Written Testimony of Suzanne Berger

Professor of Political Science and Co-Chair,
MIT Production in the Innovation Economy Commission
Massachusetts Institute of Technology

Before the
Senate Committee on Banking, Housing, and Urban Affairs
Subcommittee on Economic Policy
December 11, 2013

Chairman Merkley, Senator Heller, members of the Subcommittee and Committee, thank you for the opportunity to testify today about the challenges and opportunities for rebuilding American manufacturing.

My presentation today builds on findings from two-and a half years of research at MIT on the role of manufacturing in getting innovation into the market place. The research was conducted by a group of twenty MIT faculty from disciplines ranging from engineering, social sciences, management, to biology. The United States is a powerhouse of new ideas, new technologies, new products and processes. Many people question, though, whether we need production capabilities located in the United States in order to reap the full benefits of these innovations in the form of good new jobs, strong companies, and sustainable economic growth. Many of the companies that have been most profitable over the past two decades are ones with R&D, design, and distribution in the U.S., but which outsource their manufacturing around the world. Without production capabilities in the U.S., can we generate new growth and jobs? Is this a model that would allow us to grow new industries in sectors like biotech, medical devices, and new materials where there seems to be a tighter connection between R&D and production? Can we even sustain innovation without manufacturing capabilities in the U.S.? The bottom line finding of our research is that manufacturing does play a vital role in commercializing innovation. To move our economy onto a trajectory of sustainable growth and creation of new good jobs, we need to bring innovation from across the country—from high tech start-ups, Main Street manufacturers, Fortune 500 companies—at greater rate and speed into the market. The critical policies to accelerate these processes are private-public partnerships to rebuild the industrial ecosystem.

At the time the MIT research began in 2010, pessimism about the future of production in the United States was sweeping across the country. Millions of manufacturing jobs had disappeared over a decade. People were questioning whether U.S. manufacturing could ever compete with Asian low-wage production. The trade deficit in advanced technology products was deepening—equal to 17 percent of the total U.S. trade deficit by 2011. It seemed that even high-tech sectors of industry were doing better overseas than here.

Everyone agreed that the U.S. needed a higher rate of good job creation, but no one seemed to know where jobs could come from. Could manufacturing jobs come back? The brightest corporate superstars, like Apple, were locating production abroad and still reaping the lion's share of profits within the U.S. Was this going to be the American model for the future? In emerging technology sectors, like batteries, solar, and wind, even when the startups were created in the U.S. out of U.S. innovations, commercialization of the technology was taking place abroad. What could Americans do to leverage their strengths in new science and technology to rebuild a dynamic economy? Would production capabilities at home be needed to capture the flow of benefits from invention and entrepreneurship? Which capabilities? And how could they be created and sustained?

The point of departure for the MIT Production in the Innovation Economy research was recognizing that innovation is critical for economic growth and for a vibrant and productive society. Our question was: what kinds of production do we need—and where do they need to be located—to sustain an innovative economy? As Professor Richard Freeman, a Harvard economist, has put it, a person knows it's a manufactured product when he drops it on his foot. But for most valuable activities today, the traditional line between "manufacturing" and "services" has become so blurred that it no longer serves to distinguish separable and distinct activities or end products. Whether in a giant like Apple or in a small Ohio company that makes half-sleeves to repair pipelines and sends its technicians along with the product to stand on the oil platforms and shout down instructions to the divers, the activities that create most value, that is, the ones that are most difficult for others to replicate, are bundles of an object you could drop on your foot and of services. We focused on those bundles, and we structured our inquiry to locate opportunities and dangers for American prosperity in the changes that have taken place over the past thirty years in the linkages between an innovation and the broad range of production processes that bring it to market.

