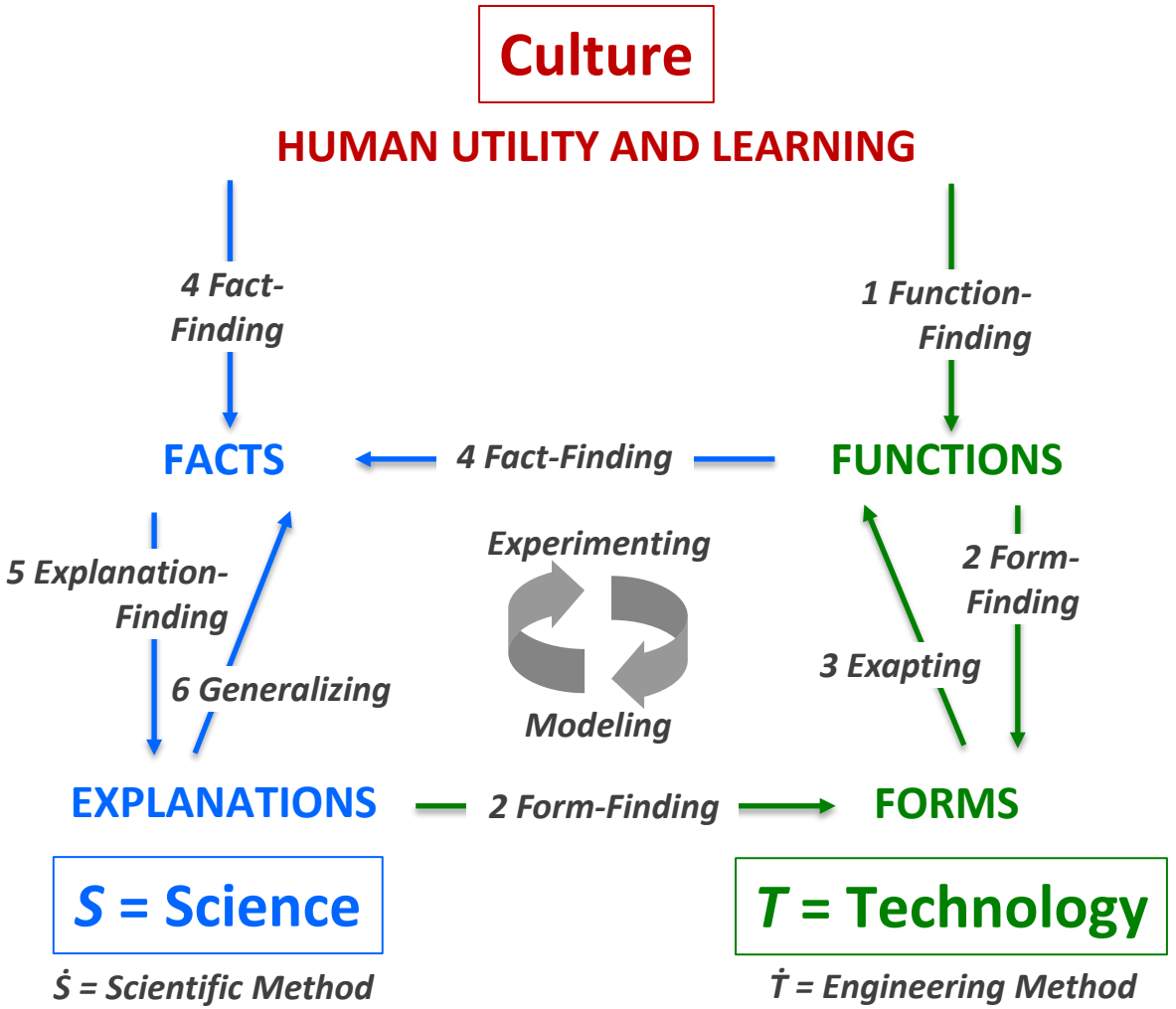


IN FACT, SCIENCE AND TECHNOLOGY PROGRESS IN CYCLES OF INVENTION AND DISCOVERY

"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."

Narayanamurti & Odumosu, 2016

The Technoscientific Method



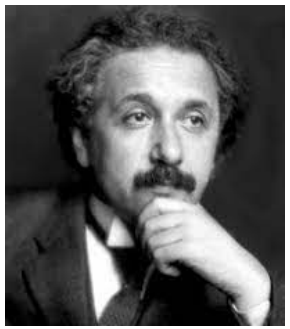
- The nouns: Science *(S)* and Technology *(T)* as symmetric repositories of knowledge
- The verbs: Scientific *(Ṡ)* and Engineering *(Ṫ)* methods as symmetric processes by which *S* and *T* dynamically *evolve*
- Most important: $\dot{S}$ and $\dot{T}$, and *S* and *T*, are deeply interactive, feeding on each other in cycles of *invention* and *discovery*

2: The Intricate Dance of Question-and-Answer Finding

FINDING ANSWERS TO KNOWN QUESTIONS IS IMPORTANT

"What are you trying to do? Articulate your objectives using absolutely no jargon. How is it done today, and what are the limits of current practice? What is new in your approach and why do you think it will succeed? Who cares? If you are successful, what difference will it make? What are the risks and the payoffs? How much will it cost? How long will it take? What are the mid-term and final "exams" to check the success?"

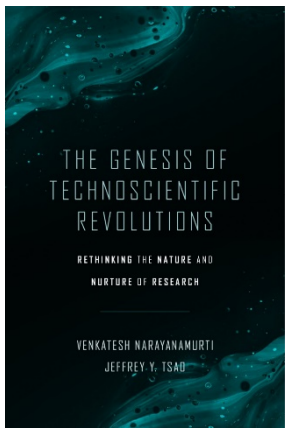
George Heilmeier, Director of DARPA, 1975-1977



BUT FINDING NEW QUESTIONS IS *ALSO* IMPORTANT

"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."

