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The New Big Science

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For several decades the character and culture of large-scale research at major facilities has been changing. Big Science isn't what it used to be.

A dignitary visiting Brookhaven National Laboratory (BNL) on 2 June 2006 left with an unusual parting gift: nanoparticles, sealed inside a glass vase.

For decades eminent visitors to the lab had received a different kind of gift. Almost always, it was sculpted pieces of accelerator magnets—a sign of the lab's most prominent facility, the Relativistic Heavy Ion Collider, and its precursors. The new gift (see figure 1), whose recipient was US Department of Energy secretary Samuel Bodman, indicated an awareness among BNL's administrators that the lab's focus was changing from high-energy and nuclear physics to basic energy sciences, defined by DOE as "fundamental research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels in order to provide the foundations for new energy technologies and to support DOE missions in energy, environment, and national security." The shift in emphasis was due in part to BNL's then-impending, now-commissioned \$1 billion construction project, the National Synchrotron Light Source II (NSLS-II).

Less obviously, the gift also marked a phase transition in the kind of large-scale science that was being carried out not only at Brookhaven but also elsewhere throughout the US national laboratory system. Large-scale materials-science accelerators, not high-energy-physics accelerators, have become marquee projects at most major basic research laboratories in the post-Cold War era. At the same time, the character and culture of

the research ecosystem at those laboratories has changed in important ways. We refer to the result of that phase transition, which has been gradual and building since the 1980s, as the New (or Ecologic) Big Science.

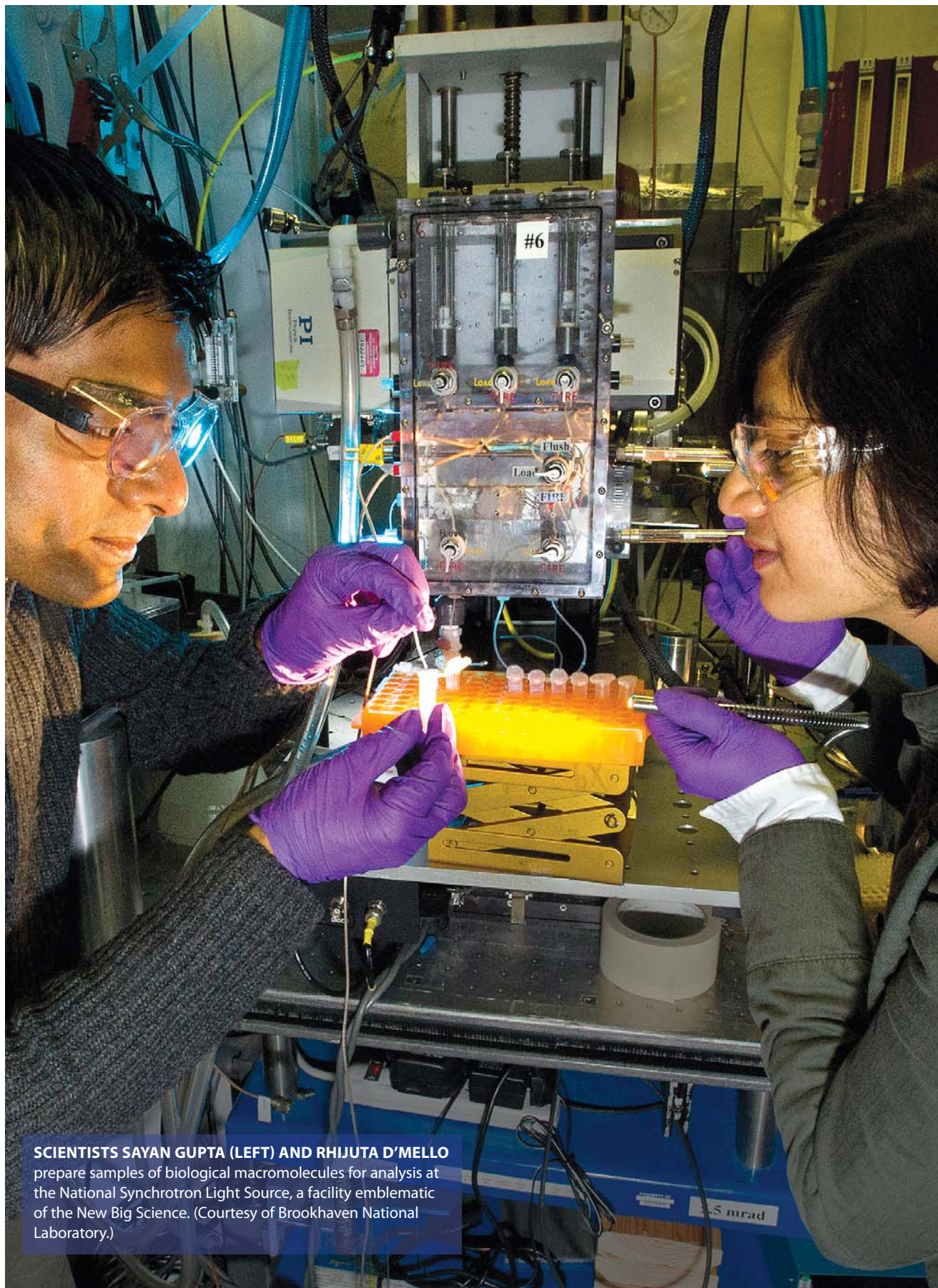
That Bodman's gift involved nanoparticles is noteworthy, for nanotechnology research is emblematic of the New Big Science. As W. Patrick Mc-