There are many serious reasons to worry about the fate of manufacturing in the United States. Virtually every week brings a new report diagnosing the state of manufacturing and emphasizing different aspects of its critical significance for the economy. One of the key danger points identified in these reports is the declining weight of the U.S. in the global economy. Even though the U.S. share of world manufactured output has held fairly steady over the past decade, economists have pointed out that this reflects good results in only a few industrial sectors. And even in those sectors, what appear to be productivity gains may be the result of underestimating the value of imported components (Houseman 2010). A close look at the composition of a worsening trade deficit shows that even in high-tech sectors the U.S. has a deteriorating picture. While the output of U.S. high tech manufacturing is still the largest in the world and accounted for $390 billion of global value added in high-tech manufacturing in 2010, U.S. share of this world market has been declining, from 34 percent in 1998 to 28 percent in 2010, as other countries made big strides ahead into this market segment. Jobs are another huge concern. The great spike in unemployment over the past five years was disproportionately due to loss of manufacturing jobs. And as the economy revived, such jobs were slow to return. Many of them never will. Over the long postwar years of prosperity, manufacturing jobs had been especially valuable to workers and valuable for middle-class opportunity because they paid higher wages and had better benefits than other jobs available to people with educational qualifications of high school or less. New manufacturing jobs now often come with lower wages and fewer benefits attached. National security is also linked to the health of manufacturing through the procurement of new weapons and the maintenance and replacement parts for the many generations of equipment still in service. The wave of disappearance of many small- and medium-sized suppliers creates worrisome and still relatively unknown degrees of dependence on foreign suppliers for U.S. military contractors. Across the entire industrial landscape there are now gaping holes and missing pieces. It's not just that factories stand empty and crumbling; it's that critical strengths and capabilities have disappeared that once served to bring new enterprises to life. Economic progress may be preceded by waves of creative destruction, as Joseph Schumpeter claimed. But we need to know whether the resources that remain are fertile enough to seed and sustain new growth.

Today digital technologies and borders open to the flow of ideas, goods, and services make it possible to build international partnerships for bringing innovation into production and into the market. For U.S. innovators there are unprecedented new opportunities to draw on production capabilities that they do not have to create themselves. But there are also long-term risks in these relationships, and they go far beyond the loss of any particular proprietary knowledge or trade secret. The danger is that as U.S. companies shift the commercialization of their technologies abroad, their capacity for initiating future rounds of innovation will be progressively enfeebled. That's because much learning takes place as companies move their ideas beyond prototypes and demonstration and through the stages of commercialization. Learning takes place as engineers and technicians on the factory floor come back with their problems to the design engineers and struggle with them to find better resolutions; learning takes place as users come back with problems. And in the challenges of large-scale production, companies like 3M and Gillette find a terrain for innovation that allows them to reap higher profits.

There are reasons to fear that the loss of companies that can make things will end up in the loss of research that can invent them. When we visited the laboratory of MIT Professor Tonio Buonassisi, a leading researcher on solar cells, he pointed out all the leading-edge equipment that came from tool makers located within a few hours of Cambridge, Massachusetts. Much of the machinery had been made in close collaboration between the lab and the instrument companies as they handed ideas and components and prototypes back and forth. Used for the first time in the lab, these tools were now being marketed to commercial solar companies. The news on the U.S. solar industry was looking worse and worse as the economy stalled, as stimulus spending on renewable energy ended, and Chinese competitors hung in, despite losses and low margins. If the local equipment makers Buonassisi worked with were to collapse it would mean real trouble for research, for the scientist relied on working with them to make new tools faster for more efficient and cheaper cells. Even in a fragmented global economy with instant connection over the Internet to anywhere in the world, the ties that connect research in its earliest stages to production in its final phases remain vital.

The MIT Production in the Innovation Economy Study: Objectives and Methods

The approach of the MIT Production in the Innovation Economy project was to focus on one broad question: how production capabilities here and abroad contribute to sustaining innovation and realizing its benefits within the United States. We organized our research to discover what it takes to sustain innovation over time and what it takes to bring innovation into the economy. We approached these questions from multiple angles, looking at innovation in products, in processes, in combinations of products and services; at innovation in startups, in large multinationals, in Main Street small- and medium-sized manufacturers, in European and Asian partners and competitors, in hotspots for new technologies, like the biotech cluster of Cambridge Massachusetts, in traditional manufacturing country, like Ohio, and in new manufacturing areas in the Southwest, in Arizona, in China and Germany.

To retrace the pathways through which an invention or a new idea about a product or a way of improving a product or process get made into goods and services for sale in the market, much of our research was conducted in firm-level interviews. National Science Foundation statistics state that in 2006-8, 22 percent of all U.S. manufacturing firms reported "a new or significantly improved product, service or process" (NSF 2012) but we did not know what they were doing or how they were doing it. There is data, too, on the high-risk venture and corporate funding of startups, but no systematic account of how these firms find the full range of inputs they need on the road to commercializing their innovations. In the interviews with senior managers we could trace out in concrete detail the trajectories along which each company moved as it attempted to make its ideas into profits. Where did the company get the inputs it needed to bring innovation into production? Did it find these inputs at home or abroad? Where and why did it decide to locate each of its operations? Which parts of its production activities does it believe it needs to keep in close proximity to its R&D in order to bring a product to market and to maximize the gains from its own innovation? In the case of innovations growing out of existing process or product technologies, our interviews in companies allowed us to track interactions between the innovators and the manufacturers in great detail from the point at which the new idea came into play through production into the hands of customers.