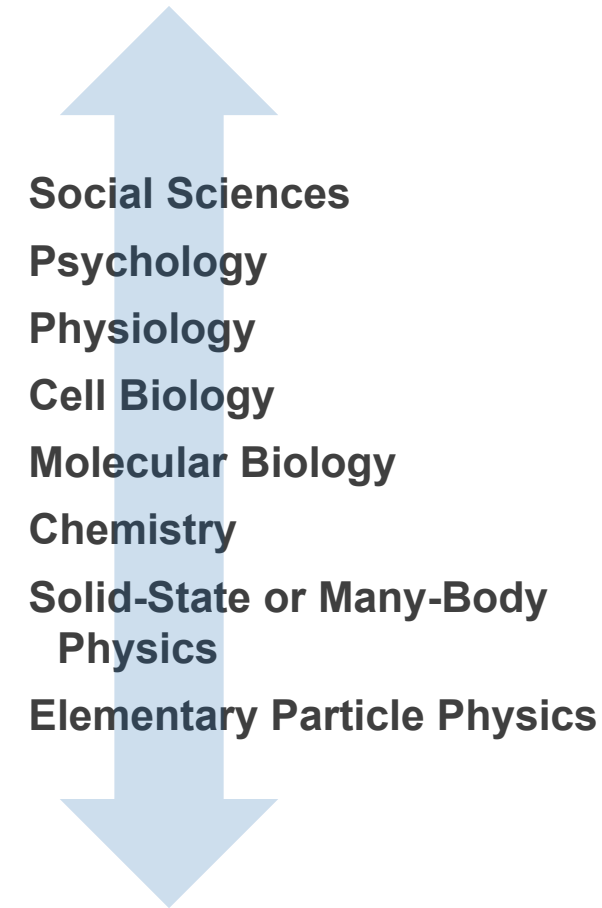
Albert Einstein



IN FACT, TECHNOSCIENCE ADVANCES IN AN INTRICATE DANCE OF QUESTION-*AND*-ANSWER FINDING

"Just as science and technology are tightly linked, question-finding and answer-finding are tightly linked. When seeking an answer to one question, an answer to another question often emerges: Louis Pasteur studied fermentation, hoping to answer the question of how to better produce wine, but he found that fermentation is a powerful tool for studying chemical transformations more broadly. Or, when trying to fit an answer to its question, a different answer to that question often emerges: John Bardeen, Walter Brattain, and William Shockley believed that a majority-carrier field-effect device would answer the question of how to create a semiconductor amplifier only to find that a minority-carrier injection device answered it instead."

The More-is-Different Nested Structure of Q's & A's



QUESTIONS & ANSWERS ARE DEEPLY NESTED AND EQUALLY PROFOUND THROUGHOUT THE NESTING: *MORE IS DIFFERENT*

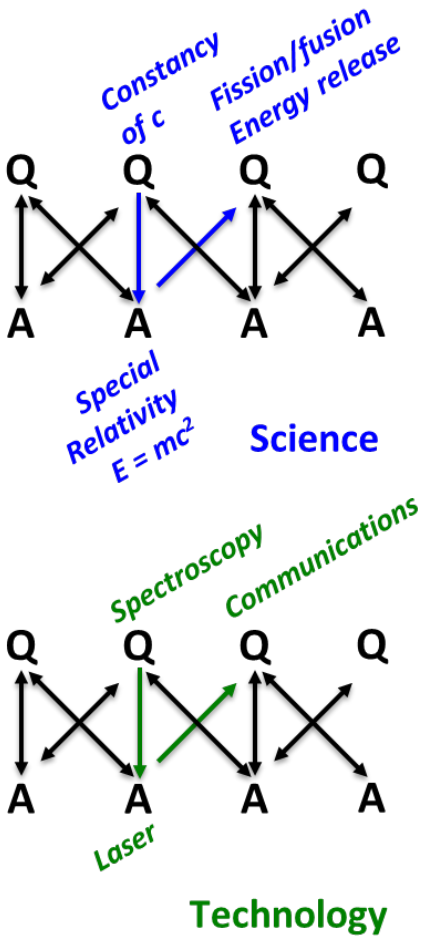
"The main fallacy in the extreme reductionist point of view is that the reductionist hypothesis does not by any means imply a 'constructionist' one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. …

At each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

But this hierarchy does not imply that science X is "just applied Y." At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry."

Phil Anderson, 1972

The Networked Structure of Questions and Answers



QUESTIONS BEGET ANSWERS (EXPLANATION- AND FORM-FINDING), WHICH BEGET NEW QUESTIONS (GENERALIZING AND EXAPTING)

In science, the constancy of c was an outstanding question; its answer was Einstein's theory of special relativity, and this answer then unexpectedly generalized to the question of energy release on nuclear fission and fusion events.

In technology, improved tools for spectroscopy was an outstanding question; one answer was the laser, whose narrow linewidths enabled unprecedented accuracy in the determination of energy levels in atoms and molecules, and this answer then was unexpectedly exapted to the question of how to achieve longer-distance communication beyond what was possible with electricity.

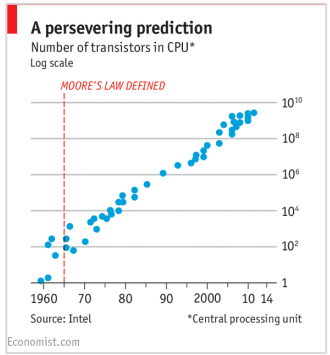
Genesis of Technoscientific Revolutions, 2021

AND THUS GET WOVEN INTO AN INTER-DEPENDENT, SEAMLESS WEB OF KNOWLEDGE

"The logical structure of modern scientific knowledge is not an evolutionary tree or a pyramid but a multiply connected web. . . . The failure to recognize this interconnectedness becomes obvious when we are presented with 'classical Newtonian mechanics, quantum mechanics, quantum field theory, quantum electrodynamics, Maxwell's electromagnetic theory' and, in a separate place, 'fluid dynamics,' as logically independent and separate rather than as, what they are, different aspects of the same physical theory, the deep interconnections among them long since solidly cemented."

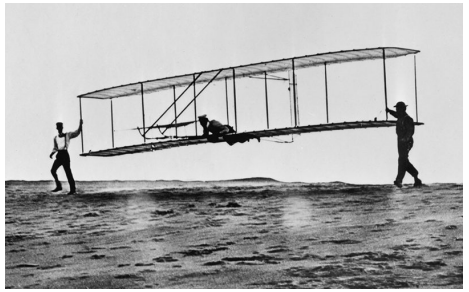
Phil Anderson, 2001

3: The Punctuated Equilibria of Surprise and Consolidation



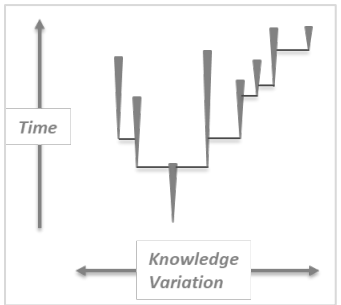
CONSOLIDATING AND EXTENDING CONVENTIONAL WISDOM ARE IMPORTANT

The advances in the mid-2010s in deep learning were largely not algorithmic in nature; they were due to the cumulative advances in computation power and data availability associated with underlying technologies.



