Tacit Knowledge as a Factor in the Proliferation of WMD: The Example of Nuclear Weapons

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> “*How important is tacit knowledge to the task, and how essential is such knowledge in the proliferation of such weapons?*”

What would it take, in addition to the will, for a nation to join the club of nations possessing nuclear weapons? An incomplete list of the prerequisites would include: enriched uranium or plutonium, physicists, chemists, computational power, processing plants, specialists in materials and electronics, money, institutions capable of building and managing a large scale construction project, and a site or sites to build and test a device.

Despite their destructive power, nuclear weapons are fragile objects. They require an elaborate sociotechnical support system that costs millions, if not billions of dollars each year simply to maintain their existence. One item not explicitly on the above list and seldom discussed in the analysis of this problem is “tacit knowledge,” the knowledge acquired through the actual experience of building and developing an atomic bomb. How important is such knowledge to the task and how essential is such knowledge in the proliferation of such weapons?

The probable answer is that lack of tacit knowledge is not likely to a stop an illicit program in its tracks, but without it, a weapons program is likely to fail more often in its early stages, cost more through a period of trial and error, and take longer to reach fruition. Acquiring tacit knowledge requires time, providing analysts and policymakers with a much needed resource for thought and action. And because timing is a key element in intelligence analysis and policy responses, tacit knowledge is an important factor in the analytical equation. A clear understanding of the sources of tacit knowledge and how it is transmitted from one place to another is central in the consideration of policy responses to a technology development program with security implications.

In the following, I examine the nature and character of tacit knowledge, its origins, and its role specifically in the construction and spread of nuclear weapons since World War II.

An Introduction

Tacit knowledge first emerged as a concept for understanding the actual practice of research in the work of Michael Polanyi, an émigré chemist in mid-20th-century Great Britain. Polanyi’s interest in tacit, or personal, knowledge, stemmed from his overarching fear that states, especially Nazi Germany and Stalinist Russia, had successfully attacked and endan-

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gered the very freedom of science. Even his new home had seemingly come under the sway of followers of J.D. Bernal, whose major work, *The Social Function of Science* (1939), called for the planning of scientific research by the state. These developments, as well as the mobilization of science for war, led Polanyi and others to form The Society for the Freedom of Science in 1940.

What made tacit knowledge central to Polanyi's conservative anti-statist ideology was the idea that tacit knowledge was so personal that it would prove impossible for the state to possess. Given that such knowledge was essential to the growth and development of science, only those who had successfully practiced research might actually understand and manage the enterprise. That framework suggested that scientists need not be subject to the whims of politicians or government bureaucrats; instead, science had to remain an autonomous domain.[1]

Regardless of the political merits of Polanyi's beliefs, the concept of tacit knowledge has emerged as a powerful resource in understanding the growth and development of technical knowledge. Historians and sociologists of science have made use of the concept to understand how knowledge is made, used, and moved around.[2] Rather than assuming that technical knowledge refers to some simple correspondence among researchers, scientific knowledge, and the natural world, the idea of tacit knowledge recognizes the complex interactions at work in making science.

Experience matters. It cannot be acquired through the transmission of information or the act of reading a scientific paper. As Polanyi once explained, tacit knowledge was simply the observation that "we can know more than we can tell." Instead, as a vast literature demonstrates, moving scientific knowledge around requires a substantial amount of effort.[3] Even the seemingly trivial act of replicating a scientific experiment turns out to require a degree of skill that is difficult to acquire.

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Training and the time-consuming acquisition of skill, the essence of tacit knowledge, are among the vital prerequisites for successful knowledge transmission. Even more important is the actual movement of people possessing these skills. Early builders of cyclotrons, the pioneering atom-smashing technology, often found themselves unable to build a device without access to one of the students of Berkeley professor E.O. Lawrence, the inventor and developer of the technology.

Despite the many papers the Berkeley group published on the cyclotron, including Lawrence's Nobel Prize lecture, only those who had actually built a cyclotron were able to rebuild one at a distance from the original location. For example, when Merle Tuve, one of the outstanding experimental nuclear physicists of the thirties, decided to build a cyclotron at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, DC, he imported a Berkeley graduate to guarantee success.[4] This personal component—the embodied character of tacit knowledge—is crucial to understanding tacit knowledge but it can also be misleading.