Cray noted in a 2005 *History and Technology* article, the story of nanotechnology is no linear tale of scientific breakthroughs followed by practical applications. Far from it: Utopian visions, industrial benefits, interdisciplinary collaborations, and national goals were involved in nanotechnology research and its promotion from the beginning.

In describing the New Big Science in this article, we will often refer specifically to the research ecology at the NSLS-II's precursor. The original NSLS—the first facility designed from the outset to be a synchrotron source—serves as our analogue to the ecologist's quadrat; it isolates a representative region in which to analyze an ecosystem (see figure 2). We situate the New Big Science in time and consider its features, funding, and challenges. We also discuss the importance of recognizing and investigating the particular research ecology of the New Big Science, an undertaking that will require crafting new historical tools and methods.

Old and New Big Science

We use the term New Big Science to describe the current era in large-scale research at laboratories dominated by materials science; in particular, it is not meant to apply to astronomical research. The New Big Science era is characterized by much



SCIENTISTS SAYAN GUPTA (LEFT) AND RHIJUTA D'MELLO prepare samples of biological macromolecules for analysis at the National Synchrotron Light Source, a facility emblematic of the New Big Science. (Courtesy of Brookhaven National Laboratory.)

greater accountability to sponsoring agencies, a condition that favors practicality and thus industrial participation. Those traits in turn lead to a highly diverse and sizable user community, which is a plus when seeking funding; promote smaller facilities and experiments than in the Old Big Science era; and foster a greater propensity for international and multidisciplinary collaboration, especially in biomedical research.

The NSLS typifies the rise of the New Big Science because it began operation in 1982, just as materials-science facilities (synchrotron light sources and neutron-scattering facilities) began to replace high-energy accelerators as the premier projects at the largest US national laboratories. Unlike research at nuclear-physics or high-energy-physics accelerators, which explores nuclear and subnuclear length scales, research at materials-science facilities concerns phenomena at atomic, molecular, and larger scales. High-energy-physics research continues to be funded at the US national labs in the new era, albeit as an activity to be carried out mostly abroad. That research effort joins those at nuclear-physics accelerators, including some that justify the existence of medium-sized facilities. A close look at the NSLS and how it came to dominate laboratory culture at BNL shows why the unadorned term “Big Science” is not an apt description for the research that has unfolded in the new era.

The Old Big Science included BNL and other laboratories whose existence was justified by their construction and management of instruments—principally reactors and accelerators—too big for any single university to handle. By the 1960s the largest laboratories hosted high-energy-physics accelerators conceived as user facilities for the benefit of a broad spectrum of the basic research community. The Old Big Science featured a mix of facilities built for various purposes (as does the New Big Science). Thus BNL and other laboratories had a range of projects that included nuclear-physics investigations and the

building of materials-science instruments. Such smaller, lower-profile efforts enhanced a laboratory’s research reputation but were not sufficient to secure its continued existence. Industrial users and practical applications, if accommodated at all, were considered parasitic on the main basic research function.

The primary dynamic of the Old Big Science was a progressive increase in the scale of the premier high-energy-physics projects—the size of the instruments and collaborations and the duration of the experiments. As is typical for the dominant materials-science projects in the era of the New Big Science, instruments and collaborations at the NSLS did not get bigger and bigger. Instead, the research ecosystem grew more complicated; it involved more and more fields (especially biomedical fields), a wider variety of instruments, more connections between seemingly disparate research programs, and a faster turnover of research groups.