BUT SURPRISE AND OVERTURNING CONVENTIONAL WISDOM ARE ALSO IMPORTANT

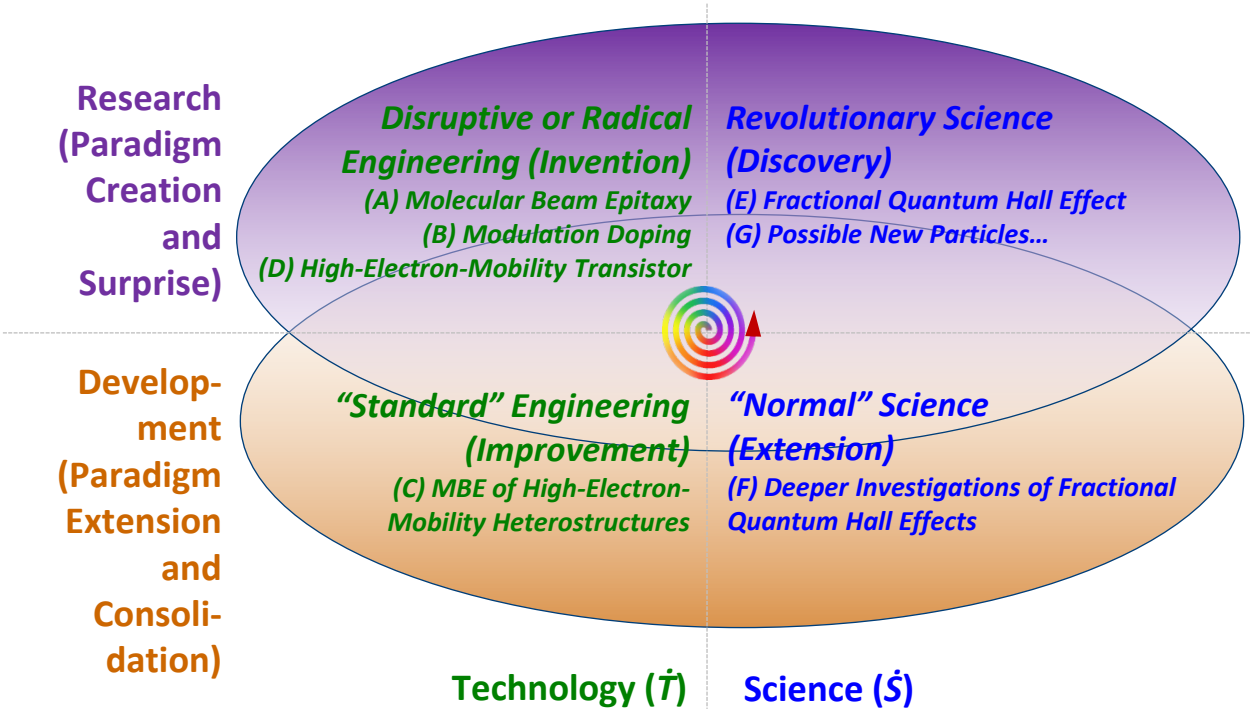
Flying machines heavier than air, evolution by natural selection, quantum mechanical action at a distance, wave-particle duality, the theory of continental drift, efficient blue LEDs fabricated from highly defective semiconductors—all these ideas were initially disbelieved but later proved correct and useful and hence changed the way we think and do.



IN FACT, TECHNOSCIENCE ADVANCES IN CYCLES OF SURPRISE AND CONSOLIDATION

Surprise and consolidation are … part of the natural rhythm of punctuated equilibria (borrowing Gould's phrase from evolutionary biology) in knowledge evolution. They are part of a natural and holistic feedback cycle in which each spawns the other.

Both Research and Development Encompass Both $\dot{S}$ and $\dot{T}$



On the one hand, research is not simply new science: it cuts across science and technology. For example, the technological inventions of molecular beam epitaxy (MBE) and modulation doping were just as much "research" as was the scientific discovery of the fractional quantum Hall effect.

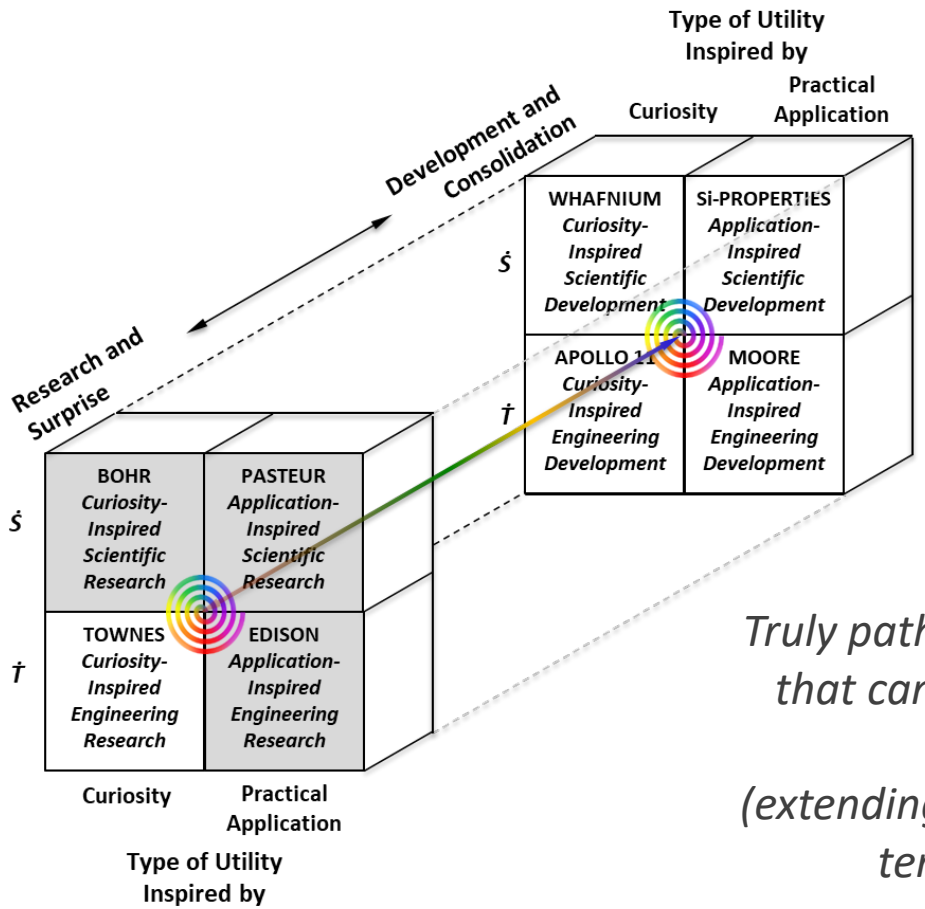
On the other hand, development is not simply new technology: it also cuts across science and technology. The subsequent deeper scientific investigations of the fractional quantum Hall effects were just as much "development" as was the ongoing technological improvement of MBE. The observation of the not-yet-observed Higgs boson, because it was widely expected to exist, can also be considered "development." Only had it had not been observed would it have overturned expectation and been a paradigm-creating scientific outcome.