Understanding tacit knowledge demands a knowledge of history, because what counts as tacit knowledge changes over time. Take the case of PCR, the polymerase chain reaction, a key development in biotechnology and a critical component of much research including DNA fingerprinting. Initially, getting the PCR reaction to work in individual laboratories required a technician with "golden hands"—that is, in each laboratory there was one technician who, through training and experience, could make the technique work. Over time PCR became standardized and "black-boxed," so that it is now available as a technology that laboratories purchase and use, much as they use any sophisticated technology.

We can make a similar point about cyclotrons; today, one can purchase a sophisticated particle accelerator, a synchrotron, for use in a variety of industrial settings, such as X-ray lithography for computer chips. Over time, a fair amount of tacit knowledge is standardized and embedded in the actual hardware of research. In turn, what counts as tacit knowledge changes as one moves from mastering a set of skills to produce a result to using a standardized piece of apparatus to achieve the same end. You don't need to be a student of Kary Mullis, the inventor of PCR, to make PCR work in a laboratory today; instead, you need training on the PCR machine used in your laboratory.[5]

The Political Challenge of the First Nuclear Weapons

The designers and builders of the first atomic bomb did not possess tacit knowledge about building a weapon. Instead, they acquired that knowledge during the Manhattan Project while drawing upon vast repositories of tacit knowledge developed in the course of early-20th-century experimental physics and chemistry. We can use the Manhattan Project's history to make a more fundamental point: building nuclear weapons is a complicated, messy, and inherently political process.

Arranging the constellation of forces necessary to start a project, let alone keep it underway as it develops the inevitable problems accompanying technological innovation, is fraught with peril. For that very reason, the Army's choice of General Leslie R. Groves to run the Manhattan Project was an inspired one. The man who built the Pentagon, then the world's largest and most complicated structure, had the requisite managerial skills to assemble the staff and materials that would span the nation's geographical territory as well as coordinate with the British and Canadians as the project raced to a conclusion.

Before Groves was appointed, the atomic bomb had a difficult conception. When Niels Bohr brought word of fission to the United States in December 1938, Merle Tuve promptly demonstrated the effect at his Atomic Physics Observatory in Washington, DC. Nonetheless, researchers found it impossible to even interest the armed services in fission's possibilities. Although the Navy expressed an interest in fission as a potential power source for ships, there was little interest in a weapon. Even after President Franklin D. Roosevelt created a Uranium Committee under the director of the National Bureau of Standards, Lyman Briggs, little was accomplished.

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Only with the arrival of Vannevar Bush and the National Defense Research Committee in June 1940 did real work begin. The nature and character of that work are worthy of comment. Bush funded research on fission and learned of British work on the topic (the MAUD Committee), but his major accomplishment was the creation of three separate National Academy of Science committees to study the problem of applying fission in a viable weapon.

Only after the third committee explicitly stated that a weapon might be built within a reasonable amount of time and with a limited amount of the isotope, U235, did Bush return to seek Roosevelt's approval to begin a full-scale effort to determine if a bomb was an actual possibility. In other words, Bush used the academy to cover his backside, but it was the academy's imprimatur that allowed the president to authorize early large-scale research. Only after Bush's research program answered the fundamental question of whether a chain reaction would even take place in uranium would FDR determine whether to proceed with full-scale production.

Fermi's group at Chicago did not achieve a chain reaction until December 1942. Ironically, Bush received FDR's initial approval in October 1941, before Pearl Harbor, and at roughly the same time that the Germans decided not to pursue their own Manhattan Project.[6]

There are two important points here. First, complex political choreography was required to orchestrate this kind of decision in a nation not yet at war and without an expanding and growing economy. Nuclear weapons are not for political neophytes. Second, our intelligence about other nations and their weapons programs has been limited since the beginning of the atomic age. The United States made one of its most important decisions based on the assumption that Nazi Germany would do the same, and our entire program operated under the equally false assumption that we were racing the Germans. Much as in the race to the moon, only one party was actually running.

Tacit Knowledge and the First Weapons

Those new to the making of an atomic bomb may not possess the tacit knowledge of how to build one, but they will be required to possess explicit and tacit knowledge in a host of necessary precursor fields, ranging from metallurgy and detonation to theoretical and experimental physics. Physicists in 1930s America, especially experimentalists, also shared another common area of experience—ham radio. Amateur radio was the one hobby shared by virtually every male of a technical inclination in interwar America. With the hobby, which entailed building and modifying one's own radio, came a toolkit for then modern electronics, including skill at soldering; diagnosing the various afflictions that affected vacuum tubes; and the ability to read and write in the shared language of a circuit diagram.