A more detailed look

It is important to examine the character of the new research ecology to understand its habits and looming problems, so that challenges can be met in a systematic and careful way. To that end we offer several features of research at the NSLS to illustrate how New Big Science materials-science projects differ from the high-energy-physics projects emblematic of the Old Big Science.

The first distinguishing feature is the integration of an industrial presence from the beginning in many of the NSLS research projects. One purpose of the facility was to provide opportunities for a spectrum of industrial users and others interested in applications; no longer would such users be seen as parasites. The scanning IR microscope that operated at the U2B beamline for a few months in 1994 provides an example. Built by the engineering company Spectra Tech, the instrument was installed in collaboration with Northrop Grumman and the Geophysical Laboratory of the Carnegie Institution of Washington. Spectra Tech collaborated with Polaroid to study chemical profiles of polymer-coated film. Northrop Grumman used the instrument to examine defects in superconductors intended for several industrial devices. The Geophysical Laboratory used the microscope to study chemical compositions of geological specimens. The Federal Bureau of Investigation used it to look for traces of explosives in various materials and for drug residue in human samples. University of California scientists used it in collaboration with researchers from the analytical testing firm MVS to study interplanetary dust particles.

Contrast that temporarily positioned IR microscope with the instruments of Old Big Science facilities, which generally remain *in situ*. When Old Big Science instruments are moved—as, for example, when the $g-2$ ring for the muon anomalous magnetic dipole moment experiment was transported from BNL to Fermilab in 2013—it’s an unusual event that’s big news.

A second difference between the old and new eras involves the scope and complexity of the interdisciplinary networks. An example is the Near-Infrared Scalable Undulator System (NISUS) at the NSLS Source Development Laboratory. Developing NISUS involved four other DOE labs: the Thomas Jefferson National Accelerator Facility, Lawrence Berkeley National Laboratory (LBL), Los Alamos National Laboratory, and SLAC. Its three industrial partners were Boeing, Northrop Grumman, and STI Optronics, and its three university partners were Duke,



FIGURE 1. AN UNUSUAL GIFT. Officials at Brookhaven National Laboratory presented this glass *objet d'art* to Department of Energy secretary Samuel Bodman during a 2006 visit. Instead of traditional replicas of accelerator magnets, this gift is a vase containing nanoparticles, which symbolized the lab’s shifting focus away from nuclear and high-energy physics to materials-based inquiries. (Courtesy of Brookhaven National Laboratory.)