Research and Development as the Unschedulable and Schedulable

Research, we understand as an *unscheduled* quest for surprise and the unexpected, whose outcome cannot be predicted in advance, and which both Science AND Engineering are essential ingredients

Development, we understand as a *scheduled* activity which consolidates and extends existing knowledge, with a well-defined outcome in a specified time frame

Research & Development are Both Vital, but Research is More Fragile



RESEARCH IS NO LESS VITAL THAN DEVELOPMENT

By focusing on research, we by no means intend to trivialize development. Development is vital and necessary for the full power of existing paradigms and conventional wisdom to be realized. But research is also vital.

BUT RESEARCH IS DIFFICULT TO SUPPORT, BECAUSE ITS BENEFIT IS LONG-TERM AND PUBLIC

Truly path-breaking research 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. Thus, 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).

4: Research Must be Nurtured, Not Managed

NURTURE PEOPLE WITH CARE AND ACCOUNTABILITY

"[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."

Narayanamurti & Odumosu, 2016, Paraphrasing Ralph Bown, 1953

EMBRACE A CULTURE OF HOLISTIC TECHNOSCIENTIFIC EXPLORATION

We are humans first, intellects second. Because we are humans first, we respond first and foremost to social cues, to local culture, to peer pressure, and to our organization's values and reward system. Only after we have adapted socially and culturally to our organization do we engage our intellects.

Genesis of Technoscientific Revolutions, 2021

ALIGN ORGANIZATION, FUNDING AND GOVERNANCE FOR RESEARCH

People don't just start innovating. People require an atmosphere where creativity can flourish, where ideas flow, and where personal development is encouraged…. I like to say that no one works for me, I work for my people. This is not meant to be just a cute line but is meant as a personal reminder that, even in a changing climate, today's managers must nurture—not manage—innovation.

Venky Narayanamurti, Sandia Lab News (April, 1987)

Align Organization, Funding & Governance for Research

FUND RESEARCH TO ACHIEVE METAGOALS, NOT GOALS

The ultimate impact of research cannot be predicted in advance, so research organizations should invest in research only if their purpose can accommodate benefit that is long-term and public.

INSULATE, BUT DON'T ISOLATE, RESEARCH FROM DEVELOPMENT

The deep difference in mindset— between research, which seeks to surprise and overturn conventional wisdom, and development, which seeks to consolidate and strengthen conventional wisdom—necessitates that research be culturally insulated, though not intellectually isolated, from development.

BLOCK FUND PEOPLE, NOT PROJECTS

To deal with the unanticipated, researchers and research leadership must be able to respond flexibly and opportunistically, and this requires block allocation of resources, both to research leadership at the organizational level and to researchers at the bench level.

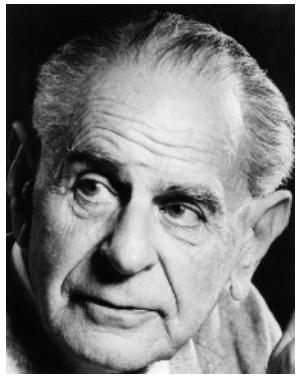
LEADERSHIP

Research is not simply a matter of assembling researchers and giving them free reign—it is a matter of nurturing and orchestrating a delicate balance between organizational focus, personal development, and individual freedom.

Embrace a Culture of Holistic Technoscientific Exploration

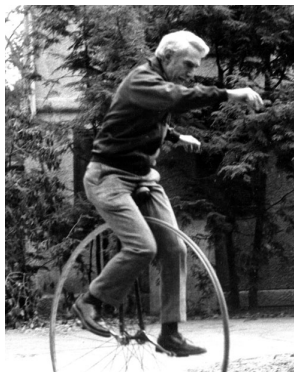
Ṫ LEADS AS MUCH AS FOLLOWS *Ṡ*: BEYOND BUSH

We reject the conflation of Ṡ with research and Ṫ with development. Instead, both Ṡ and Ṫ encompass both research and development. Ṡ and Ṫ of a development character abounds and these we might call "normal science" and "standard engineering." Ṡ and Ṫ can also both have a research character and these we might call "revolutionary science" and "disruptive or radical engineering."



THE SCIENTIFIC METHOD IS MORE THAN HYPOTHESIS-TESTING: BEYOND POPPER

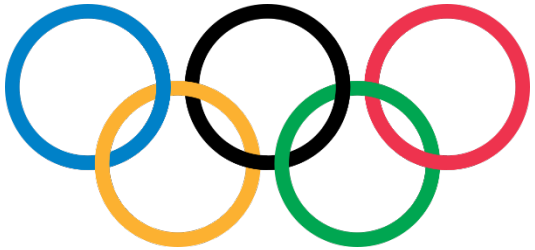
"[An] emphasis upon verification rather than discovery seems to me a distortion of the actual emphases in the practice of science. … Much more often, scientists are faced with a set of phenomena and no theory that explains them.... In this more typical situation, the … task is not to verify or falsify theories,…but to discover candidate theories that might help explain the facts." **Herb Simon, 1977**



EMBRACE INFORMED CONTRARINESS: BEYOND PEER REVIEW

Research organizations must encourage new ideas even if these ideas are contrary to the organization's own beliefs, and it must protect the quirky and eccentric researchers from whom such ideas often emerge.

Nurture People with Care and Accountability



RECRUITING, HIRING, AND MENTORING

The commitment to recruit, hire, and mentor a researcher—to give a researcher long-term support and freedom—is a major one.