In all PIE interviews (see Table 1) teams of MIT researchers raised basically the same questions, with wording adapted to the context and circumstances of each company. The interview template prompted each researcher to ask: *Tell us about two or three new ideas—new products, new processes, improvements on old products or processes—that you tried to bring to market over the past 5 years. What did you do to try to move it from the stage of being an idea (in a lab, in an R&D center, on the shop floor, in your head) into a product that was sold in the market? Where did you find the capital for the various stages of scale-up? Did you self-finance? Or get venture capital? Or bank loans? Or corporate partners? Where did you find engineers and workers with the right skills? Where did you find technical know-how? Where did you find suppliers? How did you decide what to do in-house and what to outsource? How did you decide where to locate production? What failed and why? What policies make a difference for a company like yours?*

Table 1 PIE Interviews

China	36
France	2
Germany	32
Israel	1
Japan	8
Sweden	2
Switzerland	3
United Kingdom	2
United States →	178
Total	**264**

Arizona (11)	*Michigan (1)*
California (16)	*New Jersey (3)*
Connecticut (2)	*New York (12)*
DC (2)	*North Carolina (14)*
Delaware (1)	*Ohio (37)*
Georgia (12)	*Oregon (1)*
Illinois (2)	*Pennsylvania (9)*
Iowa (1)	*South Carolina (2)*
Kentucky (1)	*Washington (1)*
Maryland (2)	*Wisconsin (1)*
Massachusetts (47)	

The first group in our interview population were American-based multinationals that figure among the largest global investors in R&D. Ten of the firms in our sample rank in the top 100 of the Fortune 500 companies. Over the past thirty years these companies have changed from almost entirely U.S. based operations to organizations carrying out R&D and production around the world.

A second research focus was the population of new companies that grew out of patents that had been created in MIT laboratories and licensed by the MIT Technology Licensing Office over the years 1997-2008. There were 189 of them. The researchers set aside the pure software start ups and zeroed in on the 150 companies that were engaged in some form of production. These are starts-ups that are especially well-positioned to succeed, because they emerge from very strong research labs, because they take their first steps in the world in an extremely dynamic regional hub of innovation with many complementary resources in close proximity, and because they have far better access to early-stage high risk capital than do firms in much of the rest of the country. At those points in the scale-up process where these firms, even with all their relative advantages, find serious difficulties in obtaining the inputs they need for getting their products into the hands of customers, we can anticipate that the "average" new American firm based on innovative technologies will also be having trouble, so there are important lessons to be learned from their experience. There are, of course, many reasons firms might fail to find resources to scale-up, relating to the market, or competitive landscape, or the product, or management.

Table 3: *MIT TLO Licensed Startups 1997-2008**

Industry	# of firms started	Percent of total	Percent receiving SBIR	Percent receiving venture capital*	Percent operating^	Percent closed	Percent merged
Advanced materials and energy	15	10	40	33	73	27	0
Biopharma	58	39	36	59	55	26	19
Medical devices	31	21	39	52	65	3	32
Robotics	5	3	60	0	60	20	20
Semiconductors and electronics	26	17	31	85	62	19	19
Other	15	10	33	33	47	27	27
All production companies	150	100	37	55	59	20	21