Graduate education in a host of fields drew upon and improved the skills the ham radio operators had taught themselves. Equally important was the role of the Great Depression in selecting talent; graduate education was not a perfect meritocracy—there was substantial discrimination against Jews, as well as African Americans and women—but the selection pressures of the economic crisis allowed only those who were very good or independently wealthy to actually pursue advanced degrees. Even with this background, the United States had genuine difficulties in constructing its original weapons.

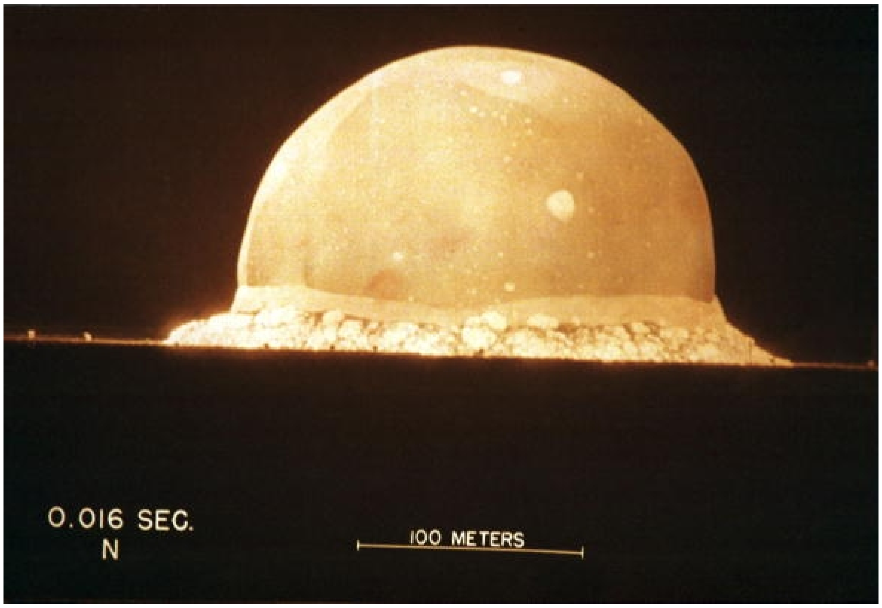
At the outset of the project it was assumed by the theoreticians that building a fission device would prove very simple. Some physicists even advised younger colleagues that the project would be solved once the raw materials were available in sufficient quantities. Chalk that up as another failed prediction.

Building the first weapons demanded the creation of new fields of research ranging from the study of the new element plutonium to the study of shock waves produced by explosives and focused through explosive lenses. As is now well known, the original plan for the weapon was that the bomb would employ a gun-type assembly in which one would fire one sub-critical mass of U235 into another; the same would hold true for Pu239.

Instead, the actual production of plutonium and the separation of the element into the required isotope and amounts required a whole new physical chemistry to understand the new substance. One can note that the much acclaimed Smyth Report, *Atomic Energy for Military Purposes* (1945), had much to say about the production and assembly of the U235 weapon but little about the Pu239 bomb. The physical chemistry and machining of plutonium, developed by Glenn Seaborg and his colleagues, were among the real secrets of the Manhattan Project.

Next, because of its chemistry and physics, Pu239 would not work in a gun-type assembly. When Pu239 was present in any quantity near that required for a bomb, the isotope underwent spontaneous fission. Rather than going "boom," the mass simply lay there, a pile of poison with no explosion. Making a plutonium bomb required a new method for the rapid assembly of the critical mass, implosion. Despite devoting the full resources of Los Alamos towards solving the problem of implosion, there remained genuine uncertainty about whether the method would actually work, even as researchers poured and molded the explosive charges that compress a hollow sphere of Pu239 into a critical mass.

One reason for the Trinity test in New Mexico in 1945 was to determine whether or not implosion would actually yield a working weapon. After all, the United States did not test a U235 gun-type weapon, but that was a decision driven by the inability to produce



The Trinity test on 16 July 1945. Photo © Getty Images.

enough U235 for another weapon before January 1946.[7]

Obviously, one important issue no longer confronts anyone struggling to build a weapon—they know it is possible. Among the other areas in which the United States produced individuals possessing tacit knowledge was in the purification and machining of plutonium, the enrichment of uranium, and the assembly of weapons.