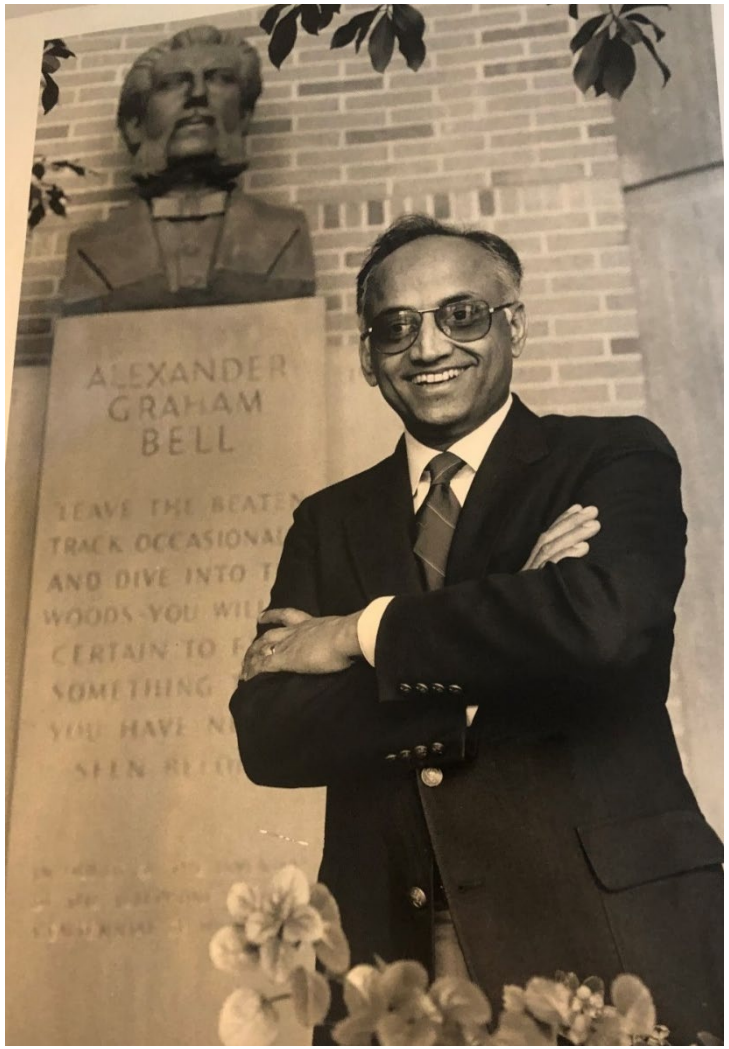
HOLD RESEARCH ACCOUNTABLE

It is a common misperception that research is a playground, a place for play, not work, a place for fun and games without judgment. A more complete analogy is of research as a competitive sport, characterized by the desire to perform at the highest levels and to be inspired by others' high performance.

PERFORMANCE REVIEW

Performance review based on meritocratic competition is critical and must be based on actual performance in research or research leadership. Elite research is no different from elite performance in any walk of life—it does not come easy or for free.

5: Back to the Future, with New Insight



LAB NEWS
VOL. 39, NO. 8 SANDIA NATIONAL LABORATORIES APRIL 24, 1987

OUTGOING AND INCOMING Vice-Presidents of Research check the agenda for a recent Research Advisory Committee meeting. Bill Brinkman (left) became Executive Director, Research Physics Division, Bell Labs on April 1. Venky Narayanamurti will take over his new post on May 1. Both share their views of heading a research group in this issue of LAB NEWS.

New VP Shares Views

On Nurturing the Novel Neocortex

*by Venky Narayanamurti**

We at Bell Labs have continued to come up with extraordinary innovations in the last five years — not just the last 10. The Karmarkar algorithm, new approaches to molecular beam epitaxy and devices, ultrashort light pulses, a megabit RAM, new single-frequency lasers, and high-capacity lightwave transmission systems are just a few examples which immediately come to my mind. Some of these achievements have already had an impact in enhancing AT&T's competitive position in the high technology arena. If history is any guide, more are likely to follow. In the ensuing, I give a personal viewpoint on nurturing innovation.

Innovation feeds on itself, and we are sure to see a continual stream of exciting new science and new technology. That's because our strength is in our *people*, in our explorers. They are the people Alexander Graham Bell would have enjoyed most. In fact, I often bring visitors, especially graduate students and postdoctorals, to Murray Hill to see Bell's statue where it says, "Leave the beaten track occasionally and dive into the woods — you will certainly find something you have never seen before."

But people don't just start innovating. People require an atmosphere where creativity can flourish, where ideas flow, and where personal development is encouraged. We at Bell Labs are fortunate that we are part of many decades of tradition in this area. I like to say that no one works for me, I work for my people. This is not meant to be just a cute line but is meant as a personal reminder that, even in a changing climate, today's managers must *nurture* — not manage — innovation.

It's tricky to create and maintain an atmosphere where ideas keep bubbling up. Such an environment is delicate, fragile and easily damaged. Kumar Patel [Executive Director of Research Physics and Academic Affairs Division at Bell Labs] has often highlighted the three F's — Freedom, Focus, and Funding — as the basic ingredients which have led to a very favorable climate for research at Bell Labs. Using that as a springboard, I would like to talk about some underlying people-related issues — communications, freedom, and focus — which are crucial to the maintenance of a special environment.

First, communications. Managers and the scientists associated with them must feel free to talk to one another, or they're not going to get very far. Unless we can talk in a very open way, there can be no exchange of ideas. I certainly can't support, endorse, or evaluate what I don't know. And you can't know which direction to go if I don't give you feedback. When people know what is going on, they function much better. I find the best way of "reaching" people is through spontaneous interactions — in a scientist's "home" (his or her laboratory), informal lunch-time seminars, the physics tea-room, and corridor encounters.

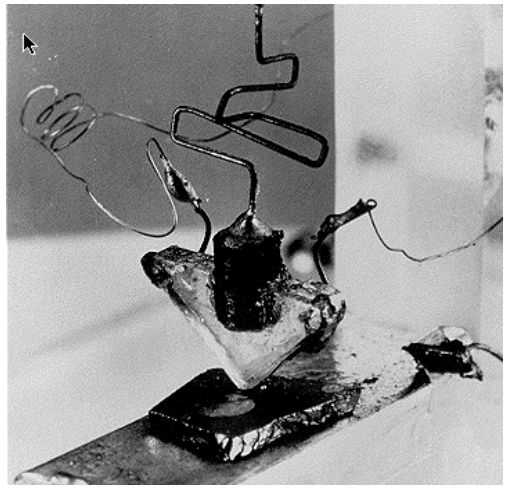
Next comes freedom, especially the freedom to fail. If one is to be successful, one cannot be afraid to fail. Sometimes it is necessary to take several wrong steps before the right route is charted, but the learning that takes place in the process can be invaluable. Of course, there are obvious exceptions to this — astronauts and physicians, for example, have a very limited margin for error — but for the most part, intelligent people learn from mistakes. And each time you learn you grow. It will be the people who feel free to explore the uncharted regions of science and technology who will be successful.