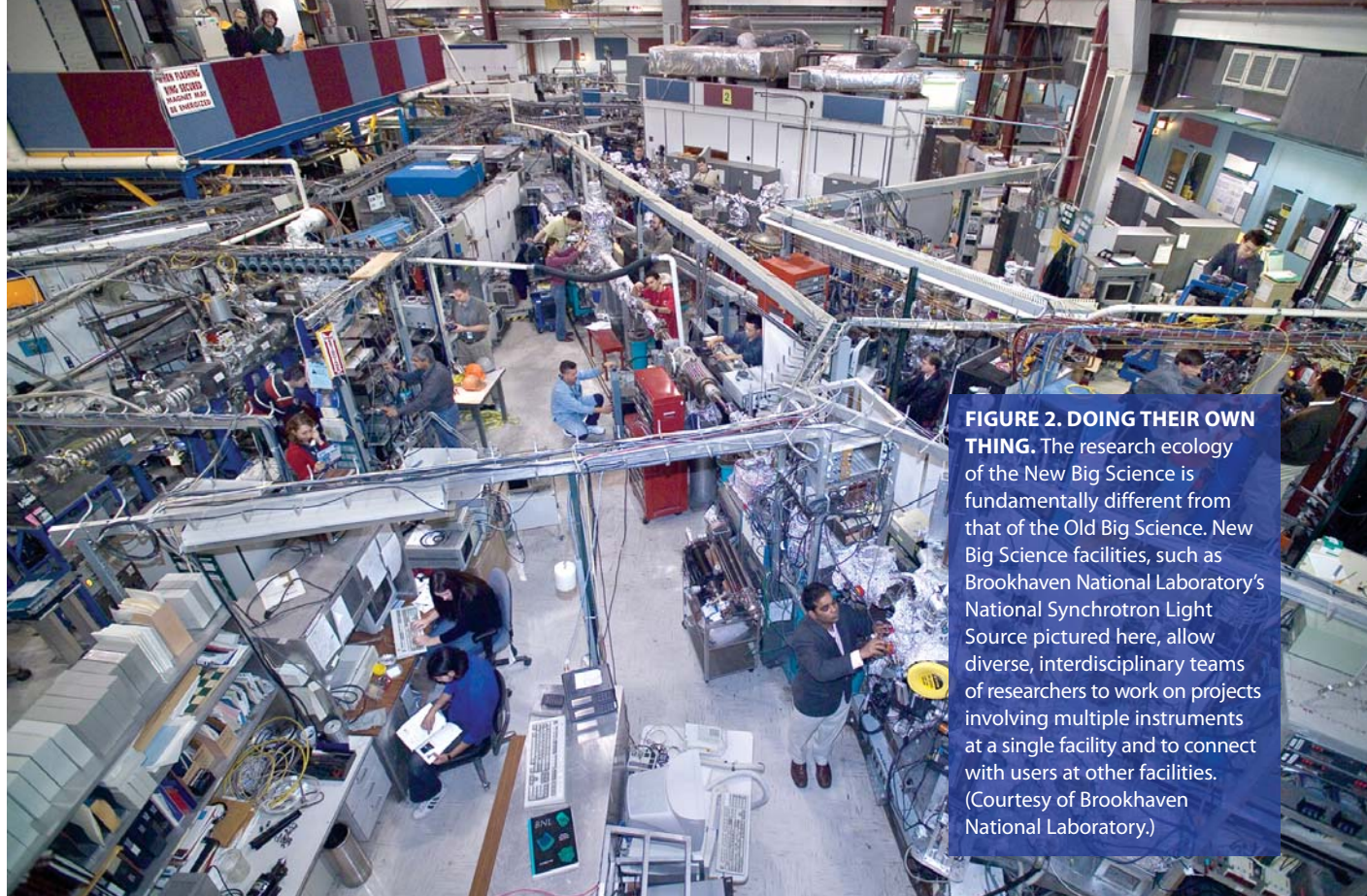


FIGURE 2. DOING THEIR OWN THING. The research ecology of the New Big Science is fundamentally different from that of the Old Big Science. New Big Science facilities, such as Brookhaven National Laboratory's National Synchrotron Light Source pictured here, allow diverse, interdisciplinary teams of researchers to work on projects involving multiple instruments at a single facility and to connect with users at other facilities. (Courtesy of Brookhaven National Laboratory.)

UCLA, and the University of Michigan. NISUS supports a network of different experiments rather than serving as their hub, and its evolution is relational rather than simply expansive. Furthermore, the materials-science projects of the New Big Science often involve technologies planned and promoted for practical applications. As a result, the projects' interdisciplinary networks can include not just webs that connect scientists to each other but also connections that link webs of scientists to webs of people preparing technologies and ushering them into the marketplace.

A third difference is what we call the octopus-like character of research networks: A single field or even a single narrowly focused research project at the NSLS could extend research threads out to several instruments at several beamlines. At a 1992 workshop on Earth and soil science at the NSLS, researchers conducting experiments at six stations on five beamlines used six synchrotron radiation techniques: x-ray microprobe imaging, x-ray absorption spectroscopy, diamond anvil cell, large-volume press, powder diffraction, and microtomography. Research programs at the NSLS can also involve techniques and instruments elsewhere at BNL and even at other laboratories.

Fourth is what we call multistability of techniques, which refers to techniques that can be adapted to new and unforeseen purposes. An example with a long history is Mössbauer spectroscopy. Already in the 1960s, Mössbauer spectroscopy had developed into an analytic technique with numerous applications. By the 1990s those applications had been refined and extended to the realm of synchrotrons. Another example is tomography, or imaging by sections, which has numerous biomedical applications. In fact, tomography is not a single technique; it has morphed into several subtechniques.

A fifth difference is that facilities such as the NSLS tend to

generate subfacilities that themselves support networks with the just-described ecological properties of the New Big Science. An example is the Superconducting X-Ray Lithography Source storage ring. That initiative began in 1986 with the goal of developing a compact synchrotron as part of a Department of Defense effort to get the US up to speed with Japan and Germany in manufacturing high-resolution computer chips. It involved both technology transfer and a specific nationally targeted interest. An entire infrastructure was set up at the NSLS to create a compact synchrotron facility where US semiconductor manufacturers would apprentice and learn to make x-ray lithography sources themselves. Two such prototypes were developed, but the project was terminated in 1992.

