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Executive Summary

Additive manufacturing (AM) is growing rapidly as a field of research, as well as an emerging technology with the potential to revolutionize manufacturing. Firms in the United States are a dominant player in the field, selling over 70% of the professional-grade machines to date. This is a fitting time to look at the evolution of the field with a critical eye toward determining the roles of various institutions—public funders, private entrepreneurs and inventors, universities, and others—in its development. Accordingly, the Engineering Directorate of the National Science Foundation (NSF) asked the IDA Science and Technology Policy Institute (STPI) to examine the role of NSF and other U.S. Government agencies in the development and commercialization of AM within the United States. Ultimately, the goal was to discover what lessons can be learned about identifying, nurturing, and promoting emerging science and engineering at NSF.

Data and Methods

STPI researchers used a combination of data sources and methodologies to address the goal of the study. These included a review of the literature, structured discussions with experts, analysis of the AM patent landscape and history, and analysis of various types of program awards made by NSF. Our aim was to identify the most important advances in the field and trace them to the institutions (particularly NSF and the broader U.S. government) involved in developing them. In the process, we also conducted six case studies to look more closely at the role of NSF in these developments.

Since AM is an application-oriented field, patent analysis, which is more closely related to technology breakthroughs than publication, was favored over bibliometric analysis as the primary analytic tool. An analysis of almost 4,000 patents extracted from existing databases, supplemented with U.S. Patent and Trademark Office metadata, confirmed the obvious—that patents, given their significance in protecting intellectual property, are the domain of the private sector. Over 90% of the AM patents were held by firms during the 35-year period examined. A review of the 100 most important patents in the AM field, based largely on expert feedback and patent and literature citations, also showed that, while the government imprint was slightly larger than in the previous analysis, the organizations assigned the patents were still mostly firms.

We also identified four foundational patents in the AM field, also based on expert feedback and citation analysis, for more in-depth analysis. Here, the imprint of the government was significantly stronger. Two of the four patents were directly supported by the government, and the other two patents were strongly influenced by it. Further, government support of early research in the field can be traced back in each of the case studies. For instance, the knowledge diffusion from precursor processes and technologies from the early 1970s influenced the development of the four foundational patents in the 1980s–1990s and later innovations.

Findings

Our overall finding is 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. Still the government, particularly NSF, has played a role in the early development of the AM field as illustrated by the following points:

- Department of Defense: Some of the earliest investors in AM were the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA), which provided steady streams of funding for both academic and industry-based researchers.
- National Science Foundation: NSF funded precursors of AM technologies in the 1970s (development of computer numerical controlled machining and solid modeling tools) and turned early AM patents in the 1980s into proof-of-concept and prototype machines in two major commercial technology areas (binder jetting and laser sintering). In subsequent years, in addition to supporting fundamental research in the field, which is fitting with its role, NSF funded application development (e.g., medical) and academically oriented networking activities. In more recent years, as AM technology has matured, NSF has supported research efforts related to new processes, new applications for existing processes, and benchmarking and roadmapping activities.
- Other support: The Department of Energy (DOE), NASA, and the National Institute of Standards and Technology (NIST) have also been involved in aspects of developing the AM field. DOE in particular played a role in developing directed energy deposition technologies.

NSF has awarded almost 600 grants for AM research and other activities, amounting to more than $200 million (2005 dollars) in funding. Within NSF, the Engineering Directorate (ENG), and within ENG, the Civil, Mechanical and Manufacturing Innovation (CMMI) program and its precursors, have provided more than two-thirds of these AM grants and more than half of NSF’s total funding in support of AM. All told, NSF support of AM-related research has been instrumental in several ways.

- CMMI’s Strategic Manufacturing (STRATMAN) Initiative provided five grants amounting to about $3.5 million, two of which were critical in the development of two of the four patents identified as foundational for the AM field. These two patents were issued to researchers at the University of Texas, Carl Deckard and Joseph Beaman, and to a team of researchers at the Massachusetts Institute of Technology led by Emanuel Sachs.

- NSF support has been pivotal in the development of three of seven standard AM processes developed over the last four years—binder jetting, powder bed fusion, and sheet lamination. NSF's primary contributions were in funding transformative basic research and translational research through support of small businesses in these three areas. Four other AM processes have been led by industry and other government agencies.
- Through its research funding, including that of the Small Business Innovation Research (SBIR) program, NSF supported—both directly and indirectly—three of the most important early firms in the AM field: DTM, Z Corporation, and Helisys. Indirect support included the support of graduate students who later went to work for those AM firms and others.

Lessons Learned

NSF and other government agencies devoted to supporting manufacturing innovation can learn the following lessons from this study's findings:

- While the STRATMAN program was well received by the AM community, some experts were critical of the lack of consistency and strategic focus in NSF's efforts to support AM. To the extent feasible, providing consistent support with strategic intent would help NSF sustain support for emerging areas of science and technology. This goal of providing a consistent strategy at the individual technology level is a difficult one to execute because not every new technology merits its own research program. Further, the goal necessitates difficult choices related to uncertain technologies. Still, it merits serious consideration.
- With respect to creating breakthroughs, advances in industry have been just as important as those in academic research. Of the four foundational AM patents, for example, two were developed within firms without any direct public funding. Likewise, NSF support of small businesses through its SBIR program played a strong role in the commercialization of laser sintering and sheet lamination technologies. In the case of laser sintering, a strong collaboration between the University of Texas in Austin and Nova Automation (later DTM Corporation), both of which were early recipients of NSF funding, shows the large potential for industry funding and university-industry collaboration to drive innovation. Given the pace of industry developments, and the sometimes

unpredictable relationship between academia and industry, NSF would be wise to continue to foster research in industry as well as in academia.

- 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, NSF would do well to continue to support both fundamental research and strategic areas like advanced manufacturing in both the near and long terms.
- The U.S. Government provided funding not only for academic research in AM but also for innovative small firms, conferences, roadmaps, standards development, and student training. Experts underscored the importance of this indirect support, particularly the training of students who go on to work 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. Supporting the broader "ecosystem" of a technology domain should be recognized as a critical, though difficult-to-document, role for government in the development of an emerging field.

This study shows that NSF support of some of the most seminal researchers, roadmaps, conferences, networking events, patents, and manufacturing firms has contributed to the emergence of AM over the last 25 years. While the momentum of the past few years may suggest to some that AM has "arrived," the recent AM roadmap effort has shown that substantial challenges must still be overcome before the technology can become mainstream. These challenges include bringing down costs, developing new materials, achieving more consistency and standardization, developing new computer-aided design tools, educating engineers, increasing process speeds, and advancing biological AM. Going forward, NSF could have a role in each of these areas.

Contents

1. Introduction

A. Background

Additive manufacturing (AM), also referred to as solid freeform fabrication (SFF) or three-dimensional (3D) printing, is a set of layer-by-layer processes for producing 3D objects directly from a digital model. Since its inception a few decades ago, the AM industry has grown to almost $3 billion in 2012 and is poised to grow to more than $6.5 billion by 2019 (Wohlers 2012).

While the field began with a limited set of processes and materials and the goal of producing prototypes quickly, new processes and materials have emerged with multiple end uses:

- *Rapid prototyping.* Early AM parts were created for the rapid prototyping market and were first employed as visual aids and presentation models. Many lower cost AM systems are still used in this way.
- *Rapid tooling.* Another class of applications for AM parts is patterns for tooling or tooling directly made by AM. AM processes can be used to significantly shorten tooling time and are especially useful for low-run production of products.
- *Direct digital manufacturing*. Unlike rapid prototyping and tooling, where AM is used as a step in the design or production process of a final good, direct digital manufacturing (or direct part production) creates a final product or component of a final product for direct use.
- *Maintenance and repair.* AM can be used in the maintenance and repair of damaged parts and is particularly well suited for products that have a long lead time or expense associated with the procurement of new parts. The ability to repair metal parts to near net shape[1] has many advantages over manufacturing new parts and is advantageous in working with large components where only a small section has been damaged.

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[1] The term “near net shape” implies that a manufactured item has been produced close to final condition without the need for surface finishing.

These end-use cases are dictated by AM's well-documented advantages compared with conventional manufacturing processes (Bourell, Leu, and Rosen 2009; Campbell et al. 2011; Gershenfeld 2012):

- Product development can go more quickly with AM because designers are able to test and iterate designs and prototypes quickly.
- Complexity is "free" in that the design and fabrication of the product are independent of how complex it is, unlike subtractive manufacturing where the time and expense of fabrication increase with complexity.
- Considerably less material can be used when building parts with complicated internal geometries that would be difficult or even impossible to achieve using subtractive techniques.
- "Mass customization" is possible since product changes can easily be accomplished by tweaking computer-aided design (CAD) drawings, allowing for new products to be tailored to the needs and wants of each customer without the costly retooling necessary in traditional manufacturing.

B. State of the Industry Today

AM technologies have become a popular topic in policy and technology circles, and have seen substantial coverage in the media over the past few years (see e.g., Lipson 2013; "Print Me a Stradivarius" 2011; Gershenfeld 2012). In 2012, the United States established the National Additive Manufacturing Innovation Institute (NAMII), a public-private partnership designed to transition AM to mainstream U.S. manufacturing. Other countries (Australia and the UK, among others) have also recently released strategies for AM research and technology development (Wohlers Associates 2011; Additive Manufacturing Special Interest Group 2012). Such initiatives are at least partly due to the perception that AM can change the economics of the manufacturing landscape through decentralization, potentially even repatriating some manufacturing from low-cost countries (Campbell et al. 2011).

The AM industry remains relatively small (~$3 billion in 2011) compared with mainstream industries like semiconductors (~$300 billion in 2011) (Semiconductor Industry Association (SIA) 2013). Nevertheless, the industry is showing signs of maturation given major initial public offerings such as ExOne, whose shares soared almost 50% on their first day of trading (Deagon 2013); mergers and acquisitions such as the Objet-Stratasys merger and 3D Systems' acquisition of Z Corporation in 2011; and recent expansions into new consumer markets such as recent increases in low-cost machines sales (Wohlers 2012). The industry today is characterized by a large number of competing processes and companies, albeit with large market power concentration. Table 1 lists the major additive manufacturing machine companies, the year they were founded, and the main processes they utilize.

Table 1. List of AM Companies, Not Including Service Bureaus

Year	Company	Country	Main Process Type	Comments
1986	3D Systems	USA	Stereolithography (SLA) and selective laser sintering (SLS)	
1988	Stratasys	USA	Material Extrusion	
1989	EOS	Germany	Laser-sintering, direct metal laser sintering (DMLS)	
1990	Materialise	Belgium	Data transfer	
1991	DTM (Desk Top Manufacturing) Corporation	USA	SLS	Acquired by 3D Systems in 2001
1992	F&S Stereolithographietechnik GmbH	Germany	Selective laser melting (SLM)	
	ReaLizer GmbH	Germany	SLA, SLS	
1994	Solidscape	USA	Investment patterns (wax)	Acquired by Stratasys in 2011
	Z Corporation	USA	3D printers (3DP)/scanners	Acquired by 3D Systems in 2011
1997	Arcam AB	Sweden	Electron beam melting (EBM)	
	Irepa Laser	France	Construction laser additive directed (CLAD) process	
	Optomec	USA	Laser Engineered Net Shaping (LENS)	
1998	POM (Precision Optical Manufacturing)	USA	Direct metal deposition	
1999	Objet Geometries	Israel	Polymer jetting	Merged with Stratasys in 2012
	Solidica	USA	Ultrasonic AM	
	Voxeljet Technology GmbH	Germany	Binder jetting	
2000	Phenix Systems	France	Laser sintering	
	Sintermask GmbH	Sweden	Selective mask sintering	
2002	Concept Laser GmbH	Germany	Laser melting	
	EnvisionTEC GmbH	Germany	Digital light processing (DLP)	
2003	Huntsman Advanced Materials	Switzerland	MicroLightSwitch (MLS)	
2004	RepRap (Project)	UK	Fused deposition modeling (FDM)	
2005	Ex One	USA	3DP, sand, metal, glass	
	Honeywell Aerospace	USA	Ion fusion formation	
	Mcor	Ireland	Paper lamination	
	Solido	USA	Design automation	
2006	Fab@Home (Project)	USA	Material Extrusion	
2007	MCP HEK Tooling GmbH	Germany	SLM	
2008	Bits From Bytes	UK	Extrusion	Acquired by 3D Systems in 2010
	DWS (Digital Wax Systems)	Italy	Vat photopolymerization	
2009	MakerBot Industries	USA	Extrusion	
2010	Delta Micro Factory Corp. (PP3DP)	China	Extrusion	
	MTT Technologies GmbH	UK	SLM, Selective Laser Printing	
	SLM Solutions GmbH	Germany	SLM	

Source: Summarized from data in Wohlers (2012) and elsewhere in the literature.

Table 2 shows the cumulative machine sales by several of the largest companies in the field as summarized from data collected annually by the Wohlers Report (Wohlers 2012). Different machines and technologies vary by at least an order of magnitude in price, so total machine sales are not an accurate predictor of company revenue. For instance, an average FDM machine from Stratasys or a 3D printer from Z Corporation (now 3D Systems) can cost in the $10,000–50,000 range, whereas a laser sintering machine from 3D Systems or EOS can cost $100,000–800,000 depending on size and materials involved. Consumer-level machines are even less expensive and can cost less than $1,000 with assembly.