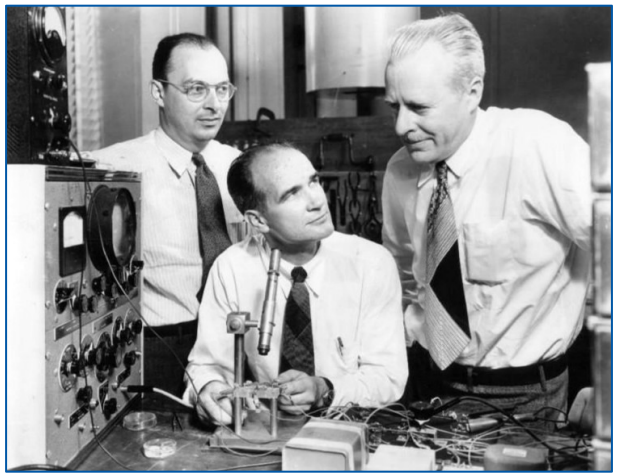
Finally, the focus, which is seemingly in tension with freedom. In research the emphasis is on freedom, but there should, depending on circumstances, be an awareness of focus, of providing knowledge in broad areas of interest to AT&T. The feedback is often of great importance to further progress in research. The transistor is a famous example of focused research, and our current work in the lightwave area is another more recent example. The focus, of course, becomes much sharper as we go to development; perhaps the toughest phase of a successful innovation is taking it from research and development on into implementation. Our culture strongly encourages the free, competitive spirit. In the early stages of research, open, friendly competition is good. In the implementation of the invention, however, one needs to channel that spirit for the corporate good. Managing this process is going to continue to make life at AT&T exciting for the next few years.

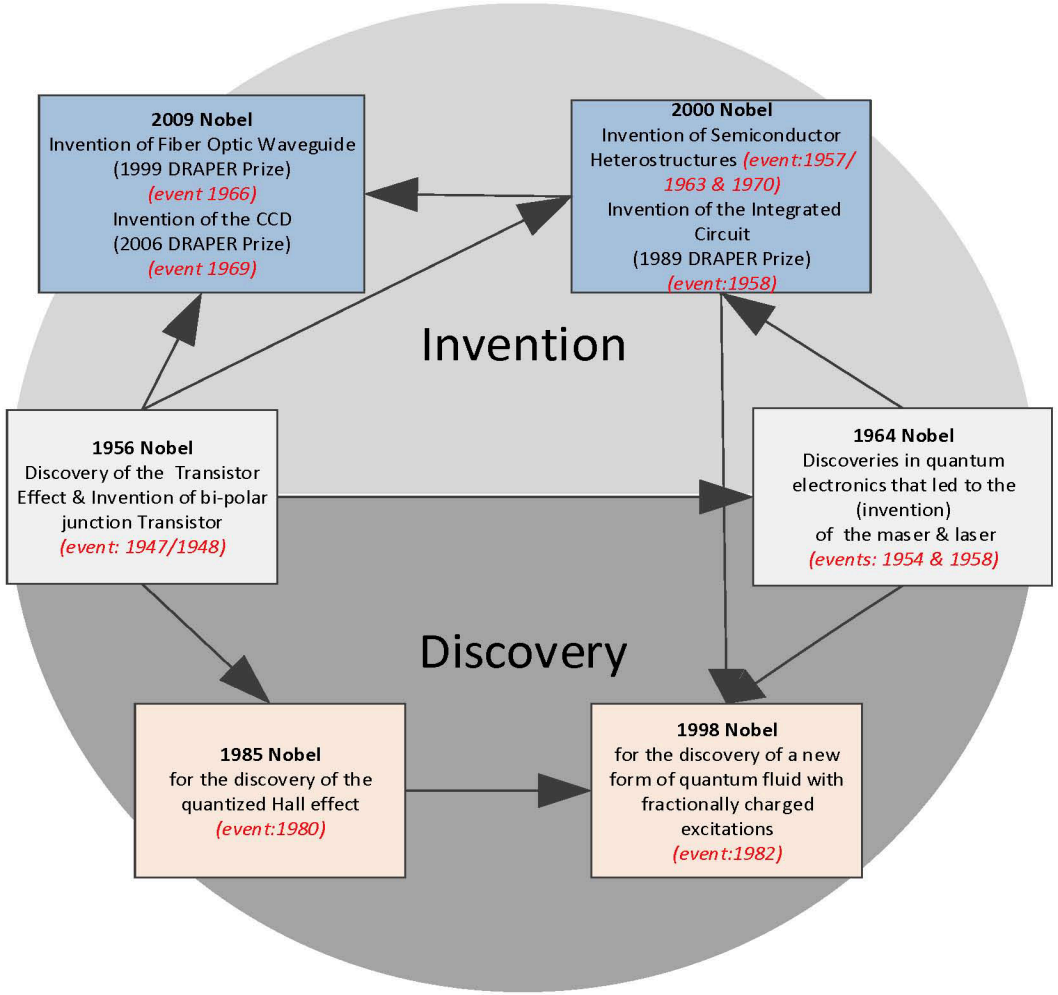
In summary, it is possible to maximize innovation by careful nurturing, but it can also be stifled by careless neglect. Our challenge for the future is to produce even more and better innovations than we have seen in the past through careful attention to the climate, to the people, and to the technology transfer. There are very few companies in the world that could experience the upheaval this company has endured and come away with their spirits intact. But we have done that, and Bell Labs has been a part of it. We should be proud of that.