Culture and politics

Some of the differences between the New and Old Big Science involve the research culture. One difference is the Krinsky effect, named after a remark by the late NSLS accelerator physicist Samuel Krinsky. At forefront high-energy-physics machines, experimenters have a certain amount of patience when the machine fails or is shut down for improvements. Why? One reason is that experimenters know that nobody will scoop them and thus render their research obsolete. Another is that they have no choice, because they are usually at the only machine able to produce relevant data for their research. Moreover, they can use shutdowns to upgrade their detectors.

At synchrotron radiation facilities, the culture is different. Researchers can be scooped if the machine breaks down. Detectors are rarely fully upgraded; generally they have to be replaced to be significantly improved. As the number of forefront accelerators in the US and the world dwindle, the number of synchrotron light sources is rising; it is now more than 60. Researchers know that dozens of other synchrotron light sources

with similar facilities are available. Those who are disgruntled can go elsewhere and even take their instrumentation with them. The research ecosystem is decentralized from within, which produces a demanding user atmosphere. NSLS experimenter John Galayda dubbed the less centralized, more demanding culture the Krinsky effect after Krinsky pointed out that x-ray users are more interested in keeping what they have than in envisioning and waiting patiently for new facilities, whereas the reverse is the case for high-energy physicists.

Another difference between the Old and the New Big Science concerns regulation. When research is highly centralized, regulations addressing, say, ethics and safety issues can be effective even if they are imposed on only the biggest institutions. However, when the research becomes more spread out in the kind of networks typical of the New Big Science, regulations become more difficult to impose and enforce; extreme decentralization threatens to undermine the entire enterprise of effective ethics and safety regulation.

The formation of knowledge is yet another difference. High-energy physicists invariably use accelerators to add pieces to a single, coherent puzzle. In contrast, materials scientists often use large machines in concert with smaller ones or even tabletop devices to piece together a mosaic of properties. Moreover, their agendas might change as properties of potentially useful materials emerge.

An ironic shift

The roots of the New Big Science go back to the 1960s and 1970s, when a growing interest in the science of materials led to a few large machines at US national labs. In the early 1960s, research reactors for neutron scattering were built at BNL and Oak Ridge National Laboratory, and by the end of the decade, the first light sources were commissioned, with most operating parasitically on machines primarily used for high-energy physics. At the same time, support for materials science at the national laboratories increased. By 1980 the DOE budget for basic energy sciences, which funded the construction and operation of materials-science research, had grown to almost \$200 million. Although that sum was less than the \$300 million allotted for high-energy physics, it was more than the \$100 million allotted for nuclear physics, which also used rather large machines.

Starting in the 1980s and culminating in the 1990s, the US science-policy environment shifted. In particular, the period saw a change in the rationale for funding large-scale projects and the national labs that hosted them. In the Old Big Science, justifications were grounded in a Cold War outlook that cast large projects as at least symbolically helpful to national defense. Basic research was viewed as an intrinsic worth, like art,

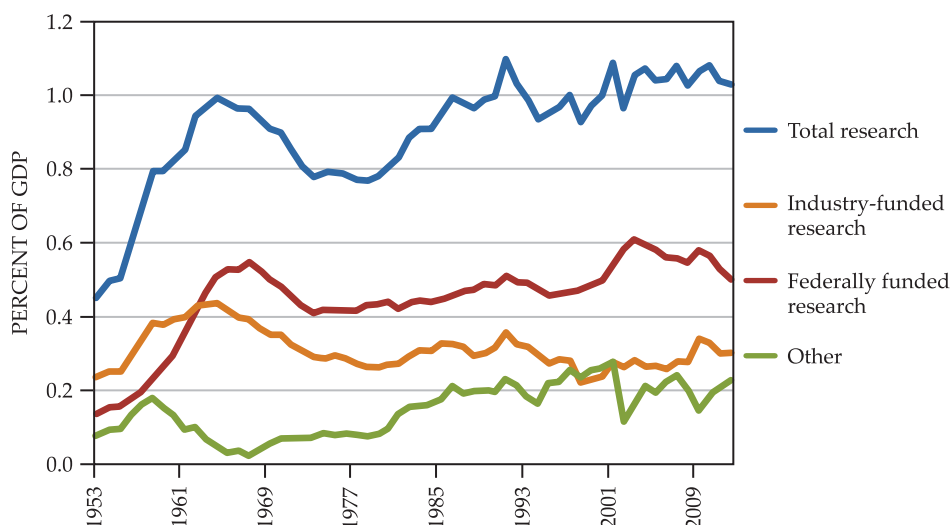


FIGURE 3. RESEARCH FUNDING AS A SHARE OF GDP. For more than a half century, the US federal government has outpaced industry and other sources as a research funder. (Adapted with permission from M. Hourihan, *Federal R&D Budget Trends: A Short Summary*, report prepared by the American Association for the Advancement of Science, 15 January 2015.)

