National Science Foundation's Role in Additive Manufacturing

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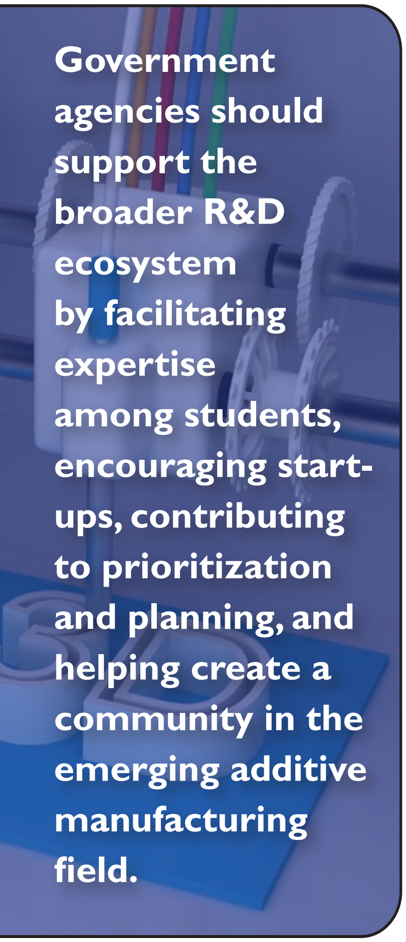
The Problem

To help the government promote emerging science and engineering at government institutions, the authors investigated lessons learned from the evolution of the additive manufacturing field and the role of U.S.-based funders (particularly the National Science Foundation) in its development and commercialization.

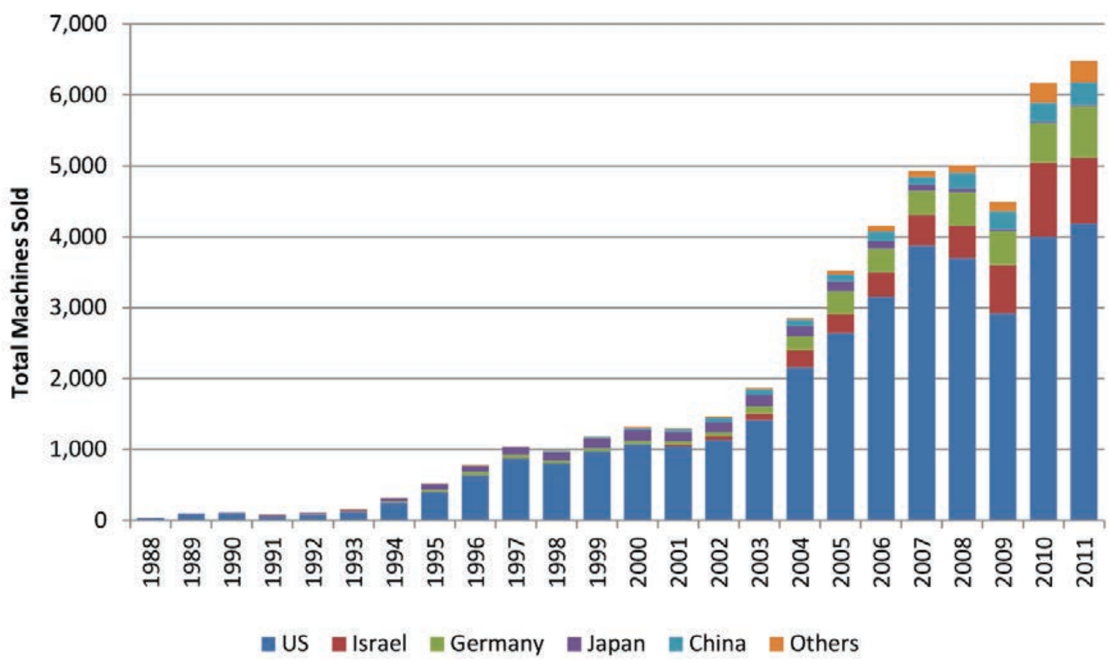


Government agencies should support the broader R&D ecosystem by facilitating expertise among students, encouraging start-ups, contributing to prioritization and planning, and helping create a community in the emerging additive manufacturing field.