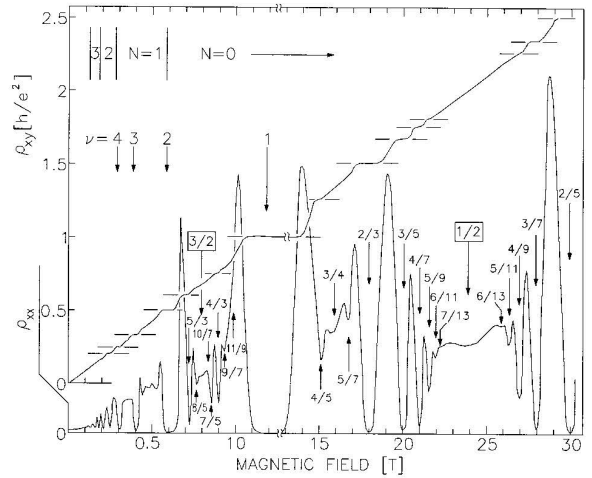
**Venkatesh Narayanamurti, director of Bell Labs' Solid State Electronics Research Laboratory at Murray Hill, wrote this article for* Bell Labs News *early this month. He's leaving Bell Labs, where he's spent more than 19 years, to become Vice-President of Research 1000 at Sandia on May 1. The article is reprinted with the permission of* Bell Labs News.

Bell Labs 1.0 circa 1920's – 1990's



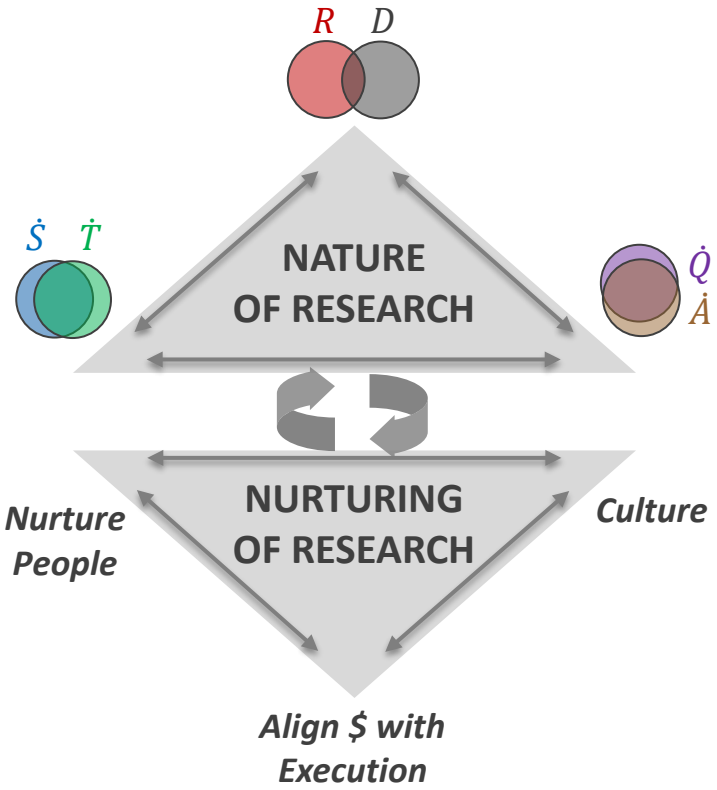


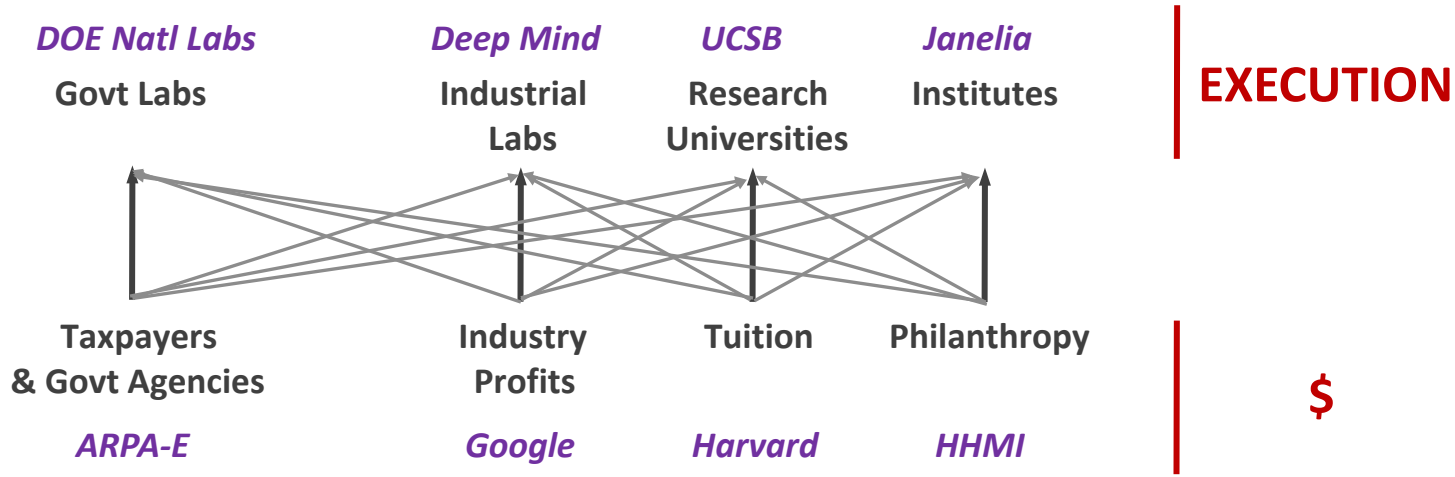




Bell Labs 2.0's circa 1990s - 2020s:

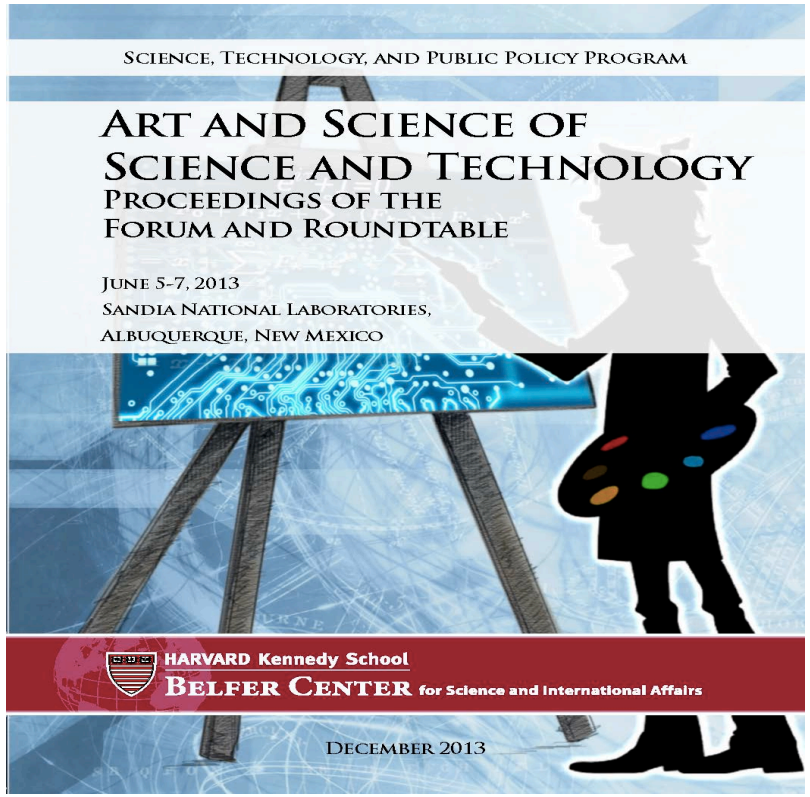
Broader ecosystems beyond the physical sciences and engineering, with multiple institutional forms and funding