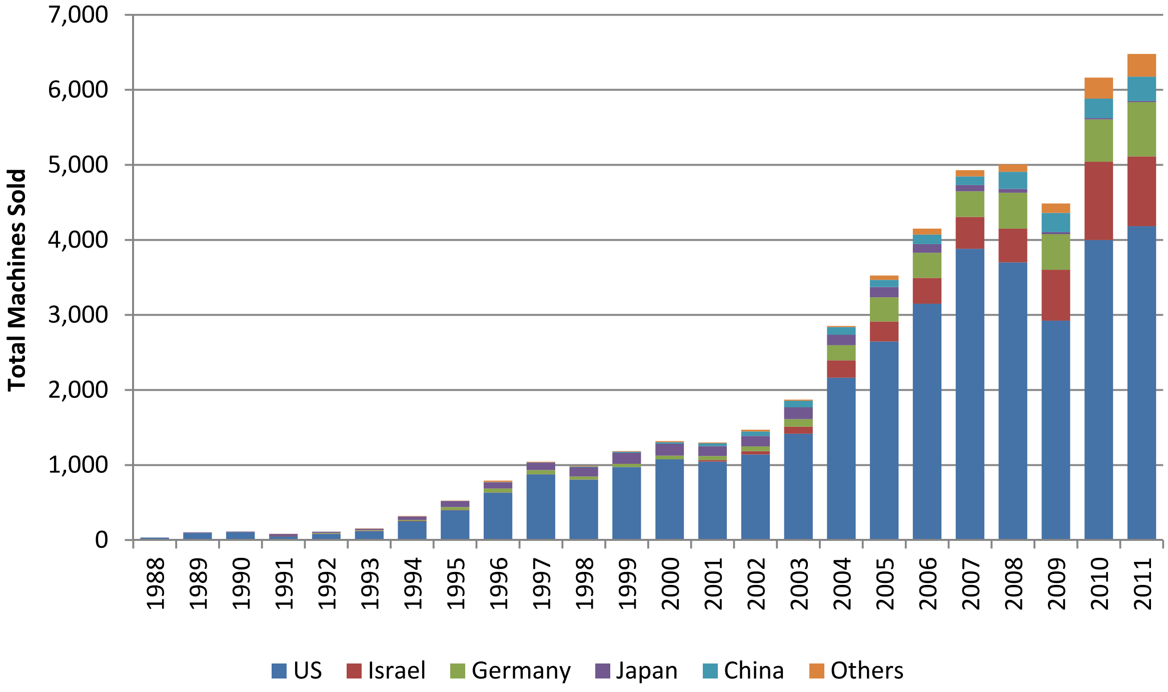
Table 2. Selected AM Companies, Cumulative Machine Sales through 2011

Company	Cumulative Sales from Origin through 2011
Stratasys (USA)	18,267
Z Corporation (USA)	7,029
Bits from Bytes (UK)—Consumer machine	6,817
3D Systems (USA)	5,521
Makerbot (USA)—Consumer machine	5,024
Objet (Israel)	3,622
Solidscape (USA)	3,472
Envisiontec (Germany)	2,618
EOS (Germany)	1,132
Beijing Yinhua (China)	1,066
Solido (Israel)	901
DWS (Italy)	572
DTM (USA)	434
Helisys (USA)	377

Source: Adapted from (Wohlers 2012).

Of course, the difference in cost between competing processes is in some sense indicative of the functionality of the different processes. Some of the less expensive processes, such as FDM and paper-based sheet lamination, are limited in materials and may primarily be used for use cases with lower required materials properties such as prototyping and personal printing. Build size, speed, and intended use also play a major role in the choice between competing processes—service providers will have different preferences than industrial machine owners, researchers, and users for whom the up-front cost is first priority. Wohlers Associates’ annual survey of service providers recently showed that while legacy stereolithography machines remain the most profitable machine type, laser sintering (particularly from EOS) and material jetting are the most likely next machine purchases.

The United States has been the global leader in AM since its inception, having been home to many of the most successful companies, including 3D Systems, Stratasys, Z Corporation, and Solidscape, over the history of the technology. In fact, as Figure 1 illustrates, over 70% of the professional-grade machines sold since the technology's infancy have been sold by U.S. companies, with over 60% of the total sold by just three U.S. companies: Stratasys, Z Corporation, and 3D Systems. Other countries have been major players as well, with Europe particularly leading the development of metals and laser-based AM processes, including industry leaders such as EOS and Envisiontec in Germany and Arcam in Sweden. An innovative Irish company, Mcor, has recently taken up the concept of paper-based sheet lamination AM originated by Helisys in the United States (see case study in Chapter 7). Still, the historical role U.S. companies have played in the technology justifies the focus on the role of U.S. public funding and U.S. patents in this report.



Source: Data from Wohlers (2012).

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

C. Goals and Scope of the Study

Given the recent attention to and growth in the field of AM, now is an opportune time to look back at the technology's history with an eye toward determining the roles of various institutions—public funders, private entrepreneurs and inventors, universities, and others—in its development. During the history of AM, traditional drivers of innovation, including public and private sector investors, have provided support. Among the U.S. Federal agencies that have invested in AM is the National Science Foundation (NSF), an organization charged with a broad mission to support scientific progress. While NSF invested in various aspects of AM research during the field's emergence and development, the impact of these investments has not yet been closely evaluated.

This work, in part, aims to investigate the outcomes of NSF support and involvement in the development and commercialization of AM within the United States. A broader goal, however, is to review the technology's history as a whole and determine which pieces, if any, can be attributed to NSF or other public support in the United States. A number of researchers have already captured portions of the history of AM through journal publications, books, and other resources (see Chapter 3), though none have attempted to explicitly connect events and inventors to public support. This report looks more specifically at elucidating the NSF's role in the technology's development. In the context of learning more about the history of AM and the role of public and private institutions in its evolution, we pose the following questions:

- How do the stakeholders in the AM community—researchers and end users—view the role of various institutions, both public and private? How do they view the role of NSF specifically?
- What does an analysis of AM-related patents reveal about the players in the field, their institutional affiliations, and funding sources? Specifically, what was the role of government in general and NSF in particular?
- What is the nature of NSF support of AM? How has it changed over the years?

D. Organization of the Report

The report is organized as follows. Chapter 2 describes the study methodology and sources of data. Given our historical perspective, it is first necessary to discuss definitions, as AM technologies have had many names over their history. After a discussion of the definitions, we discuss our analytical methods and the limitations of our analysis. Chapter 3 summarizes findings from the discussions and literature review, and Chapter 4 presents findings from the patent analysis. In Chapter 5, we discuss the findings from an analysis of NSF funding of AM. Chapter 6 presents a range of case studies that explore six AM patents and technologies and the role of public support in their development. In Chapter 7, we synthesize insights from all the methods, providing our assessment of the role of NSF in creating and developing the field of additive manufacturing.

2. Study Methods and Data Sources

This study used a combination of data sources to examine the history of additive manufacturing (AM) and NSF's role in its development:

- A review of the literature.
- A series of structured discussions with experts in the field.
- An analysis of the AM patent landscape and history.
- An analysis of the NSF awards to AM and closely related topics.

These four data sources in turn led to a list of four patents foundational to the AM field, which inspired a more in-depth look by means of a series of case studies based on them. Two additional case studies were added to supplement the foundational patent case studies, each highlighting an additional way that NSF affected the field. Each method is described below. But because the analysis is highly dependent on what may or may not be considered to be within the realm of AM, we begin with a definition of the term.

A. Defining Additive Manufacturing

While the terms *additive manufacturing*, *solid freeform fabrication*, and *3D printing* all describe a similar set of processes, their usage has evolved with the field. Today, additive manufacturing is the prevailing term, as chosen by the ASTM International Committee F42 on Additive Manufacturing Technologies, and will be the main term used in this document. In the first standard released by ASTM International (2012a), AM is defined as follows:

> A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication.

Among academics, the term *solid freeform fabrication* remains popular, in part, because it was coined during the early formation of the academically oriented Solid Freeform Fabrication Symposium at the University of Texas at Austin. The conference, which started in 1990, still takes place annually under the same name.

Although 3D printing is technically a subset of AM processes that refer to material deposition through a print head, nozzle, or other printing technology, the term *3D printing* has been adopted in mainstream media as being interchangeable with AM. 3D printing is also typically associated with a subset of mostly consumer-focused machine types in the lower cost category.

AM processes go by many different names, and these names have changed over the years and from company to company. The processes have been categorized previously by a variety of researchers, and in February 2012, the ASTM International Committee F42 on Additive Manufacturing Technologies (hereafter referred to as F42) published its "Standard Terminology for Additive Manufacturing Technologies" (ASTM International 2012a), which includes the following processes for grouping current and future AM machine technologies:

- *Binder jetting*—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
- *Directed energy deposition*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting them as they are being deposited.
- *Material extrusion*—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
- *Material jetting*—an additive manufacturing process in which droplets of build material are selectively deposited.
- *Powder bed fusion*—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
- *Sheet lamination*—an additive manufacturing process in which sheets of material are bonded to form an object.
- *Vat photopolymerization*—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

All these processes have benefits and trade-offs when compared to one another, including varying aspects such as material choice, build speed, layer thickness, surface quality, cost, and feasible part geometries, among others. Further, these trade-offs change over time with technological progress within each of the different classes of processes. Although there is overlap between the capabilities of the different ASTM process categories, the process must be selected to match an application.

This report uses the F42 standard terminology when referring to AM processes—except when it is logical to use the inventors' original process names for clarity or historical reasons.

Table 3 provides a partial list of these alternate process names and the companies associated with the ASTM processes.

Table 3. Alternative Process Names to the F42 Standard and Companies that Use Them

F42 Standard Name	Alternative Name	Companies (Country)
Binder jetting	3D printing	3D Systems, Z Corp (USA), ExOne (USA)
Directed energy deposition	Laser engineered net shaping	Optomec (USA)
	Direct metal deposition	POM (USA)
	Direct manufacturing	Sciaky (USA)
Material extrusion	Fused deposition modeling	Stratasys (USA)
		Makerbot (USA), Bits from Bytes (United Kingdom)
Material jetting	Various jetting processes	Objet (Israel), Solidscape (USA)
Powder bed fusion	Laser sintering	3D systems (US), EOS (Germany), ReaLizer (Germany)
	E-beam welding	Arcam (Sweden)
Sheet lamination	Laminated object manufacturing	Mcor (Ireland)
	Ultrasonic consolidation	Fabrisonic (USA)
Vat photopolymerization	Stereolithography	3D Systems (USA)
	Digital light processing	Envisiontec (Germany)

Source: Wohlers (2012).

B. Data Sources and Analytic Methods

1. Literature Review

The following is a list of the types of information sources consulted to review the literature related to the field of additive manufacturing:

- *Peer-reviewed journals*: Top journals that publish information on AM include, for example, *Virtual and Physical Prototyping*, *Rapid Prototyping Journal*, *Journal of Dynamic Systems*, and *Journal of Engineering Manufacture*.
- *Textbooks*: A handful of authors have attempted to capture major advancements in the field and technical topics of AM in textbook form. Recent examples include *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing* and *Rapid Manufacturing: An Industrial Revolution for the Digital Age* (Hopkinson et al. 2010; Gibson et al. 2010).
- *Conference agendas and proceedings*: In addition to the Solid Freeform Fabrication Symposium at the University of Texas, Austin, that has been taking

place since 1987, other groups have held meetings on AM, including the Society of Manufacturing Engineers' RAPID Conference and Exhibition.

- *Workshop reports*: These reports include the 2009 *Roadmap on Additive Manufacturing* (*RAM*) and a handful of others sponsored by groups such as the Air Force Research Laboratory (AFRL) and the National Center for Manufacturing Sciences (NCMS) (Bourell, Leu, and Rosen 2009; NCMS 1998).
- *Task force reports*: Examples include the widely cited Japanese Technology Evaluation Center (JTEC)/World Technology Evaluation Center (WTEC) collaboration (Prinz et al. 1997) and the more recent additive/subtractive manufacturing review (Beaman et al. 2004).
- *General-interest periodicals*: There have been numerous mentions of AM in the popular press and in sections dedicated to the topic in periodicals such as *The Economist, Scientific American, Foreign Affairs*, and others.
- *Patents*: Numerous patents relating to additive manufacturing have been filed since the technology was first introduced.
- *Industry reports*: *TCT* magazine provides "industry intelligence" on 3D printing and AM, but the most well-known industry coverage is included in the annually produced Wohlers Report.

Results from the literature review were validated and modified by the input from the expert discussions and patent analyses.

2. Structured Discussions

The literature review was supplemented with semi-structured discussions with experts to gather information on the origin and evolution of the field of AM, as well as the role of NSF and other funding agencies. The initial list of experts was developed through a literature review of prominent figures in the history of AM and U.S. Government program managers who have supported AM process technology development. The list was supplemented by asking these experts to identify other experts who may have insight to the study's goals. From January to July 2013, the study team conducted structured discussions with 22 representatives from industry (5), government (6), U.S. academia (8), and foreign academia (3). (See Appendix A for the full list of experts and their affiliations.) To encourage candid replies, all discussions were conducted on a not-for-attribution basis. (See Appendix B for the discussion protocol.) Different experts identified themselves as being more or less qualified to answer different questions, and thus not all experts answered every question. For instance, foreign discussants generally had less input on the potential impacts of different U.S. funding agencies, but were able to talk about the role of foreign government funding (such as from the European Commission).

3. Patent Analysis

Patents are an important source of information regarding dates and institutional roles in technological innovation. To supplement literature review and expert discussions, the study team created a custom database of AM patents and analyzed it to examine the various roles of universities, industry, and government in the development of AM.

a. Developing the Patent Database

The patents relevant to the AM field were identified from four sources:

1. Rapid Prototyping U.S. Patent Database (herein referred to as the *Patent Museum*). This commercially available database contains 4,368 patents from 1892 to 2012 relevant to the rapid prototyping field.[2]
2. U.S. Patent and Trademark Office (USPTO) Custom Data Extract. This database contains 4,650,302 utility patents with many millions of associated records. It is a commercially available data set containing patents from 1975 to 2011.[3]
3. USPTO Government Interest Extract. The Custom Data Extract did not contain information in the government interest clause section of a patent, which would denote attribution to government agencies for a patent's development. By special request, USPTO provided the government interest information. This extract contains a binary code identifying whether the patent contained government interest for patents from 1975 to 2011.
4. USPTO National Science Foundation Extract. Because the USPTO Government Interest Extract did not contain text to identify support from specific Federal agencies, by special request, USPTO queried the USPTO Government Interest Extract and provided a data set that identified government interest from "NSF" or the "National Science Foundation." This data set contains patents from 1975 to 2011.