Our analysis revealed that government funding to both academic and industrial researchers was instrumental in the origin and evolution of the field, with industry often leading the frontier. Three key lessons emerged for federal research and development (R&D) funding agencies: (1) provide consistent funding over long timespans, (2) support R&D and the transition of research from invention to proof-of-concept, and (3) bolster the ecosystem surrounding R&D.

Additive manufacturing (AM), also referred to as solid freeform fabrication or 3D printing, is a set of layer-by-layer processes for producing three-dimensional objects directly from a digital model. As of 2012, the AM industry had grown in the 20 years since its inception to a nearly $3 billion industry and is poised to reach an estimated $6.5 billion by 2019 (Wohlers 2012). The United States has been home to many successful AM companies, including 3D Systems, Stratasys, Z Corporation, and Solidscape. Figure 1 shows distribution of machine sales from 1988 through 2011. More than 70 percent of the professional-grade, industrial machines sold since the technology's infancy have been sold by U.S. companies; more than 60 percent of the total were sold by Stratasys, Z Corporation, and 3D Systems (Wohlers 2012). Other countries have been players as well, with European countries leading in development of metals and laser-based AM processes.

The history of AM technology points to the roles of various institutions—public funders, private entrepreneurs and inventors, universities, and others—in its development. We found that although researchers had captured portions of the history of AM through journal publications, books, and other resources, few had attempted to explicitly connect events and inventors to public support. Such a mapping reveals lessons learned for creating new fields and promoting innovation. The findings are derived from an examination by the authors and their STPI colleagues published in the IDA Paper titled *The Role*



Source: Data from Wohlers (2012).

Figure 1. Total Machine Sales by Company Aggregated to Country of Ownership

of the National Science Foundation in the Origin and Evolution of Additive Manufacturing in the United States. That 2012 report focused on the NSF's role in the technology's development. This article summarizes the findings and lessons learned with the goal of identifying, nurturing, and promoting emerging science and engineering at government institutions that have mandates related to advancing public good.

Terminology

Standard terminology outlined in 2012 by ASTM International, an international standards-setting body, is used when referring to AM processes, except when the inventors' original process names provide clarity or historical context (ASTM F2792-12a 2012). The seven AM processes include binder jetting, directed energy deposition, material extrusion, material jetting, powder-bed fusion, sheet lamination, and vat photopolymerization.

Methods

Information was gathered from a literature review, structured discussions with experts, analysis of the AM patent landscape and history, and analysis of various types of NSF program awards (Table 1) to identify the most important advances in the field and trace them to the institutions involved in developing them.

The paper examined six case studies and the role of the NSF in specific AM developments (Table 2). We identified the top 100 patents and four foundational patents based on

Table 1. Methods, Data Sources, and Description of Purpose

	Method	Data Sources	Purposes
Qualitative	Literature review	>100 peer-reviewed journals; textbooks; conference proceedings; workshop, task force, and industry reports; and patents	• Understand origins and development of AM • Search for references to historically important patents
	Structured interviews	25 AM experts: • 8 U.S. academic • 5 industry • 9 federal government, including 3 NSF program managers • 3 non-U.S. researchers	• Understand opinions on historically important events, technologies (patents), people, institutions, and networks • Identify opinions of NSF's role in AM
	Case studies	Cases on 6 technologies/patents: • 4 foundational patents (citations from literature, patents, and interviews) • 2 patents with known NSF impact	• Understand the development of specific AM processes, in depth • Identify NSF influence through patent analysis (including cited/citing patents)
Quantitative	AM patents	3,822 U.S. patents from 1975 to 2011 (identified Rapid Prototyping Patent Database[a] and metadata—assignees, cited patents, etc.—from U.S. Patent and Trademark Office)	• Analyze trends and growth in AM technologies through patenting activity • Identify highly influential technologies (highly cited through patent citations)
	NSF awards	593 awards from 1986 to 2012 (identified through 165 culled keywords)	• Analyze trends in number of awards, funding, NSF directorates, and topics

[a] Rapid Prototyping U.S. Patent Database available online.