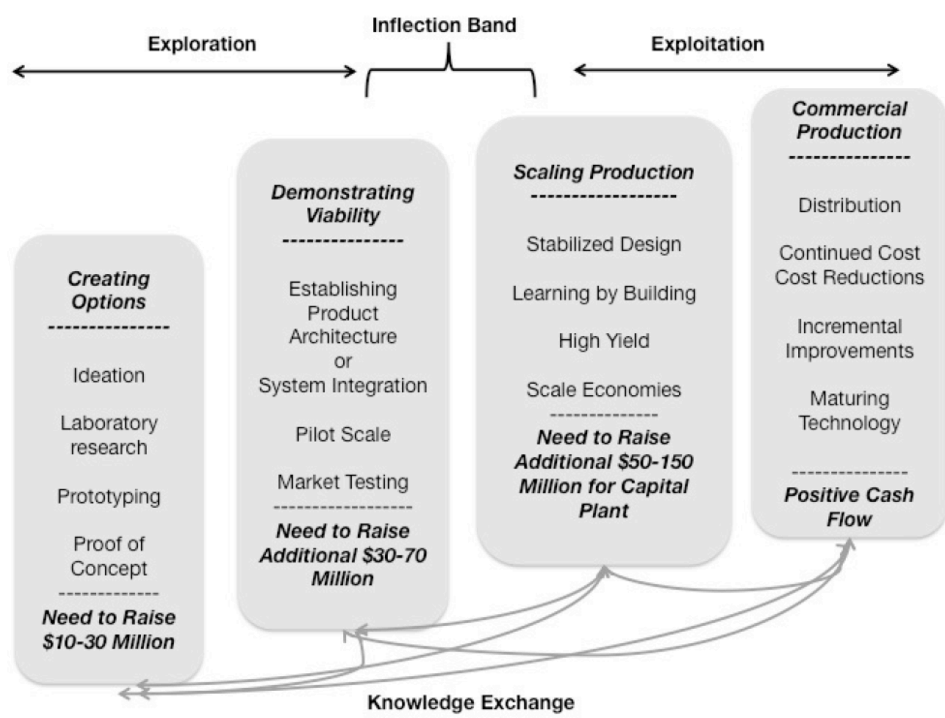
*Reported by VentureXpert

^-As of June 2012

The research team learned that these highly innovative companies were usually able to obtain funding through relatively long periods (even up to ten years) of early phases of scaling up through early market demonstration. But many of them when they came to the stage of moving to full-scale commercialization could not find finance in the U.S. As many of them made the transition from venture funding to high-volume manufacturing, they had to look for foreign investors and often moved abroad to manufacture their products.

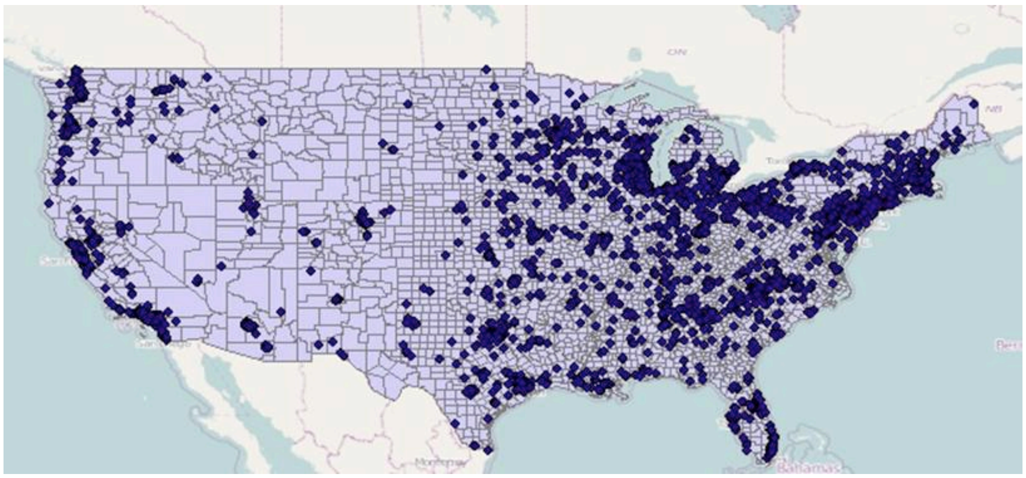
Figure 1: Scaling up

Adapted from Figure 2.1, "The four stages of energy innovation," page 11, in Richard K. Lester and David M. Hart, *Unlocking Energy Innovation: How America Can Build a Low-Cost, Low-Carbon Energy System* (Cambridge, Massachusetts; London, England: The MIT Press, 2011).



The third target population within the PIE company sample were small-and mid-sized U.S. manufacturers. To figure out how to raise the water-level of all kinds of innovations—product, process, service, incremental, radical, repurposing, business model—flowing into the economy, we need to look beyond Silicon Valley and Cambridge Massachusetts. PIE researchers started from the population of the 3,596 manufacturing companies in the U.S. which had doubled their revenues and increased head count between 2004 and 2008 and had more than $5 million in annual revenues and more than 20 employees. These companies were presumably *viable*, hence ones in shape to potentially carry forward new products and processes into the market. In Arizona, Georgia, Massachusetts, and Ohio we carried out interviews with 53 of these firms. To this group we added 43 similar firms that we discovered through other branches of our work.

Figure 2: Company locations of the 3,596 Main Street manufacturers with more than $5 million in annual revenues and more than 20 employees



Innovation is not only in patents. The novel activities of established small- and medium-sized manufacturers rarely correspond to the OECD's Frascati Manual and "Oslo" definitions of "research and development." But there's also a hidden wealth of innovation in process, business organization, and manufacturing across America in firms of all sizes. Some have leading-edge innovations (and patents). But for most Main Street manufacturers, the major innovative activity is repurposing technologies developed in one sector for uses in different products and processes. A third-generation CEO of a Midwest company that makes steel components, for example, told us of developing special lighter steel he had used in construction and experimenting with bringing it into new work he was doing in defense contracting. For an important group of Main Street manufacturers, their role in innovation is as suppliers providing vital components and services to enable scale-up in other companies. One such company, Mass Tank in Middleboro, Massachusetts, exemplifies the pattern. It's a fifty-employee firm that does its main business in fabricating tanks and selling tank inspection services for chemical, food, pharmaceutical, and water industries. But it is also working with five start-ups in the region and going back and forth with their engineers developing new materials and components that may someday be part of a blockbuster new product that Mass Tank will have helped these innovators to bring to market. In these suppliers, the greatest strength is a combination of design and fabrication capabilities.

