ESSAY

How the World's Most Underdeveloped Nations Get the World's Most Dangerous Weapons

GEOFFREY FORDEN

In 1954, Iraq's industrial economy consisted mainly of "factories" employing one or two workers. With only fifty-five Iraqi engineering students graduating that year, there was no reason to believe that that situation would change anytime soon. But in twenty years the Iraqis were laying the foundation for a massive chemical-weapons industry, setting up a nuclear program that would eventually grow into a $10 billion effort, and welding together a long-range missile program with dreams of launching satellites into orbit. Nor was Iraq the only underdeveloped country acquiring such advanced—and secret—technologies. How could this happen?

I became interested in that question as a United Nations weapons inspector shortly before the current war. During a routine search of the United Nations Monitoring, Verification, and Inspection Commission (UNMOVIC) database, I came across a copy of the contract Iraq signed to purchase the factories it needed to build long-range solid-propellant missiles. At the time, I was preoccupied with questions we needed to answer to verify Iraq's disarmament and avert war: Did Iraq's unmanned airplanes violate the UN Security Council's resolutions? What had happened to the nearly 1,000 tons of mustard gas they had produced but failed to account for? The contract, spelling out what the party of the first part would supply to the party of the second part, was striking in its normality. This was the

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banality of evil. But every time it mentioned a batch of one hundred missiles, I pictured an equal number of collapsed apartment buildings in Tehran. Could such contracts exist for poison gas factories too? And if not, how would a country get those factories?

The How, Not the Why, of Proliferation

Of course, any nation follows a unique path in its search for weapons of mass destruction (WMD), based on its own resources and strategic requirements. But it turns out that their efforts share a number of common elements. We may arrange these efforts along a self-sufficiency spectrum. At one end, a state highly dependent on foreign expertise could try to buy a complete WMD production facility: that is, find a foreign contractor to come in and design and build the plant, equip it, and train indigenous workers to run it. This is far from a hypothetical scenario; not only does it happen far too often for the good of the world, but acquiring such a turnkey facility is the most successful path a proliferator can take. The third step along this turnkey production path is quite important; just buying equipment is no guarantee of success. Conveying the tacit knowledge about production processes to the shop-floor workers is crucial to the proliferator's future success, as we know from a number of instances when production equipment was delivered, but the promised training failed to materialize. However, "successful" acquisition does not stop at that point. The customer has to assimilate the knowledge. Once he has, he can make improvements to the production process, meaning both that he can adapt it to his unique requirements and resources and that he can make the final product a more efficient or more deadly weapon.

At the other end of our spectrum, a proliferator highly independent of foreign expertise will go through the steps that an innovative civilian manufacturer would: develop a concept for the weapon, work out the design problems through engineering prototyping, and solve any problems associated with production, usually through the assembly of a so-called pilot plant in which techniques of mass production can be tested without the expense in money and time of building a large-scale production facility. A country interested in militarily significant quantities of WMD must then scale up this pilot plant to produce large amounts of whatever it is making. To fill a 2,000-liter-capacity tank with concentrated anthrax, for instance, the Iraqis had to produce the equivalent of 20,000 liters of anthrax.[1] This important fact distinguishes a nation from terrorists, for whose purposes small quantities are sufficient.

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[1] United Nations Special Commission (UNSCOM), *Report: Disarmament*, 29 January 1999, S/1999/94, 122.

However, even the most advanced countries would prefer to avoid the path of independent innovation for acquiring WMD, presumably more for fear of running into a technological dead end than out of corruption, which, as we shall see, played a substantial role in developing countries. Little else can explain the rapidity with which the United States, home of Robert Goddard, the inventor of the liquid-propellant rocket engine, gave precedence to German rocket technology and scientists after World War II over indigenous efforts.

Somewhere in between these two acquisition paths falls reverse engineering. In its purest form, a proliferator following this path buys, begs, borrows, or steals a weapon system, takes it apart to understand how it works, and duplicates it. Of course, the proliferator could steal the blueprints, as A. Q. Khan did for uranium-enrichment centrifuges, or find the chemical formula for a gas through a simple literature search, as Iraq appears to have done. But all these variations share a common feature: they seek to avoid the design and engineering phase of independent innovation by using a design originated by somebody else. Many analysts consider this the chief acquisition path for countries acquiring engineering-intensive technologies, such as ballistic missiles.