AM, additive manufacturing; NSF, National Science Foundation.

Table 2. Four Foundational and Two NSF-Impacted AM Patents and Processes

	AM Process	U.S. Patent Number and Title	Inventor(s)	Application Year
Foundational	Vat photopolymerization	4575330: Apparatus for production of three-dimensional objects by stereolithography	Charles Hull	1984
	Powder bed fusion	4863538: Method and apparatus for producing parts by selective sintering	Carl Deckard	1986
	Material extrusion	5121329: Apparatus and method for creating three-dimensional objects	S. Scott Crump	1989
	Binder jetting	5204055: Three-dimensional printing techniques	Emanuel Sachs John Haggerty Michael Cima Paul Williams	1989
NSF-Impacted	Sheet lamination	4752352: Apparatus and method for forming an integral object from laminations	Michael Feygin	1987
	Contour crafting	5529471: Additive fabrication apparatus and method	Behrokh Khoshnevi	1995

expert feedback, patent citations, and a literature citation analysis from 29 review articles of the AM field. We analyzed two additional patents with known NSF influence in the AM field to further explore the role of NSF's support for research and technology developments.

Since AM is an application-oriented field, patent analysis, which is related more to technology breakthroughs than scientific and technical publications, was favored over bibliometric analysis as the primary analytic tool. We analyzed almost 4,000 patents extracted from existing databases, supplemented with U.S. Patent and Trademark Office metadata, including inventors, assignee organization, government interest, file and issue dates, and references both cited by the patent ("backward citations") and citing the patent ("forward citations"). In addition, we culled and analyzed almost 600 NSF awards relevant to AM that provided us with insight into NSF's historical support of AM.

Results

The analysis provided insight into industry's role in developing the AM field, the origins and evolution of leading technologies, the role of the government in specific seminal inventions, and the role of NSF in supporting AM research, technology development, networking, and coordination activities.

Industry Dominates Patent Development

The overall finding was that innovation in AM has been dominated by the private sector, especially when it comes to the total number of patents and the continual advancement of the technology beyond initial invention (Figure 2). More than 90 percent of the AM patents were held by firms during the 35-year period examined.

Trends in the Origins and Evolution of Leading Technologies

In analyzing the selected top 100 AM patents, we observed an initial phase of modern discoveries, which increased rapidly in the late 1980s. This period included the inventions from Charles Hull and the formation of 3D Systems, a current industry leader, as the company began to expand its patent portfolio. Carl Deckard from the University of Texas and later Scott Crump and Emanuel Sachs from the Massachusetts Institute of Technology (MIT) patented their seminal technologies around this same time. The late 1990s and onward was a period of continued process improvements, technology