A relational database was constructed in Microsoft Access to incorporate the patents from the four aforementioned resources for a total of 4,368 patents. For detail on the database structure, see Appendix C.

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[2] Product available at http://additive3d.com/pr_pat.htm. The study team purchased the database in January 2013.

[3] Product available at http://www.uspto.gov/products/catalog/index.jsp.

b. Manually Identifying Historically Important Patents

As an additional input into developing and confirming our AM patent database, we sought to manually identify the historically important patents in the field and any connections to NSF. We tallied these patents based on an extensive review of three data sources:

1. Literature review—This data source included literature from 29 journal articles, books, reports, reviews, and manuscripts that contained references to historically important patents. Though many other resources for literature were used throughout the study, most did not directly reference any patents.
2. Structured Discussions—Fifteen (68%) of the 22 discussants in the study provided their thoughts on the most important patents in the AM field.[4]
3. AM event materials—The study team attended and received presentation materials from two AM events: (1) Additive Manufacturing Symposium held 20 August 20, 2012, sponsored by the U.S. Department of Energy and Lawrence Livermore National Laboratory and (2) USPTO Additive Manufacturing Partnership meeting held January 23, 2013.

Table 4 delineates the data sources used to identify and tally U.S. patents as historically important in the AM field.

Table 4. Sources Used to Identify U.S. Patents as Historically Important to AM

Source Type	No. of Sources	Patents (total)^	Patents (unique)
Literature Review	29	159	76
Discussions	15	53	16
AM Event Materials	2	17	12
Total	**46**	**229**	**83***

^ Differences between Total and Unique Patents by source type occur because duplicate references were provided by one or more sources within a given source type.

* The unique patent total does not add up to the sum of the unique patents for each source since there is overlap of patents identified among the source types.

The tally consisted of both U.S. and international patents referenced by the sources as historically important in the AM field. The process resulted in identifying 83 U.S. patents and 14 international patents issued throughout the European Union and Japan. Appendix D presents the results of this manual patent tally. Focusing on the U.S. patents, we matched the historically important patent tally with the Patent Museum and found that 5 patents (6%) of

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[4] Seven (32%) of the 20 discussants did not feel qualified to comment because they did not have knowledge of patenting activity or specific patents produced in the AM field.

the 83 U.S. patents were not already included in the Patent Museum data set.[5] Thus, this manual tally also helped confirm the validity of the Patent Museum data set.

c. Finalizing the Patent Database

With the relational database established, we queried and extracted bibliographic metadata from the USPTO extracts to finalize the patent database. Our intention was to extract metadata for the 4,368 Patent Museum patents and the additional 5 historically important patents identified by the tally. But 551 patents for which there was no USPTO extract data were not included in the analysis:

- Of these patents, 518 were issued outside the time period of our data set (9 patents were issued before 1975, and 509 patents in 2012).
- Of these patents, 22 were design patents (denoted by having a D in front of the patent number).[6]
- Ten of these patents were reissued (denoted by having RE in front of the patent number), and for these, the original patent was already in the database.
- One patent was withdrawn.

In total, the database used for our study analysis contains 3,822 AM patents from 1975 to 2011.

d. Data Processing and Cleaning

Because the data from USPTO were inconsistent (e.g., inventors' names misspelled, names and locations abbreviated or not), several steps were taken to clean and process the patent metadata.

We cleaned the inventors' names to disambiguate and standardize names for the same individual. We used VantagePoint[7] text analysis software to clean the names and verified similar combinations of names using the inventor's affiliation and location. Similar names were identified using an automatic fuzzy matching algorithm to match varieties of the same term, and results were manually verified. The algorithm was a conservative approach to matching differences in capitalization, punctuation, and stemming, and it identified variations in initials (e.g., John B. Smith and Smith, J. B.). We standardized location information for U.S. states and countries. We used a thesaurus that automatically identified country abbreviations and converted them to their full name.

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[5] One of these patents was from 2012, and data in the relational database is limited to up to 2011.

[6] Design patents are related to physical shape of an invention and were not considered relevant for this study.

[7] Commercially available at http://thevantagepoint.com.

To clean assignee organizations, we used a fuzzy matching algorithm from VantagePoint to identify similar names. The algorithm identified loosely similar organization names by searching for similarity across long place names; a manual inspection was therefore necessary to verify the groupings. We performed further processing of the assignee data by categorizing the assignee organizations into five areas:

- *Global industry*, which includes any U.S.-based or international private company.
- *Universities*, which include any U.S. university.
- *Government*, which includes U.S. Federal agencies and government-owned laboratories, such as Sandia National Laboratories and Lawrence Livermore National Laboratories.
- *U.S. non-profit and medical research centers*, which include foundations and hospitals.
- *International research sponsors*, which include international academic, government, and nonprofit research organizations.

4. Identifying the Top 100 Historically Important Patents

Using the tally and relational database, we developed a list of the top 100 historically important U.S. patents to search for the role of government funding in the most important AM inventions. Throughout the course of the study, the list of the top 100 historically important patents became the basis for many techniques and facilitated the overall patent analysis. The top 100 patents is an arbitrary cutoff and not meant to imply that patents not on the list of 100 are not important. The list contained 70 of the 83 U.S. patents from the manual tally that were within the time horizon of the patent database (1975 to 2011).[8] We supplemented these 70 U.S. patents with 30 of the highest cited patents in the database that were not already on the tally from literature or discussion sources, identified by examining the references cited and selecting only the patents validated by the Patent Museum.[9] The results of the analysis on the top 100 historically important patents are presented in this report using IPVision software.[10] The list of 100 historically important U.S. patents is in Appendix E.

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[8] Of the 83 U.S. patents, 12 were issued prior to 1975 and 1 was issued after 2011.

[9] Through this process, we identified 19 highly cited patents from the patent references that were not listed in the Patent Museum.

[10] IPVision is patent analytics software publicly available at http://www.see-the-forest.com.

5. Identifying Foundational Patents

From the list of 100 historically important patents, we also identified 4 patents termed "foundational" as defined by certain characteristics:

- Cited highly by three data sources—the literature review, structured expert discussions, and event materials.
- Cited highly by other patents, which were calculated from references to U.S. patents in the database during the period 1975 to 2011.
- Cited highly by discussants as representing discovery or significant advancement of an ASTM F-42 standard process or major commercial technology.

Table 5 lists the four foundational patents that were identified based on these criteria.

Table 5. Four Foundational Patents and Associated Citations from Four Sources

			Three Data Sources		
Foundational Patent	ASTM F-42 Standard Process	Total Patent Citations	Literature Review	Structured Discussions	Event Materials
4575330	Vat photopolymerization	399	12	10	2
4863538	Powder bed fusion	243	9	11	1
5121329	Material extrusion	203	6	9	2
5204055	Binder jetting	247	2	7	2

We identified patent families for each of our four foundational patents through the USPTO online patent database in two ways:

1. We searched for patents that were assigned the same Family ID ("FMID") as the foundational patent.
2. We searched the parent case information ("PARN") for the foundational patent number.

In this way, we were able to identify three types of patent applications that could be related to the foundational patent:

- Divisional: A patent application filed when a parent application describes more than one invention. In this case, the application is split such that the parent covers one invention, and any divisional patents cover other inventions in the application. Each divisional patent can claim the priority of the parent application.

- Continuation: A patent application that describes additional claims to an earlier application, for instance, to ensure the invention covers other technological applications. A continuation claims the priority of the parent application.
- Continuation in part: A patent application that describes new material to the original application, for instance, to ensure claims to later improvements in the invention. A continuation in part claims priority to the parent application.[11]

Identifying patent families is useful because divisional, continuation, and continuation-in-part applications represent additional claims related to the original patent that can be important to the development of the invention.

C. Identifying NSF Awards

A set of 593 AM-relevant NSF awards was compiled by STPI for analysis. NSF has never had a program dedicated to AM, so it was necessary to find AM-relevant awards using some type of identifier. In this study, these awards were retrieved with a list of 165 search keywords (see Appendix F) via the Award Search function of the NSF website. The search keywords were compiled from many sources, including, literature review, expert input during discussions, review of patents, and Indices of the Wohlers Report and Castle Island’s Worldwide Guide to Rapid Prototyping (additive3d.com).

Once all the search results were downloaded, the set was manually culled and refined to include those awards that were relevant only to the field of AM. This was necessary because the list included several keywords relevant to other fields as well as to AM. For example, the keyword “rapid prototyping” returned results relevant to AM to non-AM topics like prototyping of robotics, networked systems, and software architectures.

Because identifying this list of awards required some level of subjective sorting, the award set was validated by cross-comparison to a list of NSF support taken from the Wohlers Report from 1998 to 2012. The annual Wohlers Report includes a section on public support for AM, including (starting in 1998) a section dedicated to new and ongoing NSF support. The keyword method used here identified three times the number of awards as Wohlers Associates, but included all of the awards that the reports had identified over the years. Due to the nature of keyword-based searches, there is a chance that some AM-relevant NSF awards were not captured.

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[11] See https://www.acclaimip.com/how-to-analyze-continuation-patent-applications.

D. Limitations of the Study Methods

Limitations to conducting the different analyses carried out for this study are related to the conceptual scope of the study; technical and time limitations in the use of keywords for building data sets; general limitations when conducting patent analyses, such as the difficulty of evaluating recent advances that have not had commercial success; and a limited focus on U.S. patents done to gauge impacts of a U.S. funding agency.

1. Conceptual Scope

The field of AM builds on other fields, including but not limited to photonics, computer science and modeling, materials science, control theory and computer numerically controlled machining, and machine design. AM could not exist without the confluence in development of these other technologies and sciences; however, the scope of this report did not allow for a full analysis of each related technology. These analyses were performed using only data and information that were either strictly AM focused or from another field with direct application to AM—for example, AM-tailored computer-aided design (CAD) improvements or development of materials specifically for AM processes.

2. Technical and Time Limitations in the Use of Keywords for Building Data Sets

As noted, STPI developed a set of 165 keywords and phrases relevant to the AM field (see Appendix F). Examples of some common terms used to identify major works in the development of the field include the following:

- (Solid) freeform fabrication.
- Rapid prototyping.
- Rapid manufacturing.
- Additive manufacturing.
- 3D printing.
- Stereolithography.
- Selective laser sintering.
- Fused deposition modeling.
- Direct metal laser sintering.
- Fused filament fabrication.
- Melted and extrusion modeling.
- Laminated object manufacturing.

- Selective heat sintering.

We sought to validate the keyword quality by querying the keywords on the titles and abstracts of the patents in the Patent Museum metadata. A number of difficulties made it impractical to use keywords to identify and extract the relevant AM patents:

- *Changing terminology over time.* The terminology used to identify the AM field has changed and evolved considerably during the past decades, resulting in false positives incorrectly identified as AM-relevant due to changes in terminology.
- *Full-text description of the patent was not available in the USTPO custom extract.* There were limits to searching with keywords in the patent extract database acquired from USPTO because the data did not include abstracts or other full-text descriptions of the patents. Tests performed to compare search results from the extracts with those obtained from the USTPO Advanced Search online full-text feature indicated major differences between them.

Recognizing that perhaps the online USPTO Advanced Search feature could be used to get a better representation of the AM field, we attempted to identify the relevant patents using the set of keywords. It was proposed that once a set of relevant patents was identified, we would then query our database to extract any patent metadata. Unfortunately, there were also several barriers to this approach:

- *The online USPTO Advanced Search system is not developed for keywords in bulk.* Extracting patent metadata necessary for patent analysis was difficult and inefficient and would have caused considerable delays. In addition, the web browser has technical limitations and performance issues after executing a set of search queries.
- *The online USPTO Advanced Search system has limited options for keyword wildcards.* Because most keywords were wildcards, and the USPTO website has limitations on searching wildcard phrases, it was necessary to search a total of 478 keyword combinations, a time-intensive process. In addition, false positives would have to be manually filtered from the resulting lists for each keyword-combination query.
- *Several keywords are too broad to be used in the online USPTO Advanced Search system.* Broad keywords often resulted in unmanageable amounts of patents to qualitatively filter. For example, the keyword combination “additive process” resulted in 2,864 patents and “layer deposition” in 19,337 patents.

3. Limitations of Patent Analysis

One potential limitation of using patent analysis, specifically patent citations, for examining the development and commercialization of a field is the potential to underappreciate major advances that have not yet had significant citations or commercial success. A patent from 1978 has obviously had several more years to be cited than one from 2008, and likewise, industry is more apt to point to developments that have achieved commercial success than those with potential success in the future. While the goal of this project was to analyze the history of AM and identify the role of public funding in major advances, it is possible that certain contributions may not be recognized for their significance yet.

4. Focus on U.S. Patents

A large part of this study involved the use of U.S. patent data. While a more comprehensive study could be designed that would examine world patents and patenting activity in countries other than the United States, this study was limited to an examination of U.S. patents for several reasons: time and funding limitations, the study goal of identifying impacts of a U.S. funding agency, and the general importance of the United States to the development of the AM field. For context on this last point, it is worth pointing out that more than 70% of professional machine sales have been by U.S. companies (cumulatively to 2011, according to data from Wohlers Associates; see Figure 1). Given the general study goals, we intentionally limited the study to a greater focus on AM developments in the United States, with less detail on international patents, companies, organizations, and funding agencies. However, developments outside the United States were tracked for completeness and context through non-patent data-collection methods such as structured discussions and literature review.

3. Results from Structured Discussions and Literature Review

In this chapter, we summarize insights from the 22 discussions conducted with experts and the literature review. Through this review, we examined the history and growth of AM as a field, including evidence from literature and input from experts identifying major milestones, companies, and patents. It builds on several written histories of various AM technologies and the field as a whole, such as Wohlers (2011); Gibson, Rosen, and Stucker (2010); Hopkinson (2010); Wong and Hernandez (2012); Bártolo (2011); and Shellabear and Nyrhila (2004), and ends with a discussion of the role of NSF and other government agencies as well as the global context. Note that the purpose of this chapter and the next is to tell the story of how AM developed as a field, with some limited discussion of the role of NSF and government funding.