As the Cold War progressed, the United States continued to acquire experience in the design and production of nuclear and later thermonuclear weapons. Central to the process was the development of computational simulations of what took place when a nuclear weapon detonated. This software, what designers called "codes," became essential to the ongoing development and improvement of the arsenal. As readers may recall, what made the charges in the Wen Ho Lee case so serious was the potential loss of such codes to a foreign power.

What we have learned from the work of scholars such as Hugh Gusterson, Donald MacKenzie, and Graham Spinardi is that 10 to 30 percent of all US nuclear tests were not done to test a particular weapon's configuration but to confirm the reliability of codes to accurately predict what took place during a detonation.[8] What counts as close enough is also up for debate and discussion, since designers are often happy if results are within 25 percent of their predictions.

What is striking in this research is the relatively small number of people who count as genuine, journeyman designers. It takes roughly 10 years for the US national labs to turn an excellent astrophysicist into a viable and creative weapons designer. Such people possess what they call judgment, the ineffable or tacit knowledge necessary to accurately evaluate the effects of seemingly minor design changes.

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Even at the height of the Cold War, the United States had only 50 people possessing this level of knowledge. It is important to keep in mind that these people were designers. Others, ranging from those who machined the raw materials to those who assembled the weapons, possessed their own tacit knowledge, all of which proved essential in manufacturing working devices. Tacit knowledge remains vital to US national security, given the importance of the Stockpile Stewardship Program and our national commitment to the Comprehensive Test Ban Treaty.

Proliferation: Or How Do You Move Tacit Knowledge Around?

Given the thickness and stickiness of tacit knowledge, it would seem nearly impossible to move it without moving the individuals in whom it is embodied. Clearly that isn't the case—other nations have developed nuclear weapons, but they have done so not entirely under conditions of their own choosing. As Steven Flank, a most interesting student of this problem put it:

> *Nuclear system builders face limits on all resources—money, political authority and consensus, laboratory quality reagents, access to imports, and so on. The process by which these scarce resources are recruited and fixed in a stable network capable of producing the comparatively simply artifacts of 'nuclear weapons' is the process of nuclear proliferation.*[9]

Take the cases of Britain and the former Soviet Union (USSR). Both started with the same source, Klaus Fuchs, although one, the UK, had access to him personally, whereas the USSR had access to him through the documents he provided through his espionage. Each nation attempted to build an implosion device and each nation ran into problems making a copy of the Trinity test weapon. In the USSR, the explicit knowledge of the plans still demanded the production of an entire nuclear industry, a task that took four years, slightly longer than the Manhattan Project itself.

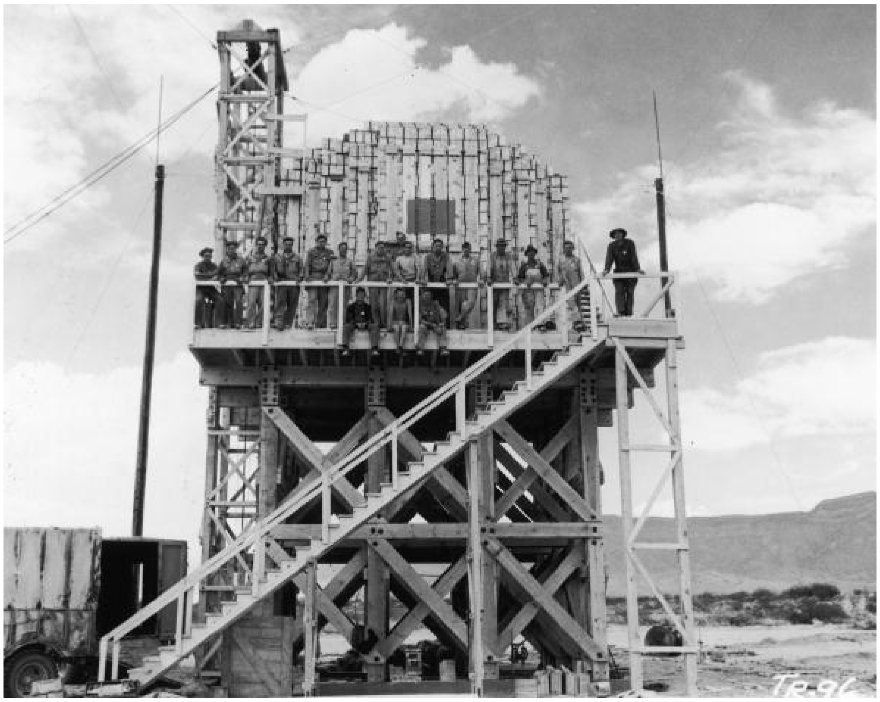
The Soviet weaponeers found themselves having to reinvent the processes and practices that the Americans had already developed. In other words, they had to reinvent the tacit knowledge of the Americans.[10]