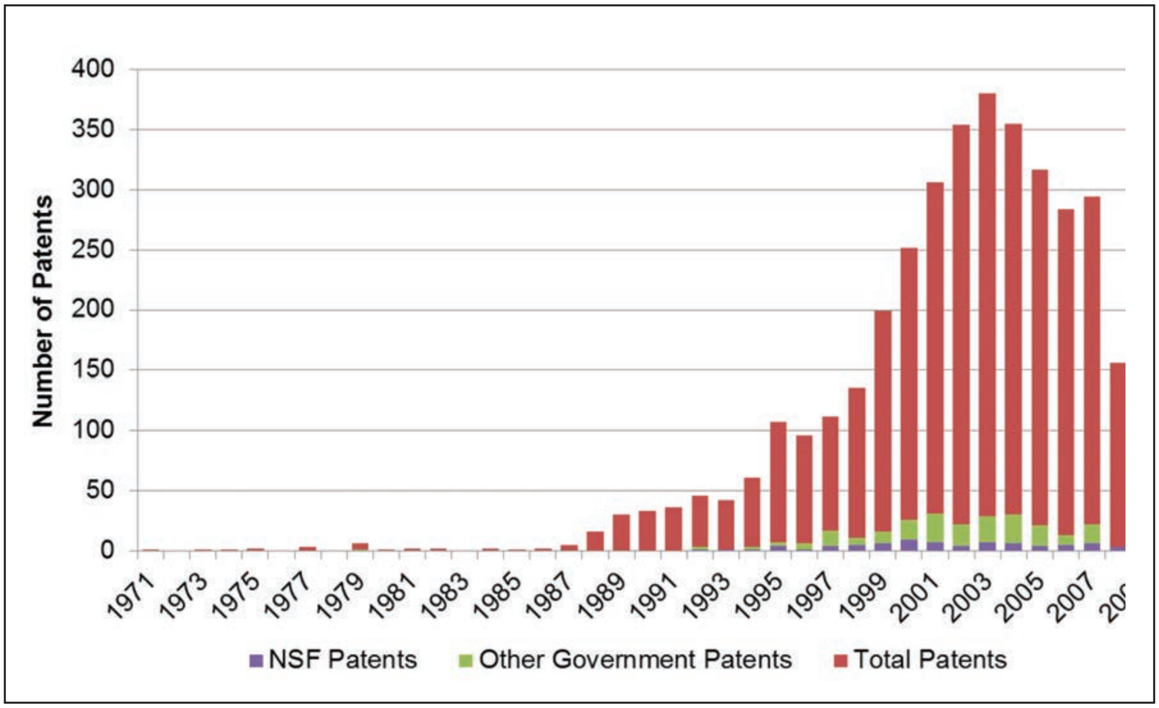


Figure 2. Industry Dominates U.S. Patents in AM

applications, and growth that resulted in establishment of leading companies in the AM market, including Stratasys (established by Scott Crump), Z Corporation (established by MIT graduate students based on Sachs' technology), and 3D Systems (Figure 3).

Small but Significant Government Role in the Development of the AM Field

The U.S. Government has played a small role in directly supporting AM patents that was critical in the early development of the AM field in the United States. After further analysis of the four foundational processes patented (Table 3) and two NSF-impacted processed patented (Table 4), the government's role was observed across three areas:

- Direct funding for developing early phases of the technology and later refinements in two of the four processes. NSF played a role in four of the six cases. In three of the processes—powder-bed fusion, binder jetting, and contour crafting (sheet lamination)—direct NSF funding supported the early R&D of the processes only after the inventors developed their initial prototypes. NSF funding included awards through the Small Business in Innovation and Research (SBIR) program and the Strategic Manufacturing (STRATMAN) Initiative. However, inventors, particularly those of powder-bed fusion and binder jetting, also leveraged investments from the academic and private sectors to improve upon and later commercialize their technologies. The government did not directly support the other two foundational patents, vat photopolymerization and material extrusion, which were fully developed by the private sector.