A. History and Growth of Additive Manufacturing

AM has roots that date back more than a century; however, much of its progress has taken place in the last three decades, with certain notable periods of rapid growth. Being well grounded in the context of key technological precursors is important to understanding the emergence of the field. This section therefore begins with a review of the period of early history (before 1984), then describes a period of active development and commercialization (1984–2006) and the more recent trends (2007–today). Each of the seven officially recognized AM standard process categories is examined, as are the major companies currently producing machines in each category.

1. Early History (Before 1984)

With the advent of photography in the early 1800s, inventors and visionaries began to contemplate how to extend the process to a third dimension and replicate physical objects. Contemporary AM techniques are reminiscent of two ideas originating from that century—photo sculpture in the 1860s and topography in the 1890s—that coalesced under the larger umbrella of additive processes.

Photo sculpture is the process of photographing a stationary subject from multiple viewpoints and then using that set of photographs to guide precise sculptures. François Willème designed a photo sculpture process in 1860 that employed 24 equally spaced, circumferentially arranged cameras to produce “exact” 3D replications of objects; however, Willème’s process still required manual carving (Prinz et al. 1997). To address this issue, Carlo Baese patented a technique in 1904 to use graduated light and photosensitive gelatin that expands proportionally to exposure (Baese 1904). In 1924, Frederick Monteah, an Australian, incrementally improved the process (Monteah 1924), and in 1935, Isao Morioka, a Japanese researcher, added nuance to the process with structured bands of black-and-white light, which synthesized photo sculpture with elements of topography (Morioka 1935). In 1951, Otto Munz patented his "photo-glyph recording" technique, which selectively exposes layers of a transparent photo emulsion while scanning cross sections of the object to be replicated (Munz 1956). Despite from the lack of computer imagery and subsequent major advances in lasers and photopolymer chemistry, the process is strikingly similar to modern day stereolithography (SLA). All these photo sculpture techniques and patents are cited heavily in active AM patents today.

The 18th and 19th centuries were a boon for topographical surveying and topographic maps. Once cartographers had acquired the data, the next step was to create precise 3D mock-ups. Joseph Blanther met this need in 1892 by patenting a molding method that used stacks of wax plates to create contour relief maps (Blanther 1892). Some improvements to this process were made in 1940 and in 1964 (Perera 1940, Zang 1964), and Yukio Matsubara of Mitsubishi Motors pioneered a photopolymer process in 1972 (Matsubara 1974). In 1974, Paul DiMatteo invented a process that used this stacking method to fabricate complex surfaces such as propellers, airfoils, 3D cams, and dies for punch presses (DiMatteo 1976). His invention also employed a mechanical contour follower device to directly replicate parts. The year 1979 at Tokyo University marked the first use of such lamination techniques to directly produce manufacturing tools, such as blanking tools, press forming tools, and injection molding tools (Nakagawa 1979).

The two aforementioned fields (topographical surveying and topographic maps) are not the sole contributors to the burgeoning of AM. It has also drawn a great deal on other advances, including the following:

- *Computers*. In particular, the growth of the personal computer and the concomitant processing power, graphics, and networking has enabled many aspects of AM.
- *Computer-aided design* (*CAD*). CAD is a critical component of AM but has been developed independently, beginning with two-dimensional (2D) uses and now supporting 3D applications as well.
- *Computer numerical control* (*CNC*) *machining*. While at first in competition with AM, hybrid processes that take advantage of additive processes and CNC machining are now being used. Each technology has driven the other to improve (i.e., remain competitive in speed, accuracy, and cost).

- *Lasers*. Early AM technologies relied on lasers, in part because they represent an easy-to-harness beam of energy that can be easily controlled. Lasers are used in heating or curing of AM products.

In 1976, the NSF funded Herbert Voelcker's CAD research at the University of Rochester (Voelcker 1976). Voelcker addressed one of the major impediments to CNC success—the lack of an unambiguous scheme for describing 3D parts. Until this point, the standard practice had been to use wireframe rendering systems, which led to ambiguities such as a circle representing either a hole or a flat surface—two very different products. Voelcker and his team developed a prototype solid modeling system, the Part and Assembly Description Language (PADL). PADL allows engineers to fully define their parts and also gives them the option to assign tolerances their parts (Fisher et al. 1978).

In 1979, Ross Housholder filed a patent for a molding process for forming 3D articles in layers using heat and powdered feedstock, which was the first manifestation of the powder bed fusion ASTM standard process of AM. His patent was originally assigned to Hico Western Products Company and was reassigned to the DTM Corporation in 1996 when the patent was reexamined (Housholder 1981).

Also in 1979, a French disclosure described the ASTM standard process of directed-energy deposition for the first time (Ciraud 1973). That same year, employees of United Technologies Corporation filed two patents relevant to AM: a powder feed apparatus and a method for fabricating articles by sequential layer deposition, which can use either powder or wire feedstock (Tourtelotte 1981; Brown 1982).

2. Development and Commercialization (1984–2006)

The commercialization process for AM began with the invention of stereolithography (SLA) by Charles Hull, who filed his well-known patent for SLA in 1984 (Hull 1986). The patent was issued and assigned to UVP Inc. in 1986. The process selectively solidifies or cures a liquid photopolymer with a scanning laser in a layer-wise process. The laser provides energy for a chemical reaction to take place, ultimately forming a highly cross-linked polymer chain. Hull's process was the first demonstration of the vat polymerization ASTM standard process, and is widely considered the process that founded the field of rapid prototyping/additive manufacturing, mentioned by the most number of experts as an important milestone. Table 6 gives a full listing of important milestones described by the experts.

Table 6. List of Major Milestones in AM History from Expert Discussions with Number of Experts that Listed the Given Milestone as a Top 5 Development

Approx. Year	Milestone	No. of Experts
1984	Stereolithography (SLA) invention	13*
1986	Selective laser sintering (SLS) invention	12*
1987	Laminated object manufacturing invention	2
1987	First SLA machine exhibited	1
1989	Fused deposition modeling invention	8*
1989	3D printing invention	4
1989	NSF Strategic Manufacturing (STRATMAN) Initiative	1
1990	First Solid Freeform Fabrication (SFF) Symposium	4
1991	International College for Production Engineering (CIRP) keynote summarizing technology (Kruth)	1
1991	First medical skull scanned and produced from stereolithography	1
1992	Development of nylon and early materials	2
1992	Autofact Conference 1992	1
1992	First NSF award for 3D printing	1
1992	Overseas Nottingham conference	1
1993	Society of Manufacturing Engineers (SME) Rapid Prototyping Group	2
1993	Soligen licensing MIT 3D Printing technology	1
1993	Next-day service from Materialise becomes available	1
1994	E-beam melting invention	2
1995	Start of *Rapid Prototyping Journal*	1
1995	Contour crafting invention	1
1996	Rapid tooling development (i.e., Quickcast)	2
1996	Laser Engineered Net Shaping (LENS) process invention	1
1997	First venture capital funding for 3D Systems	1
1997	Align Technologies adoption of SLA for orthodontics	1
1998	Automotive adoption of SLA	1
1999	First printed robot	1
2000	3D color printing	1
2000	Solid-state AM (ultrasonic consolidation) invention	1
2001	Higher operating temperatures	1
2005	Transition from prototyping to direct manufacture	4
2006	Desktop AM development	6*
2006	Emergence of metal AM	5*
2007	Multimaterial printing	1
2008	New business models (i.e., Shapeways)	2
2008	Larger build volumes in commercial machines	1
2009	Patent expiration (Crump 10/2009)	3
2009	NSF/Office of Naval Research (ONR) AM Roadmap	2
2009	ASTM F42 formation	2
2009	Boeing F-18 usage of AM-made parts	1
2011	Consumer machines outsell industrial machines for first time	1
2012	GE purchase of Morris Technologies	1
2012	NAMII establishment	3

* Top 5 milestones, as determined by the number of experts that listed it as a top 5 development in the field.

Hull founded the company 3D Systems based on his SLA technology in 1986 and exhibited the first machines for sale in 1987, commercializing additive processes for the first time in history. 3D Systems remains one of the chief players in the AM commercial sector, and it has vastly expanded its technological capabilities and acquired many companies since 1986. One of 3D Systems' major contributions to the field was developing the Standard Triangulation Language (STL) file format, which describes the surface geometry of 3D objects. The STL format is widely used for AM and computer-aided manufacturing (CAM) processes beyond SLA and has industry recognition as the de facto standard file format (Prinz et al. 1997). ASTM International launched an initiative in May 2011 to make the Additive Manufacturing File Format (AMF) the industry standard because it would be open and include native support for color, material, lattices, and constellations (STL only contains surface geometry information) (ASTM International 2012b). Whether or not AMF obscures STL, the STL file format and 3D systems have thrived for over 25 years.

The second major AM process was invented by Carl Deckard and Joseph Beaman, both from the University of Texas (UT) at Austin, who filed for a patent on selective laser sintering (SLS) in 1986 (Deckard 1989) and founded DTM in 1987, the first commercialized example of powder bed fusion. BFGoodrich bought a controlling interest in DTM in 1990, which 3D Systems then purchased in the late 1990s (Lou and Grosvenor 2012).

In 1987, Michael Feygin filed a patent for an apparatus and method for forming integral objects from laminations, which was the first appearance of the sheet lamination ASTM standard process (Feygin 1988). His company, Helisys (formerly Hydronetics), was founded in 1987 and sold its first machine in 1992.

A marked industry expansion occurred between 1988 and 1993 (as shown in Table 6 and previously in Table 1). In 1988, 3D Systems also shipped the world's first commercial SLA machine, and the Japanese SLA company, CMET, was founded. EOS, a German competitor to the American selective laser sintering (SLS) company DTM, was founded in 1989 and still remains a large international player in the SLS market.

In 1989, S. Scott Crump filed for a patent on fused deposition modeling (FDM) (Crump 1992) and co-founded Stratasys, which remains a major American player in the AM industry. FDM was the first case of the material extrusion ASTM standard process, and Crump's initial patent references three of the Householder and Hull patents at the University of Texas at Austin.

In 1989, Emanuel Sachs at the Massachusetts Institute of Technology (MIT) invented the first example of the binder jetting ASTM standard process, and was awarded a patent in 1993 (Sachs 1993). NSF funded the development of Sachs' binder jetting process in 1989 through its Strategic Manufacturing Initiative (STRATMAN) (Sachs 1989), which will be discussed further in Chapter 7. MIT first licensed this technology to

Soligen in 1993 and then to Z Corporation in 1994, which grew to be a leader in the field before being acquired by 3D Systems in 2012 (Lassiter, Lieb, and Clay 2005).

In 1992 two more influential events occurred—the first commercial presentation of an SLS machine at Autofact 1992 and the first Nottingham meeting in the United Kingdom, which brought the European research community together in a similar fashion as the Solid Freeform Fabrication (SFF) Symposium, which began in the United States in 1990.

The mid-1990s also saw the invention of several new processes. In 1994, Ralf Larsson of Arcam Ltd filed for a U.S. patent for the invention of Arcam's e-beam melting process, now commonly used for high-value metal parts (Larsson 2003). In 1995, Behrokh Khoshnevis filed for a patent for a new process called contour crafting, the first process designed to work at a multi-meter scale (Khoshnevis 1996). Several important processes associated with the growing field of rapid tooling were invented or refined during these years, including the Quickcast process invented by Philip Dickens and Richard Hague and licensed by 3D Systems (Dickens, James, and Hague 2000). Further developments in Europe began as well. In 1991, J. P. Kruth first summarized the state of different AM processes in an International College for Production Engineering (CIRP) keynote paper (Kruth 1991) and Materialise first produced a medical scan for SLA, the genesis for their influential Mimics software system for medical AM (Wohlers 1998). Finally, in 1996 several researchers from Sandia National Laboratory filed for a patent that formed the basis for the Optomec Laser Engineered Net Shaping (LENS) process, the first commercial example of the ASTM directed-energy deposition process (Jeantette, Keicher, Romero, and Schanwald 2000).

As the early processes, particularly SLA, improved, the late 1990s began to see important applications of the technology, both for prototyping and direct manufacturing. The U.S. automotive industry began adopting rapid prototyping at scale providing an important outlet for the industry. Professional societies also began to be involved in the technology—an example is the Rapid Prototyping Association, formed under the Society of Manufacturing Engineers (SME), in 1993 (Wohlers 1998).

In 1997, the orthodontics company Align Technologies provided the first major direct manufacturing usage of AM by applying SLA technology to rapidly manufacturing vacuum form molds for its patented process of teeth alignment therapy (Beaman et al. 2004). Siemens and Phonak represented some of the earliest successes in the medical industry of using rapid manufacturing at large scale. The companies used SLS to rapid manufacture hearing aids in 2002 (Beaman et al. 2004). Similar to Align Technologies, Boeing adopted AM techniques early and implemented on-demand rapid manufacturing for the production of non-flight-critical hardware on military aircraft. The U.S. Navy and Boeing partnered to introduce SLS components to reduce cost and decrease the number of components for the F/A-18 (Bourell, Leu, and Rosen 2009).

The late 1990s to early 2000s also saw important improvements in all the AM processes, as build speeds, build volumes, and operating temperatures improved and companies added new features to machines like the ability to print in color by Z Corporation in 2002 and multiple materials by Objet in 2007 (Wohlers 2012). The early 2000s also saw a gradual improvement in materials availability and quality for metals AM, although several experts suggested that quality did not achieve a level sufficient for direct part manufacturing until the late 2000s.

3. Recent Developments (2007 to Today)

Several important milestones occurred around 2007–2009 that greatly accelerated the industry's impact on manufacturing and society writ large. The first is the gradual shift from prototyping and tooling toward direct part manufacturing, which experts suggested occurred gradually between 2003 and 2009. This trend was due to several factors, including increasing part quality and materials availability, decreasing machine costs, and increased awareness of the technology's potential.