On the face of it, reverse engineering has much to recommend it to a potential proliferator, since design and engineering can account for a third to a half of the development time and resources for a weapon system. But the proliferator must still go through production prototyping and scale up, which can prove difficult for an underdeveloped country. And reverse engineering adds a step that requires its own skill set and infrastructure: reducing each of the individual parts of a weapon to a set of specifications and developing an understanding of the whole. And there is much more to understanding than mere theoretical knowledge.

Can You Keep a Secret?

We like to think that the secrecy in which we shroud our own nuclear weapons program and missile technology is effective. But is it? Does secrecy act in the straightforward manner we expect—that is, by creating a barrier that prevents key pieces of information from falling into the hands of potential proliferators? Clearly it affects the independent innovator differently than it does a proliferator who takes the path of reverse engineering or turnkey acquisition, since by definition for either of those two options to exist secrecy must have failed as a primary barrier.

Secrecy surrounding a proliferator's own weapons program may have its own adverse effects. One of the risks the independent innovator faces is failure to develop a useable weapon. He could, for instance, fail because he picks the wrong idea to work on. Iraq, to give an example, devoted considerable resources to developing aflatoxin as a biological weapon. While aflatoxin is known to cause liver cancer in mammals (including humans) at very large doses, it is not viewed in the West as a potential weapon. But the Iraqi biological weapons administrative infrastructure relied on its own mycotoxin experts, who encouraged first research and then production.[2] That encouragement may well have been self-serving, since those experts benefited from the in-pouring of research funds, but the program administrators did not have the specialized knowledge that would have allowed them to better evaluate the advice of their most capable experts. The secrecy that normally surrounds WMD influences this path to failure both by preventing policy makers from learning more of what other countries are doing and by making normal scientific peer review impossible.

If the case of aflatoxin illustrates how secrecy inside a government can adversely affect a WMD program, Iraq's Badr-2000 missile project demonstrates how secrecy between partnering governments can do so. The Egyptian government approached Iraq with a proposal for what it claimed was a completely developed missile with capabilities similar to those of the U.S. Pershing II, when in fact the missile was still in the conceptual stage, and Iraq ended up paying for much of its design and development.[3] Iraq was cheated both because its lack of familiarity with the technology prevented it from making an accurate assessment of the state of the project and because self-imposed secrecy prevented it from either hiring an impartial engineering firm for technical advice or taking punitive measures after the fact.

How Hard Could It Be?

Even after the obstacles have been enumerated, an observer might be forgiven for thinking that once a proliferator has imported a missile or a centrifuge or whatever, most of his problems have been solved. Such a misconception may be quickly dispelled by the story of Iraq's initial attempts to increase the range of SCUD missiles, the first step in its eventual effort to reverse engineer the missile.[4] This occurred in 1986, during the Iran–Iraq War. Iraq imported some eight hundred SCUDs in the course of that conflict, but although it had already fired off quite a few of them by that point,

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[2] A mycotoxin is any poisonous substance produced by fungi, which includes alfatoxin.

[3] The Pershing II is a solid-propellant missile with increased range and accuracy that was deployed in Europe starting in 1983. This deployment is generally considered one of the major reasons why the Soviet Union negotiated and signed the Intermediate-Range Nuclear Forces (INF) Treaty. Importantly for Iraq, some of the Pershing II's components were made in Germany, and eventually some of the engineers from Messerschmitt-Bölkow-Blohm who had been involved in that production left to form their own company to sell the technology abroad.

[4] The SCUD family of missiles, originally developed by the Soviet Union starting in 1955, is a rugged, road-mobile, short-range (approximately 300 kilometers) liquid-propellant missile that has become ubiquitous throughout the Third World.

Saddam Hussein was not yet particularly concerned about producing more indigenously.[5] That would come later. In 1986, the Iraqis did not have to extrapolate the entire industrial infrastructure necessary to build a missile; they simply had to understand one well enough to make it travel farther.

Extending the SCUD's range became a political necessity when Iran began to bombard Baghdad with SCUD-B missiles in March 1985, touching off the so-called War of the Cities. Iran would eventually fire a total of 231 SCUDs against Baghdad, each carrying nearly a ton of high explosive. But Tehran was considerably farther away from the frontlines than Baghdad, and Iraq was incapable of answering the attacks missile for missile. Instead, the Iraqis had to retaliate with aircraft. While this was in all probability more cost effective, it did not seem as desirable politically, and there was always the risk that a plane might be shot down, with the resulting loss of prestige. Meanwhile, Iran appeared able to strike Baghdad with impunity.