that improves the well-being of the general public and is the kind of activity that a free and democratic society does. In the emerging era of the New Big Science, with its growing emphasis on accountability that comes with a mature funding bureaucracy, what counts is government–industry partnerships and practical applications. Such priorities fit the post-Cold War moral economy that values entrepreneurship and measurable utility.

Yet the path to the New Big Science was not forged in the midst of competition between old-order high-energy physics and materials-science upstarts. Ironically, the path to materials-science dominance was cleared through frantic efforts to continue the tradition of the Old Big Science into the 21st century with the construction of the Superconducting Super Collider. Worried that conflict among competing projects would undermine the collider's prospects, DOE director of the Office of Energy Research Alvin Trivelpiece crafted a deal in 1984–85 to share the wealth with laboratory directors.

The Trivelpiece plan called for constructing three materials-science projects: the Advanced Light Source at LBL, the Advanced Photon Source at Argonne National Laboratory, and a reactor at Oak Ridge that has morphed into the Spallation Neutron Source. In addition, two nuclear-physics projects got support, the Relativistic Heavy Ion Collider at BNL and Jefferson Lab in Newport News, Virginia. When the Superconducting Super Collider was canceled in 1993, the materials-science projects that had been in its shadow took center stage.

Funding and other challenges

On the face of it, the characteristics associated with the New Big Science might suggest simply an altered resource economy in which large-scale research projects are funded through partnerships with industry, but such was not the case. Figure 3, which charts federal, industrial, and other contributions to research, shows that the federal government has funded most basic research in the past several decades.

Military funding of basic research has actually been rela-

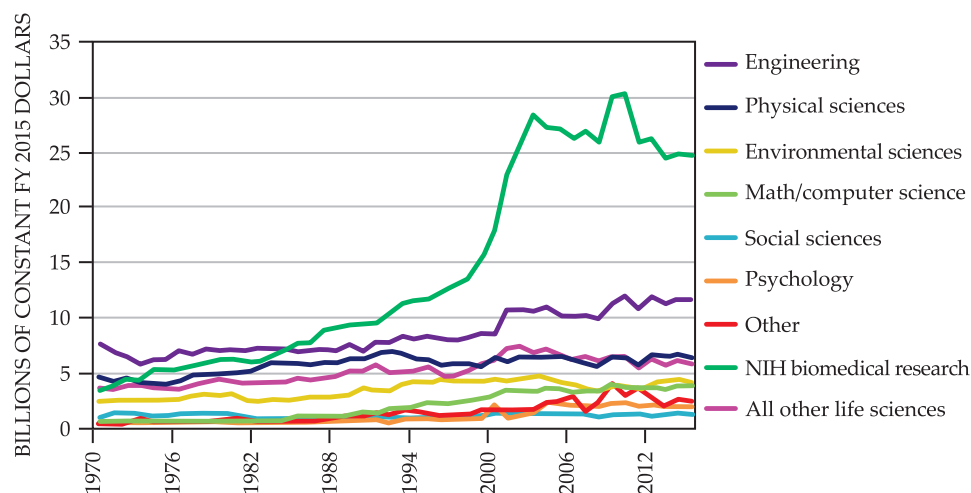


FIGURE 4. FEDERAL RESEARCH FUNDING BY DISCIPLINE. Most disciplines have seen only modest increases in federal funding since 1970. But about 20 years ago, funding for biomedical research really took off. Note that life-sciences research is broken down to National Institutes of Health (NIH) biomedical research and everything else. (Courtesy of the American Association for the Advancement of Science, based on NSF data.)

tively minor from the early 1950s Old Big Science era to the current New Big Science era. It has increased in recent years, but that is likely due to military facilities that conduct basic research on the side, as with the Z machine at Sandia National Laboratories. By far the most striking feature of funding during the past several decades, as shown in figure 4, is the enormous increase of federal biomedical-research funding that was initiated near the turn of the century.