But even the strong Main Street manufacturers we studied were not growing fast and were not creating many new jobs. Much of the reason why, we discovered, was that all scale up of new ideas depended on their internal resources. They were not finding any complementary capabilities they could draw on in the industrial ecosystem as they tried to develop new components. There are few local banks with local knowledge left in the U.S. to fund such scale up. Connections with community colleges, trade associations, research consortia are weak or not present. All these resources are plentiful on the landscape of German companies. As we wondered why the contributions to innovation of the Main Street manufacturers did not lead to greater profits and faster growth, the comparison with Germany was inevitable. An Ohio machine toolmaker is not going to take off like Microsoft or Facebook, but there are great underexploited possibilities for such firms also. We considered what it would take to galvanize more innovative activity within Main Street manufacturers, a faster uptake of new technology, and a tighter enabling connection with new start-ups across the economy.

The fourth group of firms in the PIE sample were foreign: mainly German and Chinese. Germany is one of the world's richest and most advanced industrial societies. China is still a poor-to-middle income country with rather low productivity and few companies that compete in world markets on the basis of unique products or processes. Yet both of these very different countries have companies that are world-beaters in scaling up innovation to market. In both Germany and China we found compelling examples of innovative manufacturing and scale-up that challenged many of our ideas about why innovative companies in the U.S. so often falter before attaining the size and capacity to reach large numbers of customers. The strength of German companies goes well beyond defending niches against low-cost competition with incremental advances. They create new businesses through the transformation of old capabilities and their reapplication, repurposing, and commercialization. The U.S. Main Street manufacturers we interviewed usually had only their own material, human, and financial resources to draw on when they tried to scale-up an innovation. They are "home alone." In contrast when the German firms expand into new sectors, they draw not only on strong legacy resources, but also on easy access to a rich and diverse set of complementary capabilities in the industrial ecosystem: suppliers, trade associations, industrial collective research consortia, industrial research centers, Fraunhofer Institutes, university-industry collaboratives, technical advisory committees. The differences in the density and availability of resources in the German and U.S. ecosystems explain much of the differences between the fate of manufacturing in the two countries.

The China interviews showed firms emerging with remarkable innovative capabilities in manufacturing. China's great initial assets were cheap factor prices—cheap land, labor, capital and an undervalued currency. Low-cost labor allowed Chinese companies in apparel and footwear to make huge inroads in Western markets. But today the PIE research team found Chinese firms in emerging industries like renewable energy. These are firms that excel in scale-up to mass manufacturing not because of low-cost labor, but because of their ability to move complex advanced product designs into production and commercialization. The huge China market is of course a major draw for investors of all nationalities. But even in those industries in which the main customer markets are still in the West, as for consumer electronics, photovoltaic cell and module production, American and European innovators are turning to Chinese partners. Increasingly the reason is the solid capabilities in knowledge-intensive scale-up they find in China. These capabilities involve reverse engineering and re-engineering a mature product to make it more rapidly and efficiently; making designs into new-to-the-world products and processes; and indigenous product innovation. In each of these categories PIE researchers interviewed Western companies and their Chinese partners and walked through the Chinese plants with engineers to track how exactly innovation was being produced.

Two other research groups formed within PIE to analyze critical inputs to bringing innovation to market: jobs and skills and advanced manufacturing technologies. For these research modules, the project used surveys as well as interviews. The group working on jobs and skills talked with companies, community colleges, high schools, and labor market programs across the country. Their sample of close to 900 manufacturing establishments is the first nationally representative data on what skills are needed and shortages occur. Since production workers account for over 40 percent of all those employed in manufacturing, the team focused on whether there is a shortage of skills in this population, as many have claimed. What skills do your workers need? employers were asked. Basic reading, writing and math? To use a computer? To work in teams? To take independent initiatives? Have skill requirements increased significantly over the past five years? How long does it take to identify and hire the right candidate? The median answer was four weeks. Just under 20 percent of the establishments had some long-term vacancies (over three months) equal to five percent or more of their core production workers. The analysis drilled down into the job categories and firm types where there do seem to be problems finding candidates with the right skills. The problems centered in jobs requiring skills not generally available in the region; jobs requiring advanced math skills; and very small companies. Further probing showed that firms with few or no connections to other companies in their area and few or no connections to local schools also had more hiring issues. The research group conducted interviews in regions with programs that have brought together industry, schools, and government funding to work on these problems with some success.