Around the same time two important efforts, the RepRap project in the UK (~2005) and the Fab@Home project at Cornell University (~2006) in the United States, produced machines designed for the home market. The growth of these consumer machines has been incredibly high; from around 60 sold in 2007 to 23,000 sold in 2011, the first year that consumer machines outsold professional machines (Wohlers 2012). The recent success of these projects and the consumer machine market can be attributed partly to the expiration of some of the initial foundational patents of the field, notably those related to fused deposition modeling, the process most current consumer machines use.

Also, around 2008–2009 several online companies began to offer new business models for consumers to get access to AM technology. Companies like Shapeways, Ponoko, and i.materialise (a division of Materialise) and recently Ebay, Etsy, and Amazon offer AM printing services online, including marketplaces where consumers can interact with product designers by uploading, downloading, and customizing digital designs. These companies offer fabrication services or sell designs for home fabrication.

Also in 2009, ASTM International formed Committee F42 on Additive Manufacturing Technologies to begin the process of standards development for the growing industry. This committee has since met semiannually to propose and revise AM standards as the field evolves. ASTM F42 consists of technical subcommittees, which focus on test methods, materials and processes, design (including data formats), and terminology.[12] The committee has grown to over 118 members from over 12 countries and represents industry, academia, and government.

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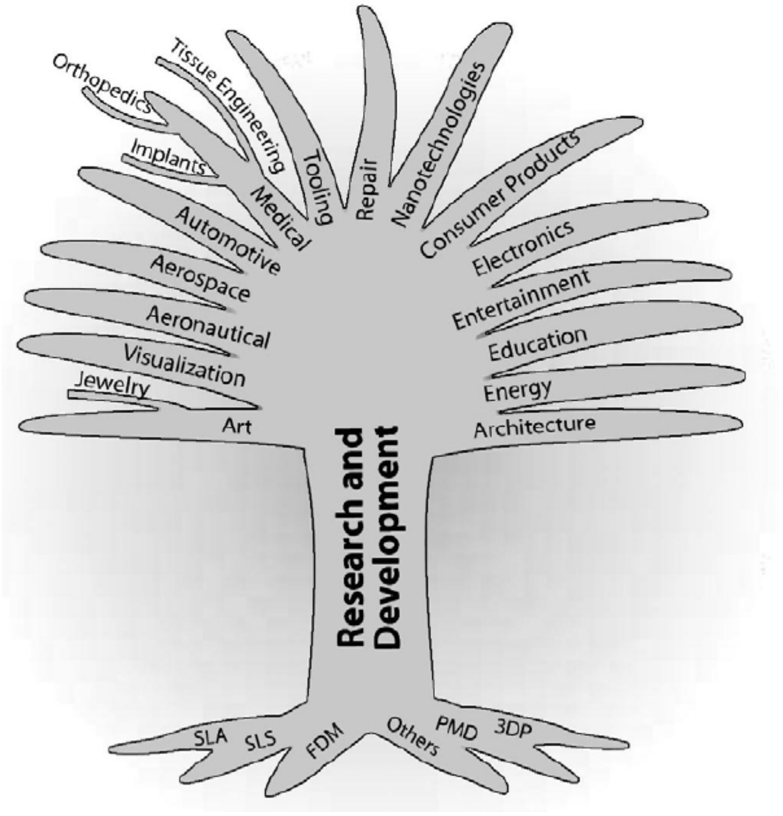
[12] Committee F42 on Additive Manufacturing Technologies, http://www.astm.org/COMMITTEE/F42.htm.

With all these important trends coinciding, researchers in academia, industry, and government held several workshops assessing the current state and future of the technology. One of the most influential was the 2009 Roadmap for Additive Manufacturing (RAM) Workshop, which was sponsored by NSF and ONR. As an output, the workshop created a document that serves primarily as a research roadmap (Bourell, Ming, and Rosen 2009). This document was one of the first that captured the plan for a national test bed center, which is now being realized in the form of the National Additive Manufacturing Innovation Institute (NAMII) in the United States. The document encapsulated the growth of the field out of its roots in R&D, as depicted in Figure 2. In the diagram, the tree shows the many processes of AM (roots) and the myriad applications (branches).

Multiple other workshops have been held in the last 3 years, with a focus on varying subgroups, including the Air Force and Navy (Kinsella 2011). Longer term efforts have also been coordinated through the Edison Welding Institute with the Advanced Manufacturing Consortium and its members (Scott et al. 2012).

A final major milestone occurred in 2012 with the solicitation and award of NAMII. This pilot institute aims to be the first in a national network of institutes and is solely focused on the development of AM. Among the members of the current institute are 40 companies, 9 research universities, 5 community colleges, and 11 nonprofit organizations. The effort was launched by five Federal agencies: the Department of Defense (DOD), Department of Energy (DOE), Department of Commerce (DOC), National Aeronautics and Space Administration (NASA), and NSF, who jointly committed $45 million to the initial institute. The NAMII was mentioned in President Obama’s 2013 State of the Union address, and initial awardees from the first call for R&D funding were announced in March 2013.



Source: Bourell, Leu, and Rosen (2009a).

Figure 2. Diagram of AM Processes and Applications

4. Future Trends

In the next decade, several trends will continue to improve additive technologies and make them more competitive with traditional manufacturing approaches. This section summarizes these trends based on Shipp et al. (2012), a report written by the co-authors of this report. Six particular trends are worth highlighting.

- *Process Improvements*—Future machines will increasingly utilize hybrid technologies that take advantage of the strengths of several types of additive and subtractive processes.
- *Speed*—The key will be the trade-off between feature size and speed, as one must typically be sacrificed for the other.
- *Quality Control*—Machines will increasingly incorporate quality control and produce parts with higher repeatability.
- *Materials*—Innovations may allow a broader material coverage by additive processes, expanding the current set of materials to include new polymers and biological materials.

- *Design Tools*—CAD software will facilitate complex geometry, parametric boundaries, complex materials, and geometry that can be tied to properties to enable complex designs.
- *Standardization*: Standardizing specifications will allow buyers and sellers to easily communicate the expected outputs from additive manufacturing.

With respect to process improvements, many of the experts consulted in the previous study (Shipp et al. 2012) said that in the coming years, processes will continue to improve, with some advancing more quickly than others. In the case of plastics, material extrusion, vat photopolymerization, and powder bed fusion are the current front-runners from a materials strength standpoint and will continue to improve. For metals, powder bed fusion technologies will continue to produce smaller feature sizes and smoother finishes.

Experts also said that future machines will increasingly utilize hybrid technologies that take advantage of the strengths of several types of additive and subtractive processes. Combining multiple additive processes for internal geometry and subtractive processes for better surface and material properties could produce a new generation of digital manufacturing machines with capabilities far exceeding what is possible today. One other development will be the automatic insertion of prefabricated components, such that additive processes could be combined with circuitry to create electromechanical systems.

With respect to speed, the coming years will see tremendous focus by machine manufacturers on increasing build speed through increased deposition rates, especially for powder-based processes. One method would create faster continuous-flow systems by moving from point processing to line, mask, or volume-based processing. An alternative approach is parallelization—using multiple lasers, e-beams, or melt pools simultaneously to build.

With respect to quality control, material issues, including thermal distortion between build layers and gas bubble inclusions, currently hamper the quality of output. Attention to these issues could lead to breakthroughs in the quality of additive-produced parts without the reliance on expensive post-processing techniques. But these breakthroughs will require the ability to sense material problems while they are occurring via closed-loop feedback systems. Many experts believe such systems will be widely in place in additive machines in the coming decade. New open architectures will allow more routine quality testing, as well as research into the basic science of thermal-distortion-layer issues.

As process improvements occur, there will be simultaneous attention given to the materials utilized in additive processes. Improvements will be achieved in single materials for additive processes, as well as new combinations of materials. New innovations may allow broader material coverage by additive processes, expanding the current set of materials to include new polymers and biological materials. Some materials may be designed specifically for additive manufacturing methods. Simultaneously, more competition among material providers should reduce the cost of materials for additive manufacturing. Innovations in machine and materials design could also allow powder recycling, further reducing materials costs.

There is also a large move toward multiple material machines, along with the requisite controls and software needed to simultaneously manufacture with heterogeneous materials. A particularly high-value application for additive manufacturing could be in functionally graded materials, where geometries or materials are graded through the component volume to provide additional functionality.

There will be challenges to achieving these new designs, notably in the education of designers and the capabilities of CAD software. Current CAD has problems with complex geometry, parametric boundaries, complex materials, and tying geometry to properties. New software providers will begin offering CAD solutions, particularly with respect to the growing consumer design market. This new generation of consumer CAD will be significantly simpler and more intuitive for nonspecialists.

As these technological improvements are being made, significant effort will take place in standardizing specifications for products made by additive processes. Currently, the same digital design has a substantial variation in material and surface properties, depending on the machine it is built with, the operator using the machine, and other local environmental conditions. ASTM International (in particular the F42 committee) is working to create specifications for different materials and processes so that buyers and sellers can easily communicate the expected outputs from additive manufacturing.

B. Role of Publications

1. Research and Media Publications

The early- to mid-1990s saw a growth in important publications and professional organizations in the field. With the increasing number of companies in the industry at this time, Terry Wohlers began producing the Wohlers Report, which provides sweeping coverage of the AM industry and its developments. He published the first issue in 1993 and has published the report annually since then. In 1995, the *Rapid Prototyping Journal* was also established, providing academic researchers an important outlet for their research. As discussed above, the proceedings of the Solid Freeform Fabrication Symposium, started in 1990, also provided academic researchers and others with an important outlet for publishing their research.

In addition to examining the cited literature from patents,[13] the experts were asked about their perceptions on the role and importance of publications throughout the history of the AM field. When asked to identify the most important publications in the field's development, their responses varied considerably. While a minority of experts (7 of 17 who responded to the question) suggested that either the main peer-reviewed academic journal, *Rapid Prototyping Journal*, or the proceedings from the SFF Symposium have been important for the field's development, an equal number of experts suggested that there were no academic publications that had influenced the field in a major way. Predictably, most of the experts who felt that either *RPJ* or the SFF proceedings had been influential were from academia, while the majority of industry respondents suggested that such publications had not been instrumental for the field.

A number of experts from both academia and industry suggested the importance of two non-academic publications—the Wohlers Report (five experts) and a series of reports in the popular media, notably in *The Economist* (four experts)—and one textbook (three experts) (Gibson, Rosen, and Stucker 2010). The Wohlers Report is widely seen as a primary reference for the industry and for newcomers to the topic, whereas popular media in recent years have served to promote the concept of AM to the general public.

When pressed to identify the importance of any single paper, only one paper was mentioned by more than one expert (Agarwala et al. 1995a). The remainder of the responses noted either single papers mentioned by only one expert or an opinion that no single papers had been particularly influential. Table 7 shows the results.

As a result of the findings on publications from the expert discussions, the study team conducted only a short bibliometric analysis. Citation analyses of the academic journals in the AM field revealed that NSF supported research contributed to two papers (Agarwala et al. 1995a, 1995b) that are among the most cited in the peer-reviewed *Rapid Prototyping Journal*. "Post-Processing of Selective Laser Sintered Metal Parts" (Agarwala et al. 1995b) appeared in *Rapid Prototyping Journal* in late 1995. The paper acknowledges the support of three funding agencies: ONR, Texas Advanced Technology/Research Program, and NSF. The NSF support came from the NSF Division of Design and Manufacturing Systems (DDM) (Grant # DDM-9312603). The research presented in this paper is an immediate follow-up to "Direct Selective Laser Sintering of Metals" (Agarwala et al. 1995a) a paper in the prior issue and the most cited paper in *RPJ*, according to Thomson Reuters' Web of Science.

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[13] For example, almost half (48) of the 100 historically important patents included literature references in the patents.

Table 7. Publications Listed by Experts as Having Influenced the AM Field

Publication	No. of Experts
Rapid Prototyping Journal	7
SFF Symposium Proceedings	7
None; publications unimportant	7
Wohlers Reports	5
Economist articles	4
Gibson, Rosen, Stucker Textbook	3
Agarwala, Bourell, Beaman, Marcus, and Barlow	2

Note: Only responses receiving greater than one expert citation are listed.

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2. Roadmaps and Technology Evaluations

In addition to mentioning traditional academic publications, industry reports, and popular media, the literature and experts both identified the importance of periodic technology assessments and industrial roadmaps that have been conducted throughout the history of the field. Two reports done in 1997 and 1998 and two industrial roadmaps in 1998 and 2009 are widely cited in the literature and are discussed as known outputs of public support for AM (see Chapter 3, Section A). Three of these four reports were supported by NSF and ONR. The Defense Advanced Research Projects Agency (DARPA), Department of Commerce (DOC), and National Institute of Standards and Technology (NIST) provided additional support for some of them:

- *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan* (Prinz et al. 1997) with support from NSF, DOE, DARPA, ONR, and DOC.
- *The Road to Manufacturing: Industrial Roadmap for the Rapid Prototyping Industry* (NCMS 1998).

- *WTEC Workshop on Additive/Subtractive Manufacturing R&D in Europe* (2003) with NSF, DARPA, ONR, and NIST.
- *Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing* (2009) with NSF and ONR.

C. Events and Conferences

Literature and experts were also consulted to examine the importance of events and conferences to the field's development. Table 8 shows the most common responses. Most experts believed that conferences and workshops have played a role in advancing the technology, particularly in the early years of the field. The SFF Symposium held at the University of Texas-Austin was widely seen in literature and expert discussions as influential because it was the first meeting where many of the researchers working on additive technologies came together and discussed them. Fourteen of the 17 experts who offered an opinion on conferences agreed that the SFF Symposium had been important to the field, since it provided an avenue for academics to publish applied research, it introduced many of the original players in the field, and it has been held annually since 1990.