Iraq first tried to import longer-range missiles from the Soviet Union, but Moscow declined, either because the Soviets did not want to assist Iraq in the middle of a war or because they had qualms about supplying such missiles to a foe of Israel. Iraq then began a program to extend the range of its SCUDs by reducing their payload of high explosive and increasing their fuel capacity. Theoretically, these were simple modifications. Practice proved more complicated.

The Iraqis first tested a reduced-warhead SCUD—a logical first step, since it allowed the engineers to try out the basic concept before lengthening the missile's fuel tanks. With its payload cut by 70 percent, they expected the missile to fly well past its 300-kilometer design range. Surprisingly, it traveled only 25 kilometers.[6]

Iraq had experienced firsthand one of the traps of reverse engineering: failure to understand the complexities of a design. For reasons known only to them, the original Soviet engineers had decided to require the output dial of the accelerometer—the device that determines the speed of the missile at any given instant—to complete two revolutions before shutting down the engines. Something had to keep the dial from shutting down the engine after a single revolution, however, and because it was a mechanical device the engineers used a timer—a blocking device that worked perfectly if the missile accelerated at the design rate. But decreasing the mass of the warhead increased the missile's rate of acceleration, causing the dial to make one full revolution sooner, so the timer, which was set to block engine shutdown at approximately thirty seconds into a flight, did not work. The orig-

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[5] UNMOVIC, "Unresolved Disarmament Issues: Iraq's Proscribed Weapons Programmes," UNMOVIC Working Document, 6 March 2003, 21. Available at http://www.un.org/Depts/unmovic/new/documents/cluster_document.pdf (accessed 19 July 2006).

[6] Ibid., 164.

inal engineers could presumably have come up with a different solution, but they did not, and the Iraqis had failed to discern this design "feature."

After the second such failure, the Iraqis did diagnose the problem. The significance of these two flights, however, must be understood in terms of their place in the development cycle. Iraq was not developing a working prototype during these tests; they made no attempt to extend the range far enough to reach Tehran. Rather, these were R&D flights, and the Iraqis were investigating the operation of the missile system as a whole—something that one might have expected they could skip for a reverse-engineering development path. The fact that they needed these tests is a statement not about Iraqi competence, but about how difficult reverse engineering is and an indication that it might not be as effective as it might at first seem. The Iraqis would encounter other production difficulties when they initiated Project 1728, with the aim of producing, not simply modifying, a SCUD engine. Project 1728 followed an approach used by other proliferators as well: the systematic replacement of one component at a time in an imported system. On the plus side, component-by-component replacement allows the proliferator to localize any problems, speeding their diagnosis and easing their solution. But it is a time-consuming method that draws out the period during which imports are needed, and it can seem inefficient and unnecessarily expensive.

As a first step in this project, the Iraqis attempted to reproduce a SCUD combustion chamber—where the missile's fuel and oxidizer are brought together to create thrust—while continuing to rely on an imported turbopump to push these chemicals together. The Soviets had developed an impressively simple design for the combustion chambers in both the SCUD and the SA-2 surface-to-air missile. (Eventually, under the constraints of UN Security Council Resolution 687, which limited the range of any missile it produced, Iraq would switch to the less powerful SA-2, or Volga, engine to power its ground-to-ground missiles.) It featured inner and outer shells of stainless steel, separated by a layer of corrugated steel. Either fuel or oxidizer flowed through the space between the shells, cooling the inner shell—which is exposed to combustion temperatures of nearly 3,000 degrees Fahrenheit—and preheating the "coolant," which increased combustion efficiency.

To reproduce this design, Iraq had to master the techniques of flow-forming the two shells to the required tolerances (after first determining those tolerances from a limited number of examples) and brazing all the pieces together. If the brazing operation, which must take place in a vacuum furnace, fails to establish a uniform gap between the inner and outer shells, there will be regions where insufficient coolant flows, and the inner shell can burn through where the shells are too close together. In fifteen years of working on liquid-propellant engines, the Iraqis failed to master the intricacies of this production process, as their illegal import of 380 Volga engines in December 2002—at the height of the world's attention—clearly shows.

Shop 'til You Drop

Missiles are, of course, mechanical weapon systems, and it might be expected that their development paths differ from those of chemical or biological weapons, which produce a bulk product. But as the Iraqi quest for the most deadly chemical weapons appears to show, it is possible to follow similar development paths for these types of weapons as for missiles or other intensively mechanical systems. In fact, Iraq appears to have tried all three of the paths outlined here in their chemical weapons efforts.