The British faced a slightly different set of problems. First, while the UK had participated in the Manhattan Project and had a group at Los Alamos, the Atomic Energy Act of

1946 cut off their American sources. Second, they seemed to have real problems with what was a wartime necessity in the United States—assembly of the weapon in-flight. Because of fears that their weapon might arm itself, the UK wound up developing a slightly different implosion device. In both cases, each nation found itself reconstructing a variant of the Manhattan Project's sociotechnical network. Tacit knowledge didn't so much move as it was invented anew.

Similar stories might be told of both France and China, and readers should examine the claims made by MacKenzie and Spinardi with respect to those national narratives. Still, an excellent example of the difficulties in building nuclear weapons took place in the United States. In the wake of the controversy over building a thermonuclear weapon, the United States decided in 1952 to build a second weapons laboratory—the Lawrence Livermore National Laboratory. What is striking is that while designers at the laboratory had access to all the explicit knowledge from Los Alamos, they were utterly unable to make a working weapon on their first two tests.

Part of their problem was that the designers at the new laboratory wanted to make weapons completely different from those made at Los Alamos and tried to use novel materials and techniques. They had never built a nuclear weapon and lacked the necessary tacit knowledge and skill. Livermore's first two tests were epic fizzles. One even failed to bring down the tower upon which the test device rested. Efforts of the Livermore group to pull down the test tower with a jeep were duly recorded by observers from Los Alamos. In other words, even in the same country and with equal access to classified information, it proved difficult for a group of well-trained and otherwise competent professionals and technicians to make a weapon.



Workers on the Manahattan Project in Alamagordo shown on a platform stacked with TNT interlaced with fission products. Explosion of the TNT was meant to make sure measuring and observation equipment functioned and was correctly calibrated before the firs test. Such testing also provided experience and built tacit knowledge in capturing data from an atomic test. Photo © Time&Life Pictures/Getty Images.

Save for India and Israel, both of which seem to have taken some of the knowledge from their civilian nuclear programs and applied it to their weapons program, other proliferation cases appear slightly different. If news reports can be trusted, Pakistan appears to have acquired knowledge of enrichment through A.Q. Khan's now well-known work at URENCO. If news reports are trustworthy, Pakistan also received blueprints for a bomb as well as enough highly enriched uranium (HEU) for two bombs from China in 1982.[11]

This gift appears to have had minimal effect on the speed at which the Pakistanis developed their own bomb. They still had to learn how to build one, and that required a reinvention of the tacit knowledge that went into the Chinese device they apparently copied. More interesting is the Libyan case, where Khan apparently promised the Libyans a turn-key system for the production of nuclear weapons. Such a system included the ability to machine either enriched U235 or Pu239. It is entirely unclear who in Libya could make use of such a technology. Importing an entire nuclear weapons complex would have been an impressive achievement, but it doesn't appear to have taken place. And if it had, Libya would have been held hostage by its supplier for

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all the skills necessary to assemble a weapon.

Kits for nuclear weapons sound frightening, and stories about them appear designed to scare Western governments. Where was the tacit knowledge and skill necessary to build a bomb going to come from? Was Khan going to set up an outpost of the Pakistani weapons complex in Libya? It is important to recall that Qadhafi purchased expensive, sophisticated weapons from the West that no one in his armed forces could actually use. One can easily imagine a program to effectively dismantle a Libyan nuclear program by sabotaging the equipment purchased from Khan. Given his scruples or lack thereof, he might even sell slightly defective equipment to unwitting buyers.[12]

Even the Iraqi program dismantled after the first Gulf War had serious problems, not the least of which was its use of calutrons—the same devices E.O. Lawrence built at Oak Ridge during WW II. What hampered our understanding of the Iraqi program appears to have been a lack of understanding by various intelligence agencies of the Iraqis' actual skill level. Apparently, we believed the Iraqis would not redo the Manhattan Project but take up where other states had started. After all, calutrons produced the raw, slightly enriched uranium that American weaponeers then poured into the massive gaseous diffusion complex, K-25.