The team working on advanced manufacturing technologies queried engineering colleagues across the country in order to try to locate the potential sweet spots for technologies that could radically speed up the passage of new goods and services from the lab bench to market. Using the surveys and interviews, the team identified and ranked the promise of seven major technology groups. These technologies could accelerate growth and energy efficiency by transforming manufacturing. Today, manufacturing is a lengthy and often inefficient process in which the raw materials which nature provides are pushed through stages of fabrication, assembly, and warehousing and emerge as goods for sale in the market. In a future which new technologies could enable, manufacturing might become a rapid process in which human-designed and engineered materials would be pulled by demand through continuous manufacturing and customization to meet specific and differentiated human needs. Today manufacturing remains highly centralized and concentrated in large factories and components and finished goods are transported at great cost and with high impact on the environment through long supply chains. Trends to offshoring and outsourcing have made manufacturing plants bigger and the distances goods traverse even longer. Tomorrow we can imagine technologies that would "destroy the tyranny of bulk" and distribute manufacturing, thus making it possible to manage capacity and demand flexibly through networks of small, localized manufacturers linked by Internet.

The Great Transformation: The New Corporate Structures of the American Economy and the Origins of the Production Problem

Fifty years ago, at the high water mark of American economic dominance in the world, 29 percent of U.S. workers were employed in manufacturing (January 1960), wages of the manufacturing workforce had been rising for decades, and innovation and manufacturing moved together in lockstep to produce a vast new stream of products for the market. Invented in the USA meant made in the USA. New products were first scaled-up, standardized, mass produced, and brought to high levels of performance and reliability in the advanced industrial countries in which they were invented. Only when production matured and the good became a commodity did manufacturing shift to less-developed countries with less-skilled workers.

Today invented in the USA no longer means made in the USA. Given the capabilities that now reside abroad, the next generations of consumer electronic products designed in the U.S. are likely still to be made in Asia—even if wages continue to rise there. In some industries today, it would be very difficult to do early-stage manufacturing in the U.S., because the technical expertise, the workplace skills, equipment, and the most advanced plant lay-outs are no longer present in the country or have degraded and fallen behind state-of-the-art elsewhere.

It's not only in "mature" industries like apparel that manufacturing has moved overseas. It's in newer sectors, like solar cells, wind turbines, and batteries. In the past chip design and chip fabrication had to be carried out within the four walls of the same company; today chip designers can send files of digital specifications to semiconductor fabrication plants anywhere in the world for production. Apple can define, design, and distribute iPods and iPhone and iPads in the U.S. without having any significant production facilities here at all.

How did this new global economy of fragmented research, development, production, and distribution come into being? What does it mean for the future of the U.S. economy? There were multiple causes of this transformation including many taking place outside the

U.S., like the rise of emerging market competitors and large new consumer markets. But what stands out in the PIE analysis is the impact of a tectonic shift in corporate ownership and control that took place well before globalization or Asian development had come into full play. The driver was financial market pressure for higher quarterly returns from companies that were less diversified, "asset-light," and organized around core competence. From the 1980s the large vertically-integrated corporations that had long dominated American manufacturing began to shed many of their business functions from R&D and design through detailed design to manufacturing and after-sales services. These activities had all once been joined under one corporate roof. By 2013, however, very few large American companies remain with vertically-integrated structures. Companies like General Electric or Procter & Gamble with a wide range of different businesses under one corporate roof and a predominant preference for integrating research through production are the exception.

First among the business functions that companies started moving out of their own corporate walls was manufacturing—for that shift produced reductions in headcount and in capital costs that stock markets immediately rewarded. Advances in digitization and modularity in the 1990s made it possible to carry out this strategy and to outsource production to manufacturing subcontractors like Flextronics and Jabil and eventually to foreign suppliers and contractors like Taiwan Semiconductor Manufacturing Company, Quanta, and Foxconn.

Out of those changes in corporate structure have come not only great new opportunities, but also some of the most difficult hurdles we face today in trying to move U.S. innovation into the market. Here we can only list some of these challenges:

- Vertically-integrated enterprises used to organize and pay for educating and upgrading the skills of much of the manufacturing workforce. They had the resources to do this. And long job tenure meant companies could hope to recoup their investment over the course of the employees' careers. Many of the employees who were trained in big companies or in vocational schools they supported ended up working for smaller manufacturers and suppliers. Today, American manufacturing firms are on average smaller, and have fewer resources. They do not plan to hold on to their employees for life. They cannot afford to, or, in any event, do not, train. How do we educate the workforce we need?