Any discussion of funding of the New Big Science comes with caveats. Understanding the resource economy of the New Big Science is tremendously challenging: Funding comes from many sources, and funding patterns are complicated. In the Old Big Science, NSF sponsored some high-energy-physics research through universities. But almost all high-energy-physics accelerators and research were funded from a single program in DOE or its predecessor, the Atomic Energy Commission. In the New Big Science, accelerator funding continues to come almost exclusively from DOE, but research funding comes from various programs in DOE and NSF, from industry, and from the National Institutes of Health. Moreover, the users of New Big Science facilities are diverse and transient, and therefore much harder to track; they include scientists from varied fields who receive money through universities, institutes, and industry, and medical doctors who obtain funding from NIH, hospitals, and pharmaceutical companies.

The rise of the New Big Science has put stress on traditional management and promotion methods developed for the Old Big Science and has prompted the development of new methods. The New Big Science is marked by greater bureaucracy and pressure for accountability.

Industrial use of synchrotron light sources, for example, continues to generate worries that were less problematic in the Old Big Science. Intellectual property issues and liability insurance are obvious examples. Timely access is another. Current approval procedures are designed primarily for academic users, who may need a year to get a proposal through the process. Industrial users typically require a much faster ap-

proval time. For a company that operates its own beamline—IBM, for example—the approval process can be fast-tracked. But for small businesses or industries without their own beamline, extended approval time can be problematic; user facilities are seeking ways to speed up access.

Another worry involves the political case for large materials-science facilities. Congressional representatives are typically interested mainly in projects that are sited in their own districts. The networks of research characteristic of the New Big Science, however, often connect users with facilities in many districts. That reality has prompted DOE to develop an interactive online map that, among other things, can reveal which users in a

given congressional district have been to a particular DOE user facility. (See <http://science.energy.gov/user-facilities/user-statistics>; figure 5 shows a screen shot of a map generated from the site.)

Getting at ecological information

The complexity of the New Big Science research ecology makes it difficult to notice patterns and changes. How is one to extract, analyze, and display information for the benefit of historians and other researchers in academia and government when both methods and data are so dispersed? Following a particular research program, or even a collection of them, is of limited value for identifying emerging trends and overall changes in how the research is carried out; there are too many overlapping and bifurcating threads. How can historians and sociologists of science investigate what is happening overall in the research ecosystem to discover and evaluate differences in the research practices of, say, 1987, 1997, and 2007? We lack a shared ground for bringing into the conversation methodologies for the analysis and visualization of “big data” along with the traditional methodologies and frameworks. What is needed is an online demographic research tool such as Social Explorer (www.socialexplorer.com), suitably adapted for use at materials-science facilities.

Let us express the problem in a different way. Several traditional methods may be brought to bear on investigations of research. We can track a facility’s operational history. That is, we can look at such things as when a facility’s storage rings were shut down for maintenance, repairs, and upgrades; what was done during those shutdowns—what devices were installed and what modifications were made to beam-monitoring systems, vacuum chambers, and power supplies; and how the shutdown changes affected key qualities of the machine such as current and brightness. We can also track the machine’s administrative history through its directors and principal administrators. Or we can look at functional history, what collaborations worked, at which beamlines, with what instruments, in

what fields, and with what outcomes—for instance, patents, prizes, and publications. Still, lists of that sort are of little value unless connected with the associated integrative networks—and making that connection is difficult because those networks are complicated.

Key changes may be taking place that would escape the notice of someone who, for example, is consulting lists of experiments, fields, or instruments. Clearly, information is present—let's call it implicit information—but we don't even know what it is. It is possible that new digital tools can be created to extract that implicit information; such an advance would help to transform the way we conceptualize history. New kinds of digital tools may be able to keep track of and image enormously intricate, changing patterns and thus bring the tools of computer analysis and visualization to bear on the study of a single, historically rich, immensely complex facility on the scale of a synchrotron light source. Such facilities, and the domains of research that they anchor, represent a set of histories too large and complex to encompass by traditional means.

Users of the new digital tools might include science-policy administrators and DOE officials with an interest in optimizing research investments; science historians interested in how particular discoveries and research programs influence and intersect with others; science-studies scholars interested in how subfields of science appear and disappear; institutional scholars interested in how facilities are connected, support each other, and evolve into each other; and scientists themselves.