Even after a year of operation, the United States had only enough raw U235 for the single device used at Hiroshima. Another uranium bomb would not be available until January 1946. Iraq may have been able to build a bomb, in time, but it was never going to be a major builder of nuclear weapons as long as it relied upon calutrons.[13]

For me, a private citizen with no access to classified materials, the Iran case is an interesting test of these ideas about tacit knowledge. At the very least, it appears the Iranians want the capability to build a weapon that a missile might deliver to a target. The November 2011 IAEA report and subsequent commentary lends credence my assertions since it appears that the Iranians imported a former Soviet weapons scientist, Vyacheslav Danilenko, to instruct them in manufacturing the specialized electronics required for fast-acting detonators.[10]

Apparently, Iran has also tried to purchase tacit knowledge by enlisting the aid of those possessing the requisite skills, in this case the ability to design and build fast-acting detonators. As Sharon Weiner observed in the *Bulletin of the Atomic Scientists* in November 2011, the US enacted an array of programs to eliminate this possibility, but the individual in question appear to have fallen between the cracks.

Iran may have been able to develop fast acting detonators indigenously, without outside assistance, but without testing they would not know if they had a working device or a chunk of subcritical fissionable material. Perhaps, they believe that importing the knowledge makes an actual test unneeded, but testing seems necessary for nuclear states to establish their atomic bona fides.

So what?

Thinking about tacit knowledge suggests new or additional approaches to stemming the proliferation of illicit programs. To date, most of our efforts to halt proliferation rely upon attempts to interdict or destroy the sources of raw materials or the technologies necessary to make them. Examples of this are the Israeli raid on the Iraqi reactor and the widely reported deployment of the Stuxnet worm, the sophisticated piece of malware that targeted the specific Siemens industrial-grade controllers used in the Iranian enrichment program.[14] Similarly, reported efforts to target top Iranian nuclear scientists might be an ominous extension of efforts to slow Iranian weapons development.

However, understanding of such weapons programs as networks of activities, institutions, people, and resources may offer a greater variety of collection and intervention strategies, which are best left to those in a position to make such decisions.

One of Steven Flank's most interesting observations was about the Indian nuclear program, which he claimed attempted unsuccessfully to forge a connection with the nation's agricultural sector. Instead, the nuclear researchers found a home within the military's dense support network. More recent research by George Perkovitch and others disagree and hold that Indian researchers wanted to build a bomb from the very beginning of their program, but Flank's point is more basic and resonates with this paper's basic argument. Nuclear programs require time and sophisticated support and resource networks. Flank believed that offers of foreign aid tied to the agricultural sector might have linked the nuclear researchers to the agriculturalists and thus to peaceful purposes, but that is a counterfactual we don't have to accept.

Interrupting the development and acquisition of tacit knowledge in regimes of proliferation concern might provide time and opportunity to allow diplomatic, economic, and other measures to take hold.

True or not, the story helps to focus us on addressing tacit knowledge rather than the usual methods of stemming proliferation. It allows us to recognize that while the absence of tacit knowledge is not a show stopper, it is a "show slower," to coin an infelicitous phrase. If nations have the resources, the time, and a civilian nuclear power program, and elect to make the acquisition of nuclear weapons a priority, stopping them will be difficult, as the case of North Korea has shown. Still, interrupting the development and acquisition of tacit knowledge in regimes of proliferation concern might provide the international community time and opportunity to allow diplomatic, economic, and other measures to take hold.

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Source notes

1. The classic sources on tacit knowledge are Michael Polanyi, *Personal Knowledge: Towards a Post-Critical Philosophy* (Chicago: University of Chicago Press 1958); and *idem*, *The Tacit Dimension* (Garden City, N.Y.: Doubleday & Co., 1966). On understanding the origins of the concept, see John R. Baker, "Michael Polanyi's Contributions to the Cause of Freedom in Science." *Minerva* 16, no. 3 (1978): 382-96; and Mary Jo Nye, "Historical Sources of Science-as-Social-Practice: Michael Polanyi's Berlin." *Historical Studies in the Physical and Biological Sciences* 37, no. 2 (2007): 409-34.