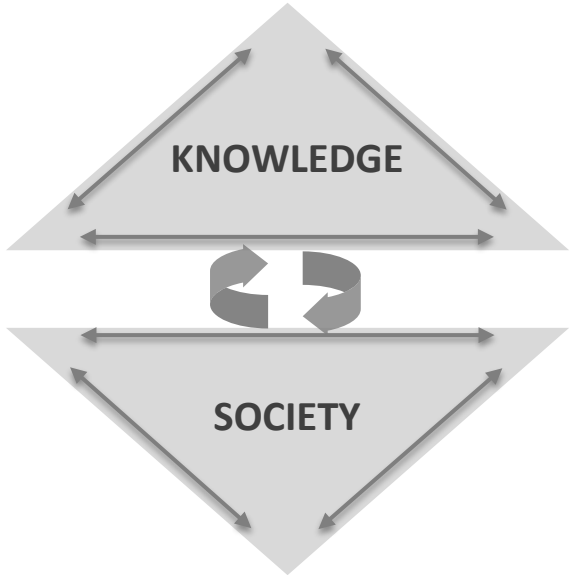




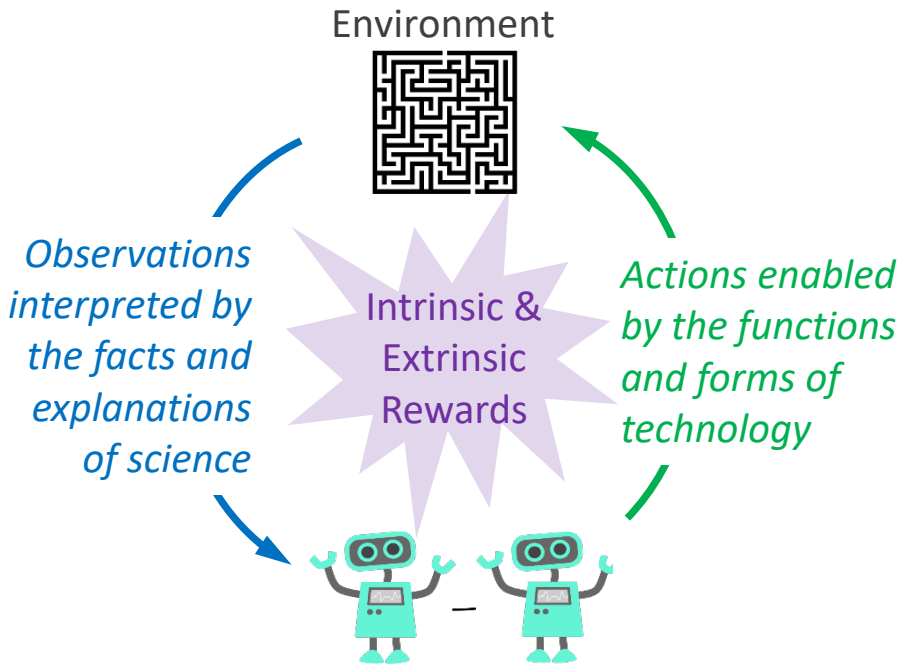
Bell Labs 3.0's circa 2020s and Beyond: Learning How to Learn

Social Science





Artificial Intelligence



Diverse Interacting Agents forming a Culture of Values & Norms

6: Selected Readings

1. Popper, K. (1935). The logic of scientific discovery: Springer (re-published by Routledge in 2005).
2. Bush, V. (1945). Science: The Endless Frontier. A Report to the President by Vannevar Bush, Director of the Office of Scientific Research and Development, July 1945.
3. Bown, R. (1953). Vitality of a research institution and how to maintain it. Paper presented at the 1952 Conference on Administration of Research. Georgia Institute of Technology.
4. Kuhn, T. S. (1962). The Structure of Scientific Revolutions, Fourth edition (4th ed.): University of Chicago Press (4th edition published in 2012).
5. Simon, H. A. (1962). The architecture of complexity. Proceedings of the American philosophical society, 106(6), 467-482.
6. Anderson, P. W. (1972). More is different. Science, 177(4047), 393-396.
7. Gould, S. J., & Vrba, E. S. (1982). Exaptation—a missing term in the science of form. Paleobiology, 8(01), 4-15.
8. Gould, S. J., & Eldredge, N. (1993). Punctuated equilibrium comes of age. Nature, 366(6452), 223-227.
9. Kauffman, S. A. (1996). At home in the universe: The search for the laws of self-organization and complexity: Oxford University Press.
10. Stokes, D. E. (1997). Pasteur's quadrant: Basic science and technological innovation: Brookings Institution Press (2011 Edition).
11. Anderson, P. W. (2001). Science: A 'dappled world' or a 'seamless web'? Stud. Hist. Phil. Mod. Phys., 32(3), 487-494.
12. Arthur, W. B. (2009). The nature of technology: What it is and how it evolves: Simon and Schuster.
13. American Academy of Arts & Sciences. (2013). ARISE II: Advancing Research in Science and Engineering: Unleashing America's Research and Innovation Enterprise.
14. Narayanamurti, V., & Odumosu, T. (2016). Cycles of Invention and Discovery: Harvard University Press.
15. Tsao, J. Y., Ting, C. L., & Johnson, C. M. (2019). Creative Outcome as Implausible Utility. Review of General Psychology, 23, 279.
16. American Academy of Arts & Sciences. (2020). The Perils of Complacency.