Table 8. Conferences Listed by Experts as Having Contributed to Development of the AM Field

Conference	No. of Experts
Solid Freeform Symposium	14
SME RAPID	9
Nottingham Meeting	7
Additive Manufacturing Users Group (AMUG)	5
EuroMold	4
Advanced Research in Virtual and Rapid Prototyping (VRAP)	4

Note: Only responses receiving greater than 1 expert citation are listed.

Experts also mentioned other workshops and conferences as important. Nine experts said that the SME RAPID conference, which has existed formally since 1993, was seen as important for industry to understand potential applications of AM and to bring together original equipment manufacturers, machine manufacturers, and service bureaus. A similar mostly industrial conference in Europe, Euromold, was mentioned by four experts. The Nottingham University conference, (now known as the International Conference on Additive Manufacturing & 3D Printing), was mentioned by seven experts as being important to bringing together the research community in Europe, and the VRAP conference in Portugal (established 2003) was seen in much the same light. Finally, the AMUG, which started as a group founded in the late 1980s associated with users of 3D Systems and DTM's machines, was discussed by five experts as important, particularly for machine manufacturers to meet with and understand how their customers were using the technology.

D. Impact of NSF Support (Evidence from Discussions only)

In addition to directly examining NSF funding and conducting other analyses for this study (see Chapters 4-6), we asked experts directly if they knew of significant contributions that NSF has made to the field. Table 9 shows all responses that were mentioned by more than one expert. Note that nearly half of the experts (8 of 20) did not feel qualified to answer this question. This may show that contributions NSF has made have not been widely recognized in the field, regardless of their size.

Table 9. Expert Opinions on Impacts of NSF Support

NSF Contribution	No. of Experts
Roadmapping/Benchmarking	6
SFF Symposium Student Support	4
UT Powder Processes	3
MIT 3D Printing Process	3
Contour Crafting	2

The largest number of experts (six) mentioned the international technology roadmapping and benchmarking exercises that NSF has supported over the years—most notably the 2009 Roadmap for Additive Manufacturing conference co-sponsored with ONR. This workshop and report was widely seen as an important milestone for defining future research directions for the field, although some in industry felt that the industry representation was not large enough. As discussed above, since the SFF Symposium's impact on the field is well known, those researchers who were aware of NSF support for this conference cited it as important. The symposium has received funding support over the years from NSF and ONR. ONR provided financial support starting in 1993 and continuing through the 2013 meeting. NSF supplemented the ONR funding for the meeting beginning in 1998, and with the exception of the 2003 meeting, NSF's support was also continuous through the 2013 meeting. ONR has supported the core conference expenses over time; the NSF funding has supported student attendance only.

Interestingly, although NSF's early support for University of Texas and MIT researchers has likely had the greatest commercial impact (see case studies in Chapter 6), this support was not widely cited by the experts. Perhaps this shows, once again, that NSF's early support for the technology is not widely recognized or, again, that establishing such attribution to a single institution is extremely difficult.

Several experts suggested that they know NSF has broadly supported the academic community, but the comments were not specific. A smaller number of respondents mentioned support for the contour crafting process at the University of Southern California (two experts), Small Business Innovation Research (SBIR) support (one), support for education and training grants (one), and support for the MIT Center for Bits and Atoms (one). Note that a small minority of experts suggested that NSF's impact has been smaller than it could have been due to a lack of consistent support for the field, a lack of strategy in its portfolio of funded research, or a tendency to fund less immediately realizable or commercially ready (fundamental) processes. We assess NSF's consistency in support in Chapter 6. The tendency to fund less commercially ready technologies is in line with the role of NSF relative to more applied R&D agencies within the broader innovation system.

E. Role of Other U.S. Government Agencies

The expert discussants were asked about which other U.S. Government funding agencies had made an impact on the development of the field. In general, experts produced similar lists of agencies and had some limited knowledge of the impacts of each agency. Table 10 shows total counts of agencies mentioned by the 17 experts who answered this question. The experts believed that DARPA, ONR, NSF, and DOE have had the most impact on the field, with some experts also noting impact from NASA, NIST, and other DOD agencies.

Table 10. Expert Assessment of U.S. Funding Agency Impact on AM Field

Agency	Agency Abbrev.	No. of Experts
Defense Advanced Research Projects Agency	DARPA	15
National Science Foundation	NSF	13
Office of Naval Research	ONR	11
Department of Energy	DOE	9
National Aeronautics and Space Administration	NASA	6
Department of Defense	DOD	5
Air Force Research Laboratory	AFRL	5
National Institute of Standards and Technology	NIST	4
Army Research Laboratory	ARL	4

Note: Only agencies mentioned by more than one expert are shown. Several other agencies were mentioned by one expert, including the Federal Bureau of Investigation, Defense Logistics Agency, Army Corps of Engineers, National Institutes of Health, and the U.S. Patent and Trademark Office.

Experts believed that DARPA and ONR had both supported the field strongly and relatively continually since its inception, including particularly important early support for ceramics research from DARPA and early support for the SFF Symposium from ONR.

Experts generally believed that NSF, DARPA, and ONR have provided relatively steady support for the field, though with different focuses in line with agency missions—NSF providing more open-ended support for basic science questions, and DARPA and ONR striving more toward applications, particularly related to aerospace and defense. Several experts mentioned that NSF and DOD support has often worked in tandem, with initial support for an idea coming from NSF and further (and often larger) support from DARPA, ONR, or other DOD entities (for an example, see case study on contour crafting in Chapter 6).

Unsurprisingly, experts' assessments of the relative impact of the different agencies were colored by personal experience: those who had received substantial NSF support generally gave NSF significant credit for the field's development, and those who had received substantial DARPA funding tended to give more credit to DARPA. Academics also gave more credit generally to NSF, while those from industry gave more credit to DOD agencies and DOE. DOD research laboratories like AFRL and ARL have also conducted applied research in AM for many years, and AFRL is now the executive agent in the government for the NAMII.

A smaller number of experts also mentioned the impact of DOE, NASA, and NIST. DOE provided substantial early support for AM research at national laboratories, including notably Sandia National Laboratories, which was foundational in the invention of the Optomec LENS process, the first directed-energy deposition process. DOE has also recently provided substantial support through the NAMII and the Oak Ridge National Laboratory's Manufacturing Demonstration Facility, which works with midsize to large manufacturers to examine AM applications.

For over a decade, NASA has researched AM processes like electron beam fabrication at Langley Research Center and Marshall Space Flight Center, with the eventual goal of building spare parts in space to avoid the need for heavy and costly spare parts libraries during launch. In 2013, NASA funded a start-up called Made in America to take a 3D printer (utilizing material extrusion technology) to the International Space Station. NASA's Innovative Advanced Concepts (NIAC) program has also supported contour crafting, funding researchers at USC to apply the technique to researching their application to build lunar habitat.

NIST has largely been involved in AM standardization, taking a leading role in the ASTM F42 process.

Note that a number of industry experts said that they did not believe U.S. or international public funding had a large impact on the field except through the obvious role of training of graduate students and researchers for private industry to subsequently hire. These experts tended to believe that private research and development conducted within AM companies and between AM companies and other manufacturing companies has largely driven the field’s development. This opinion held across different technologies.

F. The Global Context: International Funding Agencies

While this study is focused on U.S. public funding, several experts from Europe were also consulted to help examine the impacts of public funding outside the United States and any differences that may exist. We also built on the primary authors’ prior work in the area (Shipp et al. 2012).

In general, the impact of European funding on the AM field, as seen by leading AM experts in Europe, has been relatively limited, described mostly as encouraging applications for the technology rather than developing new and innovative processes, materials, etc.

Several experts said that due to differences in university-industry interactions and funding priorities between the United States and European Union, European funding (such as through the European Commission or national governments) in manufacturing technology requires industry participation and cost sharing more often than in the United States. This requirement in turn can shape research goals toward more applications-based research, with industry (and academia) seeking answers to specific manufacturing problems. This generality is well exemplified by the early origins of EOS, a worldwide leader in laser sintering. While European co-funding was provided for a major project that helped the company in its initial phase, the funding was a minority share compared with industry funding provided by BMW and Electrolux, and the goals of the research were driven more by user needs than by European funding agencies. Individual projects such as these were reported to have been relatively common throughout the 20-year history of AM, although experts noted that neither the European Commission nor any national governments have had major programs focused specifically on AM (though the recently funded Centre for Innovative Manufacturing in Additive Manufacturing at the University of Nottingham and Loughborough University represents a recent exception).[14]

As with leaders in American industry and academia, European experts agreed that a major role for public funding has been and continues to be educating future researchers for private industry to hire and designers who understand the strengths of the technology.

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[14] This center, which the United Kingdom’s Engineering and Physical Sciences Research Council (EPSRC) funded in 2011, brings together two UK universities, several AM machine companies, and other manufacturers for collaborative research.

G. Future Public Support for Additive Manufacturing

AM has come a long way from its active development and commercialization, which began in the 1980s, to the point that now there are dozens of successful machine manufacturers and material and service companies. While the momentum of the past few years may suggest to some that AM has “arrived,” substantial challenges remain before the technology becomes truly mainstream. These challenges include bringing down costs, developing new materials, achieving consistency and standardization, developing new design tools and educating designers, and increasing process speed. These needs cut across the roles of both industry and public support and reflect a variety of technology readiness levels. Thus, there is no clear delineation of where future public support from basic and applied science and technology agencies would be most helpful to advancing the field.

STPI researchers asked experts to comment on areas that would benefit from future support from science agencies such as NSF. Table 11 summarizes their responses. In general, the responses closely follow many of results of the 2009 roadmapping exercise—one expert even recommended directly using the roadmap as a guide for investments—though the level of emphasis varied substantially, with from one expert to nine experts mentioning a particular topic.

The most common response was related to scientific development for design and optimization models, including improved AM-capable CAD modeling and optimization models comparing different AM processes for different designs. Several of the next most common answers dealt with materials, from developing new materials for AM processes (six), improving materials properties without compromising build speed (five) and increasing functionality through processes with multiple materials (four). Several experts encouraged investment in the education of AM technologists (who could immediately join the AM workforce) or designers more broadly, since AM processes are better able to compete with traditional manufacturing processes when parts are designed to take advantage of AM’s features. Two of these experts specifically mentioned NSF support for workforce development within the NAMII as a critical component of the overall initiative. Support was also recommended, though by fewer experts, for needs identified in the roadmap such as faster processes (three) and closed-loop controls (three), perhaps suggesting that the applied nature of these advancements is better suited to industry or other agencies.

Some experts suggested that it was important for agencies such as NSF not to overspecialize, instead focusing on the role AM could play within cyber-enabled or digital manufacturing as a whole (four responses), how to couple additive techniques with subtractive techniques (two responses) and, general scientific support as the field progresses (two responses). Some also focused on the possibility of developing or advancing new application areas for AM technologies, including existing ones such as biomedical applications (two responses) and printable electronics (one response), as well as new application areas entirely (one response). Finally, a small minority mentioned small business support (two responses) and support for small inventors to receive access to AM services.

On the whole, these suggested directions match relatively well both the role of NSF within the science and technology community and the role it has played in the AM field in the past. As Chapter 5 will show, NSF has already provided support for AM materials development, new process development, design tools, and education. That the single most mentioned area for future support is design and optimization models and the fourth highest is education fits well with the growing amount of NSF support for education-type awards. On the other hand, the declining support for design tools and software may be of concern, as experts in the field feel that such tools are still lacking.

Table 11. Topics Mentioned by AM Experts that Would Benefit from Future NSF Support

Topic	No. of Experts
Design/optimization models	9
New materials development	6
Improved materials properties	5
Education of designers and researchers	4
Use of multiple materials in the same build	4
Exploring role of AM within cyber/digital manufacturing	4
General science for AM	3
Faster processes (existing or new)	3
Closed-loop control/evaluation	3
Interagency/field-wide coordination	2
Hybrid additive/subtractive manufacturing	2
Get program officers experienced with AM	2
Educational support for NAMII	2
Nanoscale AM	2
Biomedical applications	2
Meso/large-scale am	2
Small business support	1
AM access for small business inventors	1
Use roadmap to guide investments	1
Printable electronics	1
Am software security	1
New applications for AM	1

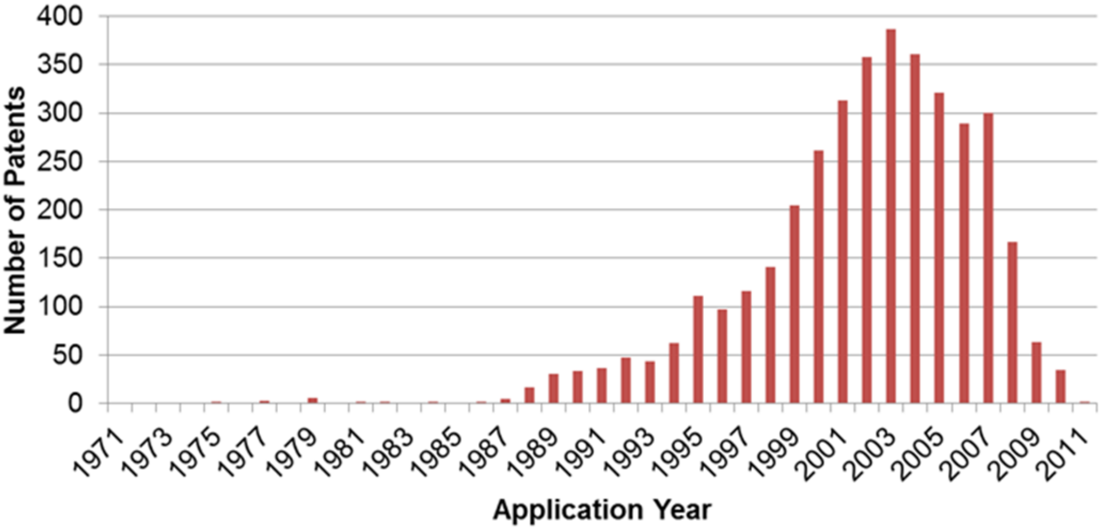
4. Patent Analysis

A. Description of the Complete Patent Data Set

As noted in Chapter 2, the overall patent database includes 3,822 AM patents between 1975 and 2011.