- Vertically-integrated enterprises like AT&T used to support long-term fundamental research in centers like Bell Labs and Xerox PARC and Alcoa Research Lab, each employing thousands of scientists and engineers. As corporate structures have been resized, basic research has been drastically cut, these centers have mostly disappeared, and corporate R&D is now far more tightly linked to the near-term needs of the business units. How should we fund a strong stream of basic and pre-competitive research today? If much cutting-edge research no longer is taking place within companies—but in universities or small start-ups or in government labs—how can we propel these innovations through to commercialization? How can we diffuse new technologies into established companies?

- When innovation grew out of large firms, they had the resources to scale up to mass commercialization. In the thirties, a corporation like DuPont not only invested for a decade in the fundamental research that led to nylon, but once the lab had a promising product, DuPont had the capital and the plants to bring it into production. Today, when innovation is more likely to emerge in small spin-offs or out of university or government labs, where do the scale up resources come from? How available is the funding needed at each of the critical stages of scale up: prototyping, pilot production, demonstration and test, early-manufacturing, full-scale commercialization? When scale-up is funded mainly through merger and acquisition of the adolescent start-ups and when the acquiring firms are foreign, how does the American economy benefit? How do American taxpayers who paid for much of the research at the origin of the process benefit?

- Big American corporations used in effect to provide public goods through spillovers of research, training, diffusion of new technology to suppliers, and pressure on state and local governments to improve infrastructure. These spillovers constituted "complementary capabilities" that many others in the region could draw on, even if they had not contributed to creating them. As the sources of these "complementary capabilities" have dried up, large holes in the industrial ecosystem have appeared. How can these capabilities be recreated and sustained in order to maintain a terrain favorable for innovation?

As the PIE researchers looked across the interviews and surveys we carried out in the project, we saw the holes in the industrial ecosystem as the single most challenging obstacle to creating and sustaining production capabilities in the United States that enable innovation to come to market. What we have come to think of as "holes" might be less picturesquely described as "market failures" or as absence of "complementary capabilities" that companies can draw on to supplement their own resources when they seek to develop their new ideas. These holes in the industrial ecosystem are ones that have been hollowed out by the disappearance of large numbers of suppliers under pressure from global competition and by the disappearance of local capabilities once provided by large corporations as part of their own business operations. As national banks have bought up local banks, local bankers with intimate understanding of local manufacturing have become an endangered species—making it harder to get bank loans. Critical suppliers have dwindled in numbers. In small firms as well as large defense contractors, we found companies considering the costly option of internalizing some of the functions their suppliers currently perform, for fear that what's become a single-source supplier will go out of business. These are concerns even for current production. But the difficulties are far more challenging when a company seeks to develop a new or improved product or process. New inputs are needed, like different skills, finance, and components that firms cannot efficiently produce all by themselves. Even startup companies with great novel technologies and generous venture backing cannot do it all in-house: they need to find suppliers, qualified production workers and engineers, expertise beyond their own. Established Main Street manufacturers in the regions we visited find little beyond their own internal resources to draw on when they seek to develop new projects. They're "home alone." This environment is far different from that of the German manufacturers we interviewed who are embedded in dense networks of trade associations, suppliers, technical schools, and applied research centers all within easy reach.

What's to be done? Pathways for growth

There is much work to be done on all fronts to renew the production capabilities that the United States needs in order to gain full value from its innovation. The PIE research, however, points to one objective as most urgent: rebuilding the industrial ecosystem with new capabilities that many firms of all kinds could draw on when they try to build their new ideas into products on the market. New research suggests that it's the colocated interdependencies among complementary activities, not narrowly specialized clusters, that over time produce higher rates of growth and job creation, and they do so across a broad range of industries, not just in high-tech or advanced manufacturing. The examples we have observed in the PIE research of trying to create public goods—or semipublic, or club goods—in the industrial ecosystem is the approach that may pay the greatest dividends.

The cases we have studied in detail are extremely diverse, but the institutions they have set in place involve a few common principles. The key functions that such mechanisms perform are convening, coordination, risk-pooling and risk-reduction, and bridging. They are public goods that the market does not generate. There are initiatives in which a private company or a public institution performs a *convening function*. The initiative usually starts with the "convenor" putting new resources on the table for use by others on condition that they too contribute to the pot. One well-known example is the SEMATECH Consortium that the semiconductor manufacturers and equipment makers formed in 1987 with financing both from the U.S. federal government and industry. SEMATECH today functions with funds from its members. By bringing companies together for roadmapping next generation chips, SEMATECH reduces the costs and risks of each company as it moves along the Moore's Law trajectory. New York State's investments in new fabrication facilities and new nanotechnology research in upstate New York at the College of Nanoscale Science and Engineering at the State University of New York, Albany, create common resources that the industrial partners can use.