According to the Iraq Survey Group's *Comprehensive Report*, the Iraqis began research on the powerful nerve agent VX in 1985 with a literature search for published work on its synthesis and production.[7] While that is generally considered the official start of Iraq's chemical weapons program, the incident that eventually led Iraq to its mustard-production facility occurred some ten years before.

In 1975, the *Sunday Times* of London revealed that the British patent office had, a number of years earlier, approved and published the formula and method of synthesis for a whole family of organophosphate chemicals, including VX.[8] One of the more benign uses of organophosphates is as pesticides, and one such pesticide, amiton, bears a striking similarity to VX (fig. 1). While the patent covered the synthesis of both VX and amiton, the methods described were more suitable for laboratory-scale than industrial- or military-scale production. But the story, and the patent, did apparently start the Iraqis thinking about producing nerve gases, and within the year Iraq was exploring the purchase of a complete, industrial-scale plant for the production of amiton from the Pfaudler Corporation of Rochester, New York. Pfaudler is a major manufacturer of corrosion-resistant, glass-lined chemical-processing equipment vital to the processing of both modern organophosphate pesticides and chemical weapons; the firm also designs and builds complete chemical-processing facilities worldwide.

Iraq initially sought a pesticide-formulation plant, which would use imported concentrates. (Formulation involves mixing a pesticide concentrate with water, oil, or an inert solid, whichever is appropriate for a specific application.) While such plants need corrosion-resistant mixing tanks, they

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[7] Iraq Survey Group, *Comprehensive Report*, vol. 2, *Evolution of Chemical Warfare Program*, 15.

[8] "Terrorist's Deadly Nerve Gas Secrets Are Revealed," *Sunday Times*, 5 January 1975. I thank Brian Balmer for pointing this incident out. His account of the controversy surrounding the revelation of the V-agent patents, "A Secret Formula, a Rogue Patent and Public Knowledge about Nerve Gas: Secrecy as a Spatial-Epistemic Tool," will be published in a forthcoming issue of *Social Studies of Science*.

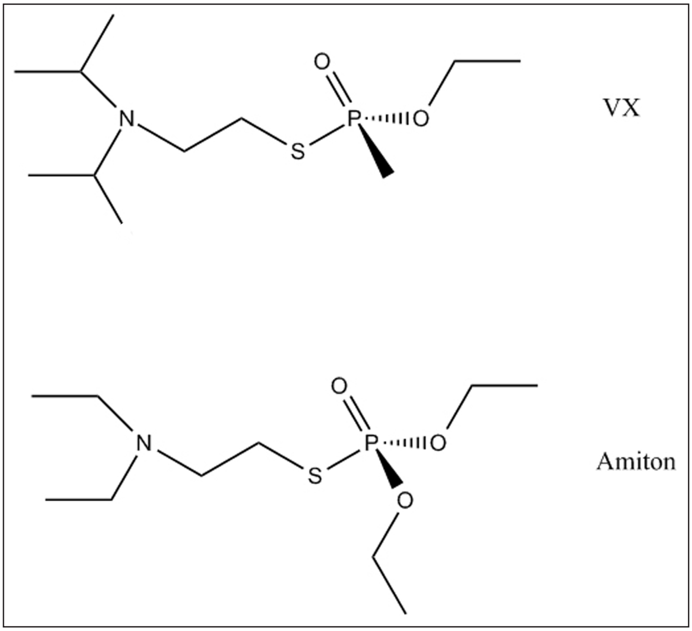

FIG. 1 The chemical structures of VX and Amiton.

are fairly simple and therefore relatively inexpensive; the original contract called for a plant valued at only $3 million in 2006 dollars.[9] But there were hints from the Iraqis that a more profitable request would soon follow, and by the end of the year they were proposing that Pfaudler build a production facility capable of producing 1,200 tons of pesticides annually, half of which would be amiton.