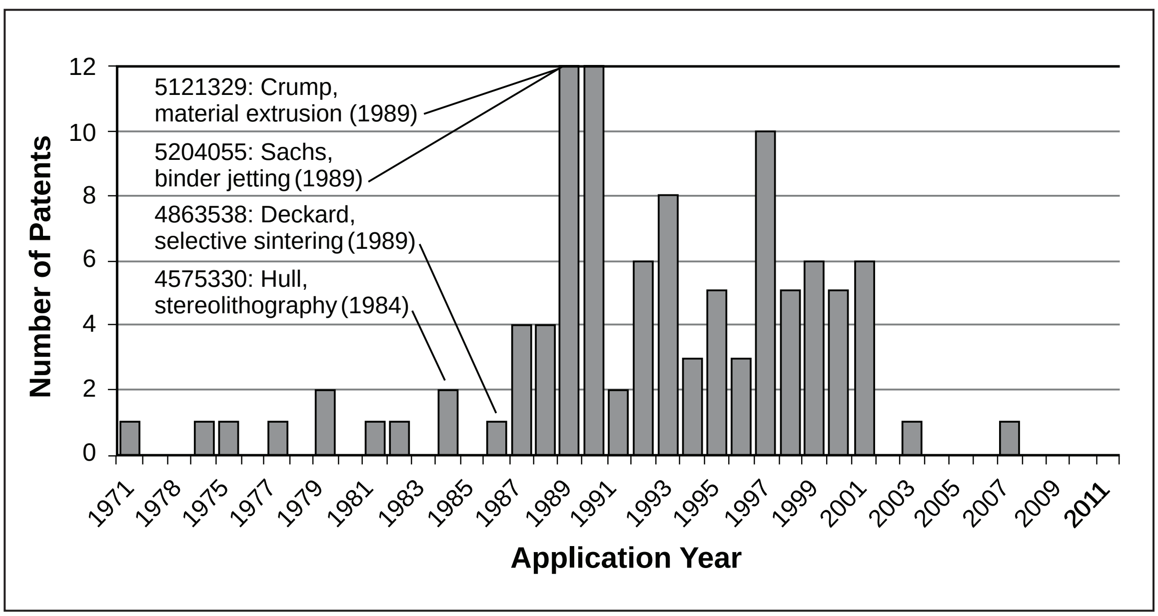


Figure 3. Top 100 U.S. Patents in AM, Including Four Foundational Patents

Table 3. Four Foundational AM Processes and the Federal Role

AM Process	Federal Role: Direct NSF Funding	Early Research	Knowledge Diffusion
Vat photopolymerization	None	Influenced by research, researcher later sponsored by DARPA	DOD, Navy/ONR, Air Force, DOE, and NSF supported diffusion of invention
Powder bed fusion	Early funding (e.g., seed funding) supported initial technology development Awards (e.g., small business and research awards) funded technology improvements	Influenced by work sponsored by DOD, Navy /ONR, and Air Force	DOE, DOD, Navy/ONR, Air Force, DARPA, NSF, NASA, and NIST supported diffusion of invention
Material extrusion	None	Influenced by work sponsored by DARPA and Deckard (possibly NSF supported)	DOD, Navy /ONR, NSF, NIH, and NASA supported diffusion of invention
Binder jetting	Role in early development; but only after a prototype was established Funding supported MIT graduate students and theses research Awards closely align with the time period of filing patents Support in later developments and improvements	Influenced by earlier research sponsored by NSF, Navy/ONR, Army, and DARPA	Army, Navy/ONR, DARPA, DOE, NSF, NASA, NIST, and NIH supported diffusion of invention

DARPA, Defense Advanced Research Projects Agency; DOC, Department of Commerce; DOE, Department of Energy; HHS, Department of Health and Human Services; NASA, National Aeronautics and Space Administration; NIH, National Institutes of Health; NIST, National Institute of Standards and Technology; NSF, National Science Foundation; ONR, Office of Naval Research.

Table 4. Two NSF- Impacted Processes and Federal Role

AM Process	Direct Funding
Sheet lamination	DOE seed funding Two NSF small business awards supported the design and testing of an automated machine
Contour crafting	Three NSF research awards supported early research and later developments Navy/ONR, Army, and NASA funding supported later developments

- Support of early research that created the knowledge, technologies, and tools later adopted in the AM field and applied by inventors to develop foundational AM patents and technologies. The knowledge generated from federally sponsored R&D from the early 1970s influenced the patents filed in the 1980s and 1990s and later innovations. Observations from the backwards citations analysis of the foundational patents show that some of the earliest investors in AM were the Department of Defense Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA), which provided steady, continual streams of funding for both academic and industry-based researchers. NSF support was also instrumental in the development of early relevant AM research in the 1970s.