1. The “Universe” of AM Patents

These 3,822 patents are associated with 4,708 unique inventors. As Figure 3 shows, the participation of individuals patenting in the AM field was initially stagnant until around the late 1980s, thereafter significantly increasing and peaking in 2003. However, this peak is at least partly due to the time lag between application and publication date and should not be interpreted as a drop-off in AM R&D.[15]



Note: Patents are plotted by application year rather than publication date to emphasize the time of invention.

Figure 3. Distribution of AM Patent Universe through Time

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[15] According to the database of issued patents, the number of patents decreases after 2003. But note that, although this could indicate a decrease in activity over the past decade, some portion of this decrease is due to the time lag associated with the patenting process that is not captured in the analysis. For instance, there may be patents filed after 2003 that are under review and not yet issued, so they are not included in the database. For patents in the patent database, the time lag can range from 4 months to 11 years.

Of the 3,822 AM patents, 3,403 (89%) listed an assignee organization. The vast majority of patents (75%) in the database are issued to corporations, while academic organizations make up a much smaller share (9%), with government, international research sponsors, and nonprofits and medical research centers making up the remaining 5% (Table 12).

Table 12. Assignee Organizations by Type for 3,822 AM Patents

Organization Type	No. of Patents	Percentage of Patents
Global industry	2,882	75%
University	345	9%
Government	55	1%
International research sponsors (nonprofit)	98	3%
U.S. nonprofit and medical research centers	23	1%
No assignee organization	419	11%

The database contains 722 unique organizations associated with the 3,403 patents listing an assignee organization. Figure 4 displays this set of patents with the type of assignee organization over time. Patenting activity from industry increased significantly starting in the late 1980s, with 596 total companies (83% of organizations) patenting in the AM field. Around the 1990s, a small number of universities, including the University of Texas, MIT, Clemson, and University of Southern California, also started to produce AM patents. In total, 66 universities (9%) have supported AM patents over the past two decades. Later into the mid-1990s, government agencies, such as the U.S. Navy and NASA; international research sponsors, such as Germany’s Fraunhofer Institutes; and U.S. nonprofit and medical research centers, such as SRI International, began to increase support of AM patents, representing 10 (1%), 13 (2%), and 37 (5%) of the total organizations, respectively.

Based on the location information on the patents, assignee organizations are located globally across 30 countries and the United States as shown in Figure 5 and Figure 6. U.S. organizations make up 72% (2,451) and international organizations 28% (952) of the 3,403 patents with assignee organization information. Within the United States, assignee organizations are located in 45 of the 50 states, with the highest representation in California (656, 17%), Idaho (237, 6%), and Massachusetts (212, 6%).

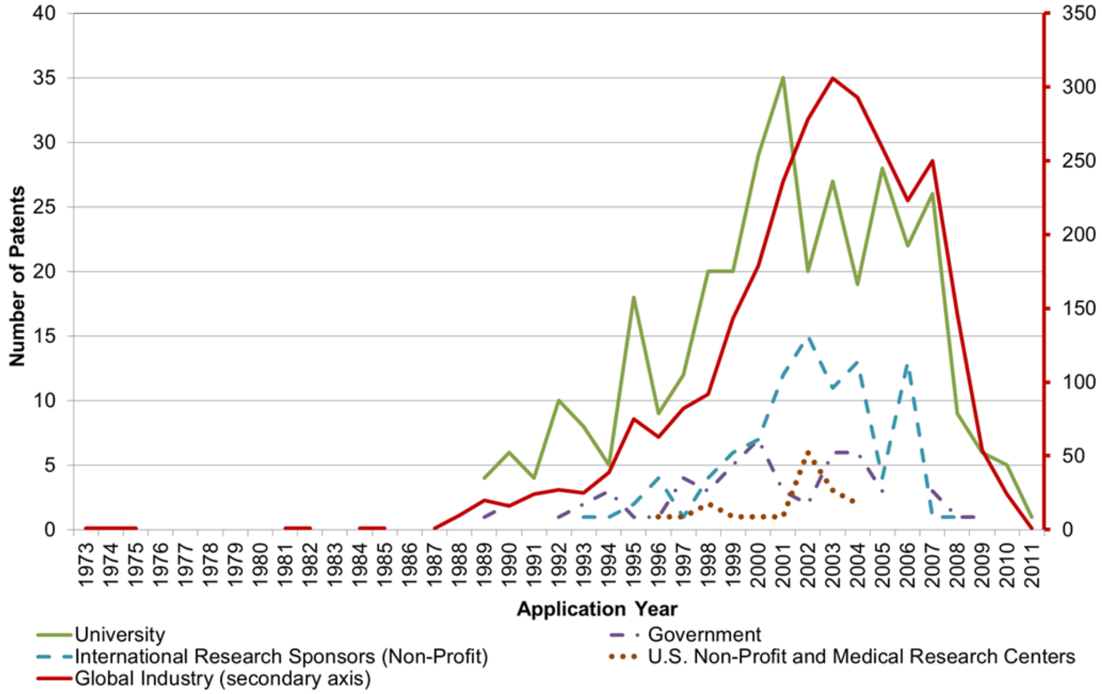
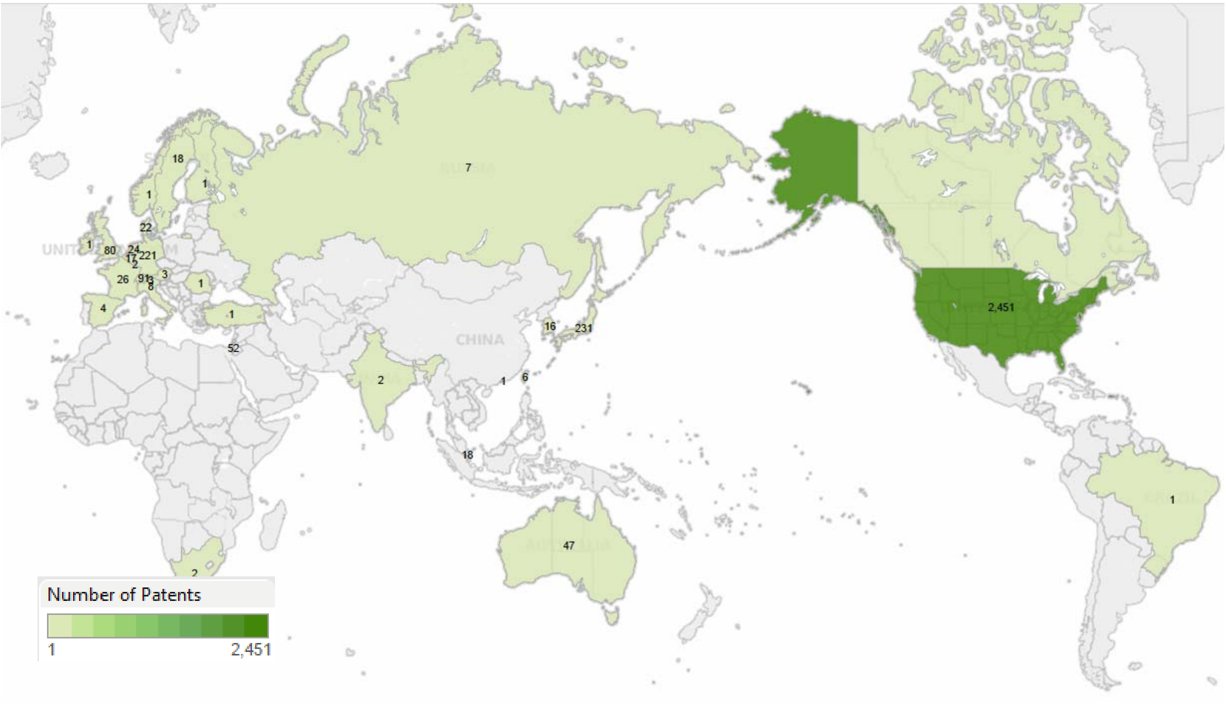
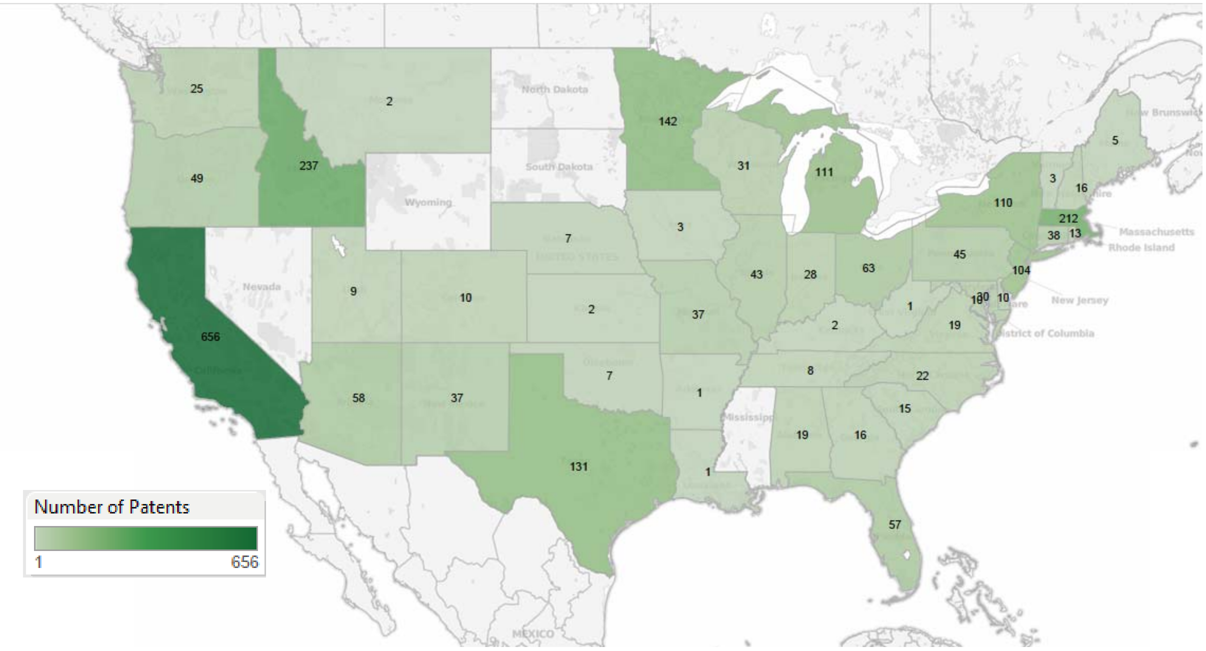


Figure 4. Distribution of Patent Application Years for Assignee Organizations by Type for 3,403 AM Patents



Made with Tableau Public software.

Figure 5. Global Locations of Assignee Organizations for 3,403 AM Patents, 1975–2011



Made with Tableau Public software.

Figure 6. State Locations of Assignee Organizations for 2,451 AM Patents in the United States, 1971–2011

2. Top 20 Inventors

Table 13 shows the top 20 most prolific inventors in the AM patent database; they have produced 610, or 16%, of the AM patents reviewed in this study. Most of the top 20 inventors were sponsored by multiple organizations as Table 13 shows. Universities have played a minimal role in sponsoring research for the top 20 inventors compared with industry. Only two universities are listed as assignees—the University of Southern California and MIT. Some of the industry organizations are large industry machine manufacturers such as 3D Systems and Stratasys. Others are spin-offs of, or mergers with, other companies (e.g., Aptina Imaging Corporation was created as a spin-off of Micron Technology's Image Sensor Division in 2008, and 3M acquired LingualCare in 2007).[16]

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[16] The multiple organizations per inventor also suggests that individuals may have changed organizations over time. For instance, Charles Hull, founder of stereolithography and 3D Systems, worked at UVP Inc. when he filed for the initial patent on the technology. Adam Cohen worked at the University of Southern California for several years to develop microfabrication technology with support from the DARPA prior to founding Microfabrica. Industry partnerships with academic organizations are another dimension shown through this patenting activity. For example, Michael Cima, a professor at MIT since 1986, has many patents issued from MIT and a few sponsored by Therics, a company that uses 3D printing to manufacture biomedical devices.

Table 13. Top 20 Inventors and Their Assignee Organizations Representing 893 of the 3,822 AM Patents

Inventor (Last Name, First Name}	Total Patents	Organization 1	No. of Patents	Organization 2	No. of Patents	Organization 3	No. of Patents	Organization 4	No. of Patents	Patents with No Assignee
Farnworth, Warren	94	Micron Technology	93	Aptina Imaging Corporation*	3	—	—	—	—	1
Smalley, Dennis	84	3D Systems	52	Microfabrica	30	—	—	—	—	2
Hull, Charles	69	3D Systems	64	Seagate Technology.	1	UVP Inc.	1	—	—	3
Chishti, Muhammad	62	Align Technology	62	—		—	—	—	—	—
Cohen, Adam	61	Microfabrica	38	University of Southern California	13	3D Systems	10	—	—	—
Wood, Alan	47	Micron Technology	44	Aptina Imaging Corporation*	2	—	—	—	—	1
Rubbert, Rudger	43	Orametrix	36	3M	4	LingualCare^	2	Natural Dental Implants	1	—
Wen, Huafeng	42	Align Technology	41	Inpronto	1	—	—	—	—	—
Kuo, Eric	41	Align Technology	41	—		—	—	—	—	—
Akram, Salman	40	Micron Technology.	38	Aptina Imaging Corporation*	2	—	—	—	—	—
Silverbrook, Kia	38	Silverbrook Research	38	—		—	—	—	—	—
Lockard, Michael	36	Microfabrica.	28	3D Systems	8	—	—	—	—	—
Weise, Thomas	35	Orametrix	30	3M	3	LingualCare^	—	—	—	2
Phan, Loc	32	Align Technology	31	Sonitus Medical	1	—	—	—	—	—
Collins, David	30	Ford	15	Hewlett-Packard	10	Visteon Global Technologies	3	—	—	2
Cima, Michael	29	MIT	25	Therics	3	Children’s Medical Center	1	—	—	—
Sachdeva, Rohit	29	Orametrix	29	—		—	—	—	—	--—
Grigg, Ford	28	Micron Technology	28	—		—	—	—	—	—
Kirby, Kyle	28	Micron Technology	25	Aptina Imaging Corporation*	3	—	—	—	—	—
Batchelder, John	25	Stratasys	22	IBM	3	—	—	—	—	—

* Aptina Imaging Corporation, which was created as a spin-off of Micron Technology’s Image Sensor Division in 2008.