Toward a flourishing ecology

In the New Big Science, large-scale materials-science accelerators have replaced high-energy-physics accelerators as the premier projects that exemplify the mission of the largest US national laboratories. This new phase has brought important changes in the character and culture of the research ecosystem at those laboratories. The nature of leadership at the national labs may change; for instance, the labs may require leaders with different skills than the strong and charismatic Old Big Science bosses in the mold of Ernest Lawrence, J. Robert Oppenheimer, and Robert W. Wilson. How New Big Science projects are sold to politicians and the public will have to change as well; it may prove harder to generate enthusiasm for networks of smaller facilities than for those of the gigantic, “throw-long” variety.

High-energy and nuclear physics will not disappear as research fields, nor will they fuse into a new field or disappear from the mix of projects supported at the US national laboratories in the era of the New Big Science. Disciplinary niches will not vanish; rather, the research ecology will become ever more complex and extended. In the Old Big Science, a chief problem was narrow focus. To justify the existence and cost of their tools, scientists had to make an elaborate case based on the intangible value provided by the science and the unpredictable practical benefits of its spinoffs. In the New Big Science, a chief problem is diffuse focus. Machines are more diverse, and because they are used by an amorphous, ever-changing collection of users, research agendas are open-ended. As a result, managers and funders have had to de-

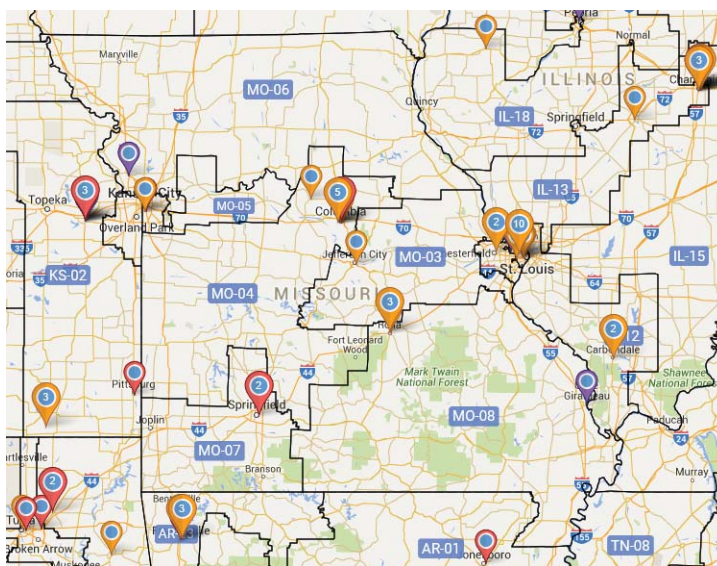


FIGURE 5. WHERE THE USERS ARE. The US Department of Energy has developed an online, interactive, customizable map that provides geographic data about scientists' use of DOE facilities. This screen shot includes labels of congressional districts in Missouri, home to more than 200 scientists who in fiscal year 2014 performed research at DOE Office of Science user facilities in other states. The clickable markers reveal the users' institutions and their associated facilities. (Courtesy of DOE Office of Science. Visualization with Maptive, powered by Google Maps APIs.)

velop new methods for handling, promoting, and evaluating research.

Historians and other scholars of the New Big Science can make a constructive contribution by crafting new tools to extract, analyze, and display information about the new research ecosystem. Armed with such data, we can help figure out ways to make it flourish.

ADDITIONAL RESOURCES

- US Department of Energy, Office of Science, <http://science.energy.gov/bes>.
- W. P. McCray, “Will small be beautiful? Making policies for our nanotech future,” *Hist. Technol.* **21**, 177 (2005).
- R. P. Crease, “The National Synchrotron Light Source, part I: Bright idea,” *Phys. Perspect.* **10**, 438 (2008); “The National Synchrotron Light Source, part II: The bakeout,” *Phys. Perspect.* **11**, 15 (2009).
- R. P. Crease, “Physical sciences,” in *The Oxford Handbook of Interdisciplinarity*, R. Frodeman, J. T. Klein, C. Mitcham, eds., Oxford U. Press (2010), p. 79.
- O. Hallonsten, “Contextualizing the European Spallation Source: What we can learn from the history, politics, and sociology of Big Science,” in *In Pursuit of a Promise: Perspectives on the Political Process to Establish the European Spallation Source (ESS) in Lund, Sweden*, O. Hallonsten, ed., Arkiv Academic Press (2012), p. 81.
- C. Westfall, “From the ground up? Launching the ESS, Fermilab, JLab, and the APS,” in *New Big Science in Focus: Perspectives on ESS and MAX IV*, J. V. Rekers, K. Sandell, eds., Lund U. (2016), p. 25.