Another example came from our Ohio interviews: the Timken Company, a manufacturer of tapered bearings and of specialty steels, initiated a partnership with the University of Akron and transferred Timken's coatings laboratory, its equipment, and several of its key researchers to the university. With resources from the company, the university, and the state, new graduate degree programs are starting; a new consortium on coatings and engineered surfaces has been created that is open to other corporate members; and a set of promising coatings technologies that had been "stranded" in a bearings company can now be developed as potential start-ups in which both the university and the corporate consortium members can invest. Potentially, companies from outside the region might join, but much of the value from participation will derive from face-to-face presence in the labs at the University of Akron, from being able to use university labs (funded at least in part with public money) instead of keeping these facilities in-house, and from the chance for local companies to hire graduates. In these cases the "convenors" hold out the lure of the use of common facilities and expensive equipment and training and proximity to cutting edge researchers. In contrast to tax breaks, which many states hand out, new resources are embedded in institutions that do not stand or fall on the participation of any one member.

Sometimes the lead in creating new *coordination* was taken by a private company. In other cases, coordination comes from a public intermediary. In Springfield, Massachusetts, the Hampden County Regional Employment Board (REB) is mandated by federal job training legislation to work with firms, localities, and educational institutions in the operation of the Workforce Investment Act. When the local machining association faced a shortage of skilled workers as the result of the closing of several large companies that had previously trained apprentices, it approached the REB. The REB brought the firms together with five vocational high schools and two community colleges. The connections between the schools and the companies had been thin and intermittent. With active intervention from the REB, the parties started to work on curriculum development; on training programs for supervisors and for unemployed workers; on organizing career fairs and firm visits to encourage high school students to consider machining jobs; and the gaps began to close.

Risk-reduction and risk-pooling are among the original functions for all forms of insurance and standard setting, and virtually all trade associations develop these functions to a greater or lesser extent for their members. For example, as we traced out the network mentioned above that connects Mass Tank to start-up companies in the New England region, we discovered that Mass Tank itself depends on a trade association, the Steel Tank Institute, for standards, testing, expertise, and insurance. The dangers of leaky tanks create enormous potential hazards—and lawsuits—and no small company on its own could afford adequate insurance from the regular insurance market. By working with the Environmental Protection Agency to develop safety standards, the Steel Tank Institute has been able to offer its members technology, testing, and insurance that covers them.

These very old uses of association for risk-pooling today are being put to new purposes in harnessing them to innovation and to commercializing innovation in the United States. The first of the National Manufacturing Innovation Institutes, the National Additive Manufacturing Innovation Institute (NAMII) in Youngstown, Ohio, offers companies, universities, and government agencies a way to distribute the risks of investing in new technologies while still deriving many of the potential benefits. As one industrial partner from a metal-working company expressed his perception of the risks: "We don't make plastic toys, so we couldn't justify investing in-house in a technology like this that may just be a flash in the pan. But just suppose it does work out and we're not close enough to it to have a voice in shaping its development … what then?" For those firms that do already have proprietary stakes in additive manufacturing there are yet other risks, and some forms of association with NAMII can help protect against them. For a region like Northeast Ohio and Southwest Pennsylvania, there's the enormous promise of technologies that could revitalize many of the small and medium-sized manufacturers but no way of finding a single industrial champion that would have an interest in carrying the project. The gains from 3-D printing, if it ever succeeds in overcoming its many current limitations, would be harvested by a multiplicity of users across diverse industrial sectors. When gains from innovation are significant but distributed thinly across many firms, it's unlikely that any single one of them will invest enough to bring it to life. NAMII offers potential ways to induce collaboration and spread its risks that could bring a new technology to life and inject new vitality into the regional economy.

The cases we have described as exemplifying new approaches to rebuilding the industrial landscape are so new that we cannot know if any one of them will ultimately work or not. If we believe, nonetheless, that they have a real chance, it's because what's held manufacturing in the United States in the last resort—even as so much turned against it—was the advantage firms gain from proximity to innovation and proximity to sophisticated users. Even in a world linked by big data and instant messaging, the gains from colocation have not disappeared. If we can learn from these ongoing experiments in linking innovation to production, new streams of growth can flow out of industrial America.