- Support of knowledge diffusion from the foundational patents to improve the technologies and develop new applications. The government leveraged and sponsored technologies stemming from the four foundational patents. For instance, in binder jetting, NSF supported patents stemming from the original patent and those developed by co-inventors for later applications of the technology, such as in tissue regeneration and medical devices.

NSF's Support for Research, Technologies, Networking, and Coordination Activities

NSF has provided almost 600 grants for AM research and other activities over the past 25 years, amounting to more than $200 million (in 2005 dollars) in funding. The NSF's Directorate for Engineering, its Civil, Mechanical and Manufacturing Innovation Division, and its precursors have provided more than two-thirds of those AM grants and more than half of the NSF's total funding support of AM. The Civil, Mechanical and Manufacturing Innovation Division's STRATMAN Initiative provided five early grants amounting to about $3.5 million (in 2005 dollars), and two of the five grants were critical to two foundational patents in the AM field for powder-bed fusion and binder jetting.

Other NSF awards supported education, benchmarking, and roadmapping activities that are critical for the private sector but not funded by industry. Experts interviewed remarked that the 2009 Roadmap for Additive Manufacturing conference co-sponsored by NSF and ONR was an important milestone for defining future research directions for the field, although some in industry felt that industry representation was not large enough. NSF and ONR have also supported student attendance at the Solid Freeform Fabrication Symposium held annually at the University of Texas over the past decade.

Discussion of Lessons for the Government

This research provides lessons for the NSF and other government agencies devoted to supporting knowledge generation and innovation. While the STRATMAN program was well received by the AM community, some of the academic experts interviewed, including those supported by this early program, were critical of the lack of consistency and strategic focus in the NSF's efforts to support AM. To the extent feasible, providing consistent funding with strategic intent would help the NSF sustain its support for emerging areas of science and technology. Providing a consistent strategy at the individual technology level may be difficult to execute, but it merits consideration.

With respect to creating breakthroughs in AM, industrial advances have often been more important than academic research. Of the four foundational AM patents, for example, two were developed within firms without any direct public funding. Analysis of the foundational patents showed that inventors leveraged resources and research from industry, academia, and government to commercialize certain technologies. Networking between industry and academia can be critical for the development of a field and could facilitate identifying areas of common research interests. The government should explicitly support these types of interactions. Funding agencies should support both industry and academia more freely, perhaps through programs that facilitate more seamless university-industry collaboration.

As the case study of contour crafting technology shows, not all AM research found sustained commercial success immediately. Research can also develop in unanticipated directions, eventually proving useful. This is highlighted in potentially ground-breaking work in large-scale construction and the growing application of AM in the manufacturing of aerospace and biomedical devices. The role of serendipity in research, as well as external factors such as new business models, standardization, and patent expiration, should not be underestimated. Therefore, government agencies should focus both on supporting the immediate application of research as well as a range of technological readiness levels with commercial potential in both the near and long terms.

The U.S. Government funded not only AM research in academia but also innovative small firms, conferences, roadmaps, standards development, and student training. Experts underscored the importance of this ancillary support, particularly the training of students who go on to work and innovate in the private sector. Case studies show that several NSF-funded graduate students played a critical role in the development of laser sintering and binder jetting research and patents. Government agencies should support the broader R&D ecosystem by facilitating expertise among students, encouraging start-ups, contributing to prioritization and planning, and helping create a community in the emerging AM field.

While the momentum of the past few years may suggest to some that AM has "arrived," the recent AM roadmap effort has revealed that such challenges as bringing down costs, developing new materials, furthering efforts for consistency and standardization, developing new computer-aided-design tools, educating engineers, increasing process speeds, and advancing biological AM (Bourell, Leu, and Rosen 2009) must be overcome before the technology can become mainstream. The federal government in general and the NSF in particular have an important role in each of these areas.

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