Even with outside experts building it, such a plant would require considerable skill and specialized knowledge to run. Pfaudler, aware of that fact, urged the Iraqis to first construct a smaller pilot facility so that their technicians could learn the production process without the difficulties and dangers inherent in large-scale operation. But the Iraqis insisted on the need to reach maximum production quickly, and as discussions wore on Pfaudler proceeded with the engineering and design work. But in mid-1976, Pfaudler concluded that it could no longer accept the risk to Iraqi technicians and backed out of the deal. Iraq, however, retained the specifications that Pfaudler had drawn up in the course of the year. The Iraqis approached another large chemical firm, Imperial Chemical Industries (ICI)—the company that had invented amiton and the other compounds in that family of agents—

[9] David Ignatius, "Iraq's Thirteen-Year Search for Deadly Chemical," *Washington Post*, 25 September 1988.

but ICI, citing the sensitive nature of the chemicals the plant would produce and perhaps mindful of the media uproar that followed the *Sunday Times* story on the V-agent patent, declined to become involved.

These first failures to purchase outright an industrial-scale plant that might be easily modified to produce VX did not discourage the Iraqis. Eventually they found a partner in the German firm Karl Kolb, which would go on to design and supervise the construction of five large research laboratories and the first Iraqi production facilities for tabun and sarin, two important nerve agents.[10] Iraq then duplicated several of those plants almost brick for brick, all the while transferring the knowledge it had obtained by observing their design and production and the skills Iraqi workers gained from their foreign advisors to an indigenously designed plant for producing mustard, the deadly blister agent introduced in World War I.

That Certain Something

Is obtaining the necessary equipment, then, the key to making weapons of mass destruction? Not to judge from the Libyan experience when that country attempted to acquire facilities for converting uranium ore to uranium hexafluoride, the vital substance needed for enriching uranium to bomb grade.[11]

Production of uranium hexafluoride is accomplished through a fairly complex and prolonged chemical process involving a number of steps, many of which employ very corrosive materials heated to high temperatures. A would-be nuclear-weapons proliferator must have considerable skills in both design and production to make the raw material he needs. Libya came to possess the first but not the second, and so became an illustration of the importance of shop floor knowledge.

Lacking domestic uranium ore deposits and therefore forced to import concentrated ore—the now infamous yellowcake—Libya focused on developing the processes downstream. In 1981, it launched a multipronged effort to acquire the theoretical understanding and the infrastructure that the next step in the chain of production, converting yellowcake to uranium hexafluoride, would require. Since it had signed the nuclear nonproliferation treaty the year before, Libya first requested assistance from the International Atomic Energy Agency (IAEA)'s Department of Technical Cooperation. The IAEA declined to assist with production but was willing to sponsor a small

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[10] Iraq Survey Group, *Comprehensive Report*, vol. 3, *Evolution of Chemical Warfare Program*, 6.

[11] Uranium hexafluoride, a chemical compound in which one uranium atom is bonded to six fluorine atoms, is used as feed material for many of the enrichment processes—including both centrifuges and gaseous diffusion plants—that separate the explosive isotope U235 from the more benign U238 that makes up roughly 99.3 percent of all naturally occurring uranium.

project training Libyan scientists in the underlying fluoride chemistry. Over the next nine years, Libyan scientists accumulated a theoretical understanding of the chemical processes involved in converting uranium into uranium hexafluoride and some experience working with foreign counterparts on uranium chemistry experiments, including the dissolution of yellowcake in acid solutions, small-scale purification of uranium solutions, and production of small quantities of uranium metal and uranium tetrafluoride. But it is important to distinguish the skills acquired by doing such experiments from those required to operate even a modest-sized pilot plant producing several tons of uranium per year. Simply put, it is the difference between a chemist and a chemical engineer.

Libya next sought to purchase from a Western European company the major components—buildings and equipment—of a facility capable of converting 100 tons of yellowcake to uranium tetrafluoride, an intermediate product in some methods of producing uranium hexafluoride.[12] Construction never began, nor was any equipment delivered, but the Libyans did end up with detailed specifications of buildings and chemical processes, which would have considerably advanced their understanding of the practical side of uranium fluoridation. Not only would the chemical processes have described the relevant operating parameters, but the building drawings would have supplied important operational information, such as vessel sizes, power requirements, needed utilities, and flow rates (through the sizing of pumps).

It is not clear from publicly available information why both this project and a subsequent attempt to obtain a complete uranium hexafluoride production facility from what is described as a "nuclear weapon state" failed. Libya has declared to the IAEA that it does not have any technical documents from its discussion with the second potential supplier. However, Libya could at the very least have used the second round of negotiations to verify the information it obtained the first time around and to further train its administrators in the process of purchasing a production facility. This latter benefit is far from trivial, as the number of engineering companies selling specifications-writing services to developing countries seeking turnkey plants of all kinds attests.