2. To begin to understand how practitioners of science and technology studies have used tacit knowledge, see Harry Collins, *Changing Order: Replication and Induction in Scientific Practice* (Beverly Hills: Sage Publications, 1985); and *idem*, *Tacit and Explicit Knowledge* (Chicago: University of Chicago Press, 2010). A thought provoking article about tacit knowledge that also addresses its role in other fields is Tim Ray, "Rethinking Polanyi's Concept of Tacit Knowledge: From Personal Knowing to Imagined Institutions" *Minerva* 47 (2009): 75-92.

3. On the problem of moving scientific around, see Shapin, Steven. "Here and Everywhere: Sociology of Scientific Knowledge." Annual Review of Sociology 21 (1995): 289-321; and *idem,* "Placing the View from Nowhere: Historical and Sociological Problems in the Location of Science." *Transactions Institute of British Geography* 23 (1998): 5-12.

4. On the spread of the cyclotron, see Heilbron, J.L, and Robert W. Seidel. *Lawrence and his Laboratory: A History of the Lawrence Berkeley Laboratory.* Berkeley: University of California Press, 1989.

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6. On the decision to build a weapon, the definitive source is Stanley Goldberg, "Inventing a Climate of Opinion: Vannevar Bush and the Decision to Build the Atomic Bomb." *Isis* 83 (1992): 429–52.

7. There are many histories of the Manhattan Project. The best place to start remains Martin J. Sherwin, *A World Destroyed: Hiroshima and the Origins of the Arms Race*. New York: Vintage, 1975; 1987. Another excellent source to mine for information about tacit knowledge in the project is Hewlett, Richard G., and Oscar E. Anderson. *The New World, 1939-1946*. University Park: Pennsylvania University Press, 1962. On the centrality of ham radio in interwar technical culture, see Haring, Kristen. *Ham Radio's Technical Culture*. Cambridge: MIT Press, 2006. On the problems related to plutonium at Los Alamos see Hoddeson, Lillian. "Mission Change in the Large Laboratory: The Los Alamos Implosion Program, 1943-1945," in Peter Galison and Bruce Hevly (eds.), B*ig Science: The Growth of Large-Scale Research* (Stanford: Stanford University Press, 1992): 265-89; and Hoddeson, Lillian Hartmann, Paul W. Henriksen, Roger A. Meade, Catherine Westfall, and Gordon Baym. *Critical Assembly: A Technical History of Los Alamos During the Oppenheimer Years, 1943-1945*. Cambridge: Cambridge University Press, 1993.

8. See Gusterson, Hugh. *Nuclear Rites: A Weapons Laboratory at the End of the Cold War.* Berkeley: University of California Press, 1996; and Mackenzie, Donald, and Graham Spinardi. "Tacit Knowledge, Weapons Design, and the Uninvention of Nuclear Weapons." *American Journal of Sociology* 101, no. 1 (1995): 44-99.

9. See Flank, Steven. "Exploding the Black Box: The Historical Sociology of Nuclear Proliferation." *Security Studies* 3, no. 2 (1993/94): 259-294, quote 260-1. This is among the most astute and thoughtful essays written about nuclear proliferation.

10. The standard source on the Soviet program remains Holloway, David. *Stalin and the Bomb*. New Haven: Yale University Press, 1994. For this identification, see Sharon K. Weiner, "Who's a Weapons Scientist?" Bulletin of the Atomic Scientists (16 November 2011), http://www.thebulletin.org/web-edition/features/whos-weapons-scientist. [last accessed 27 November 2011]

11. R. Jeffrey Smith and Joby Warrick. "A Nuclear Power's Act of Proliferation: Accounts by Controversial Scientist Assert China Gave Pakistan Enough Enriched Uranium in '82 to Make 2 Bombs.," *The Washington Post*, 13 November 2009; and Feroz Hassan Khan, *Eating Grass: The Making of the Pakistani Bomb*, Stanford Security Studies (Stanford University Press, 2012).

12. John Prados, "How Qaddafi Came Clean," *Bulletin of the Atomic Scientists* 61, no. 6 (2005): 26–33.

13. On Iraq and calutrons as well as its entire program, see David Albright and Mark Hibbs. "Iraq's Bomb: Blueprints and Artifacts," *Bulletin of the Atomic Scientists* 48, no. 1 (1992): 30–40.

14. IAEA Report, November 2011, http://www.thebulletin.org/whos-weapons-scientist.

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