Libya's next attempt to procure a uranium-conversion facility was both qualitatively different and, it could be said, more successful. Instead of trying to purchase a production plant specified, designed, and built by a foreign supplier, Libya used the design information gained from its previous attempts to specify a facility and sought outside bids only for its construction. A Japanese company, whose name has yet to be publicly released

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[12] Each molecule of uranium tetrafluoride, or UF4, consists of one uranium atom and four fluorine atoms. While the United States does not use a uranium hexafluoride production path that has UF4 as an intermediary, some other countries do. Iran, for instance, uses a production path that has UF4 as an intermediary, and there is reason to believe that China does also.

by either the IAEA or the Japanese government, contracted to produce what are called "modular" conversion facilities: the plants were based on Libyan specifications and built in modular form in part to enable them to be moved around the country for "security reasons." But in the end these plants never processed uranium, at least in part because, the Libyans said, the supplier did not provide assembly or operating instructions. Libya, in short, had reached a point where it had sufficient theoretical understanding of uranium conversion and the knowledge necessary to design and specify a production plant—but not the shop-floor knowledge needed to actually run the facility they designed.

A Coming Sea Change

A recurring theme in the vignettes presented here is the complexity associated with obtaining weapons of mass destruction. A would-be proliferator must develop not only a weapon, which often uses some of the most advanced technologies, but also the tools and machines and skills needed to produce it in volume. Even when a proliferator grasps the scale of the task, his success will also depend on his perception of the relative importance of the various components. Some acquisition strategies are better adapted to this multifaceted task than others.

Consider one aspect of this equation, the relative importance of acquiring machinery and acquiring skills and tacit knowledge. The fate of Iraq's Badr-2000 missile project illustrates the significance of the latter: the Iraqis failed to assimilate the technology contained in factories they purchased whole because the contract was canceled before the shop-floor workers could be trained. Similarly, Libya might very well have acquired the skills needed to design uranium-conversion plants both by training scientists and by skillfully manipulating the bidding process, but it never was able to actually use the equipment.

Turnkey acquisition strategies often provide for including training right from the start. Of course, they can also leave a proliferator at the mercy of unscrupulous profiteers. In the Badr-2000 episode, Iraq had what amounted to fictive legal recourse—the contract detailed whose courts had jurisdiction over what disputes—with no hope of enforcement. Perhaps that is why the Iraqis tried to reverse engineer SCUD missiles soon afterward. Then, Iraq was able to bring in foreign experts as contract advisors, a much different power arrangement, and to visit foreign manufacturing plants. Yet it still failed to make engines on the scale necessary for military operations, and the problem again seems to have been the lack of shop-floor knowledge.

These observations are not relevant only to engineering-intensive fields such as missile production. Iraq was able to initially scrape by with an indigenously designed plant for the production of mustard, but more complicated nerve agents required massive outside assistance. And even Iraqi mustard production improved as general skills and know-how were transferred from those foreign-designed plants.

None of this is good news for the future of nonproliferation. There are always unscrupulous profiteers willing to sell the world's most dangerous technologies if the price is high enough. And much of the shop-floor skill and tacit knowledge we are talking about can be gained by honing general manufacturing capabilities. A machinist can just as easily learn to operate a flow-forming machine by making a tuba horn as a rocket nozzle; a technician can learn to control a fermenter to brew a vaccine as well as a pathogen; producing a nerve agent is not so different from producing a pesticide. As such beneficial knowledge spreads—and no one would deny a developing country the right to produce vaccines or refine its own agricultural chemicals—it will become that much easier for proliferators to find the necessary population of skilled workers already within the country.

We do still need our supply-side-oriented nonproliferation regimes to try to prevent crucial technologies from being shipped to countries that might abuse them. But those regimes need to adapt to a world that is rapidly modernizing. There are precision machine shops in Singapore and Malaysia, Brazil and Vietnam that can produce all the components needed for almost any weapon system. Instead of concentrating on preventing the shipment of individual pieces of equipment, our nonproliferation regimes must take a global view and track worldwide shipments, looking for correlations of suspicious items. New proliferators will still try to purchase turnkey facilities, just as they and other countries do to acquire civilian technologies. The correlation of such purchases on a global scale might be tracked by existing mechanisms, such as the Harmonized Commodity Description and Coding System developed by the World Customs Organization, if only someone was looking.