^ LingualCare, founded by top 20 inventor Rudger Rubbert, was acquired by 3M in 2007.

3. Top 30 Assignee Organizations

The top 30 most prolific assignee organizations, shown in Table 14, represent 1,660 patents (49%) of the total 3,403 patents that listed an assignee organization. The majority of patents produced by the top organizations is from industry and include machine manufacturers as well as companies that apply AM technologies in various sectors, such as Align Technology, maker of Invisalign, and Therics Inc. in the health and medical sector. A smaller number of top universities and government departments and laboratories also play a role in research and patenting activities.

Table 14. Top 30 Assignee Organizations Representing 1,660* of the 3,403 AM Patents

Assignee Organization	No. of Patents
Global Industry	**1,461**
Micron Technology Inc.	230
3D Systems Inc.	211
Align Technology Inc.	186
Ciba Specialty Chemicals Corp.	82
Stratasys Inc.	71
3M Innovative Properties Company	66
The Boeing Company	57
EOS GmbH	48
Microfabrica	48
Siemens	47
Ford	45
Hewlett-Packard	44
Fujifilm	41
Silverbrook Research Pty. Ltd	38
Orametrix Inc.	37
Phonak AG	32
Objet Geometries	28
United Technologies Corporation	26
E.I. DuPont de Nemours and Company	23
Z Corporation (now 3D Systems)	23
DSM N.V.	20
General Electric	20
Honeywell International Inc.	19
Optomec	19
Therics Inc.	18
University	**138**
Massachusetts Institute of Technology	69
University of Southern California	38
University of Texas	31
Government	**43**
U.S. Navy	24
Sandia National Laboratories	19

* The total number of unique patents is not equal to the sum of the patents since patents can have multiple assignee organizations.

4. Direct Patent Attribution: The Government Context

Government sponsorship for a patent entails direct government funding for research that yields an invention.[17] Based on the 1980 Bayh-Dole Act, Federal patent policies require Federal grantees to include on U.S. patent applications a *government interest* clause—a statement acknowledging that the government supported the invention and has certain rights to it. NSF adopted the requirement by issuing 45 CFR Part 650.4(f)(4), which delineates the grantee action to protect the government interest:

> The grantee agrees to include, within the specification of any United States patent application and any patent issuing thereon covering a subject invention, the following statement: "This invention was made with Government support under (identify the grant) awarded by the National Science Foundation. The Government has certain rights in this invention."

There are similar regulations for Small Business Innovation Research (SBIR) grants, based on the current Small Business Administration policy directive on SBIR.[18]

Institutions receiving government funding agreements are required to report related inventions to a Federal system called *Interagency Edison* (*iEdison*), which was designed specifically so that the funding recipients can comply with the Bayh-Dole and SBIR requirements. Institutions can submit inventions, patents, and invention utilization reports to any number of Federal agencies through this single user interface, which has been in place since 1995.[19]

The government interest clause in U.S. patent applications can be searched for government interest and attribution to specific agencies. The majority of patents (3,542, 93%) in the AM patent database are reported to be sponsored by nongovernmental sources, as shown in Table 15. Conversely, 280 of the patents in the database do contain a government interest clause. Of the total 3,822 patents, 204 (5%) have been sponsored by

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[17] If sponsorship was less direct (e.g., sponsoring graduate students producing the innovation, sponsoring work in previous years that paved the way to the innovation), an inventor is not likely to identify the government as having had a role in developing the patent.

[18] The policy states:

> (v) Patents. Include an appropriate statement concerning patents. For example: "Small business concerns normally may retain the principal worldwide patent rights to any invention developed with Government support. In such circumstances, the Government receives a royalty-free license for Federal Government use, reserves the right to require the patent holder to license others in certain circumstances, and may require that anyone exclusively licensed to sell the invention in the United States must normally manufacture it domestically. To the extent authorized by 35 U.S.C. 205, the Government will not make public any information disclosing a Government-supported invention for a minimum 4-year period (that may be extended by subsequent SBIR funding agreements) to allow the awardee a reasonable time to pursue a patent."
>
> (vi) Invention Reporting. Include requirements for reporting inventions. Include appropriate information concerning the reporting of inventions, for example: "SBIR awardees must report inventions to the awarding agency within 2 months of the inventor's report to the awardee. The reporting of inventions may be accomplished by submitting paper documentation, including fax."

[19] See http://www.iEdison.gov.

government agencies other than NSF (including DOD, DOE, and NASA) from 1979 to 2011.

Table 15. Government and Non-Government Sponsorship of 3,822 AM Patents

Sponsor	Patents	Percentage
Non-Governmental Organizations	3,542	93%
Other Government Sponsors (Except NSF)	204	5%
NSF	76	2%

a. Direct Patent Attribution

So that we could analyze direct patent attribution of NSF in the grant data, the USPTO extracted within the Government Interest data field for us. As Figure 7 shows, NSF is identified in 76 (27%) of the 280 patents between 1992 and 2011 with a government interest clause. As would be expected, universities dominate these 76 NSF-sponsored patents. Patents with NSF attribution peaked in the early 2000s, as shown in Figure 8, which shows the total number of AM patents with NSF attribution per year, reaching a maximum yearly total of patents in 2000 (9 patents).

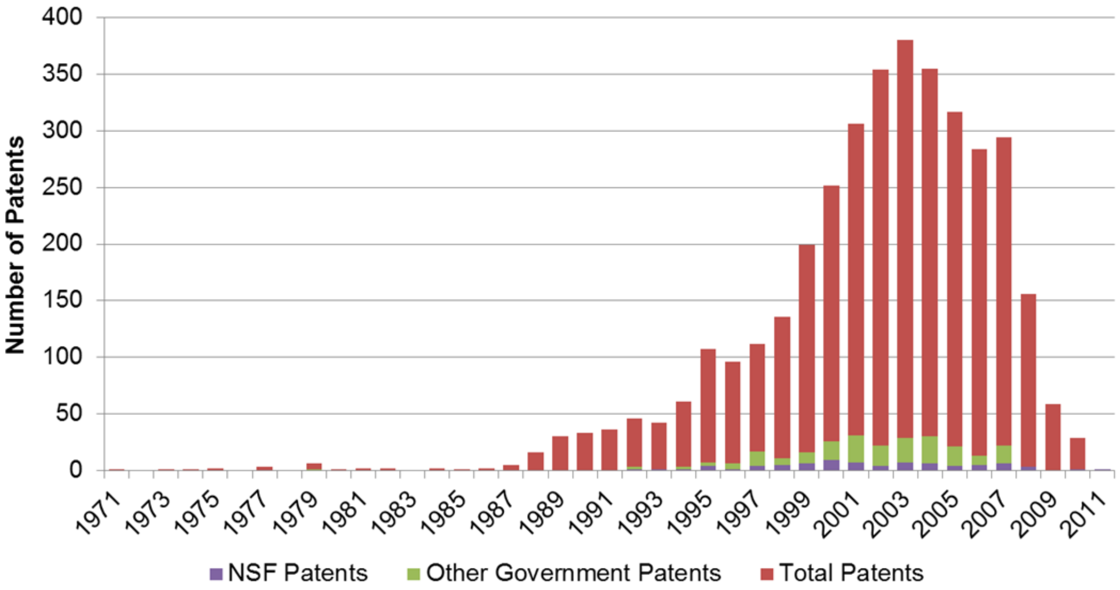

Figure 7. Industry Dominates U.S. Patents in AM

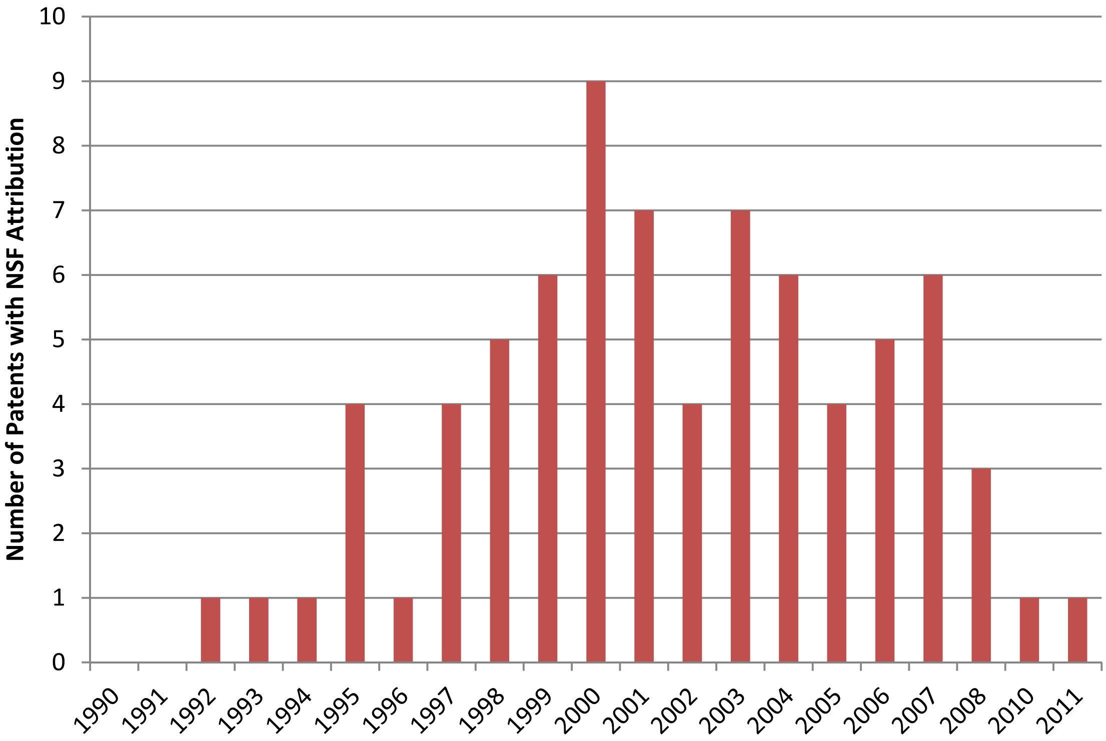

Figure 8. Total U.S. Patent Awards with NSF Attribution in the Government Interest Clause by Year

Table 16 breaks down the assignee organizations of these NSF-attributed AM patents. University patents that attribute NSF in the government clause are led by the Massachusetts Institute of Technology, where 24 MIT patents in the AM patent database can be directly linked to the agency.

In addition, in the AM patent database, three corporations have patents with NSF attribution in their government interest clause. These companies are Nanotek Instruments Inc., Grassroots Biotechnology Inc., and Microfabrica; two of these three NSF-sponsored industry assignees received an SBIR grant, and one received a research award from the Directorate for Biological Sciences.

Table 16. University Patents in the AM Patent Database That Have NSF Support in Their Government Interest Clause

University	Total (*n* = 65)
Massachusetts Institute of Technology	24
Northwestern University	6
University of Southern California	5
University of California	5
University of Illinois	3
Princeton University	2
University of Dayton	2
University of Iowa Research Foundation	2
Stanford University	2
Texas A&M University System	2
William Marsh Rice University	2
Cornell University	1
Georgia Tech Research Corporation	1
Harvard College	1
New York University	1
Rensselaer Polytechnic Institute	1
The Research Foundation of State University	1
Tufts College	1
University of Arizona	1
University of Colorado	1
University of Washington	1

b. NSF Principal Investigators in the Patent Database

Because funding agencies can have impact beyond direct research sponsorship for an invention (e.g., if earlier or later funding supported the development of the technology; see the case studies below), the study team performed an additional analysis to determine the extent of potential impact outside of direct government sponsorship. The principal investigator (PI) names (and corresponding awards and institutions) were extracted from the NSF awards database (see Chapter 6) and compared to the list of inventors from the AM patent database. This query produced a list of 345 AM patents (9% of the total 3,822) that have an inventor who is also a PI in the NSF awards database. Of those patents, 104 (30%) had a government interest clause, with 48 of them (14%) acknowledging NSF specifically. Thus, taking a broader perspective of potential impact of NSF funding increased the total number of NSF-associated patents from 2% of all AM patents to 9%. But note that this is likely an overestimate of the number of patents affected by NSF research because it only represents a link between a minimum of one inventor and one NSF PI and because the research funded by NSF may have been wholly unrelated to the patented technology (even if both are relevant to AM).

B. Top 100 Historically Important Patents

As discussed in Chapter 2, STPI identified what could be considered the top 100 patents in the field of AM, and this list is provided in Appendix E.

1. Distribution over Time

The findings for the patent analysis are similar to those for the literature review. The top 100 patents also follow several phases of development in the field of AM (Appendix E). Besides the early phase of patenting dating back to the 1800s, there was an initial phase of modern discoveries, which increased rapidly in the late 1980s. Connecting patent data with our discussions with experts shows that this time period included the stereolithography-related inventions from Hull and others at 3D Systems as the company began to expand its patent portfolio and the selective laser sintering related inventions from Deckard and the UT researchers.

By the mid-1990s, two technologies—one by Crump on material extrusion and one by MIT researchers on binder jetting—became prominent in the field. Meanwhile, 3D Systems and UT continued to patent and expand their claims.

This was followed by a later phase of process improvements and technology applications from the late 1990s and onward (see Figure 9). Some of the recent important processes in the top 100 include Optomec and Sandia National Laboratory’s LENS process, Solidica’s ultrasonic object consolidation, and the direct laser sintering of metals by Suman Das and Beaman at University of Texas. AM technology applications starting in the late 1990s include Align Technology’s Invisalign products and Micron Technology’s fabrication of semiconductor devices.

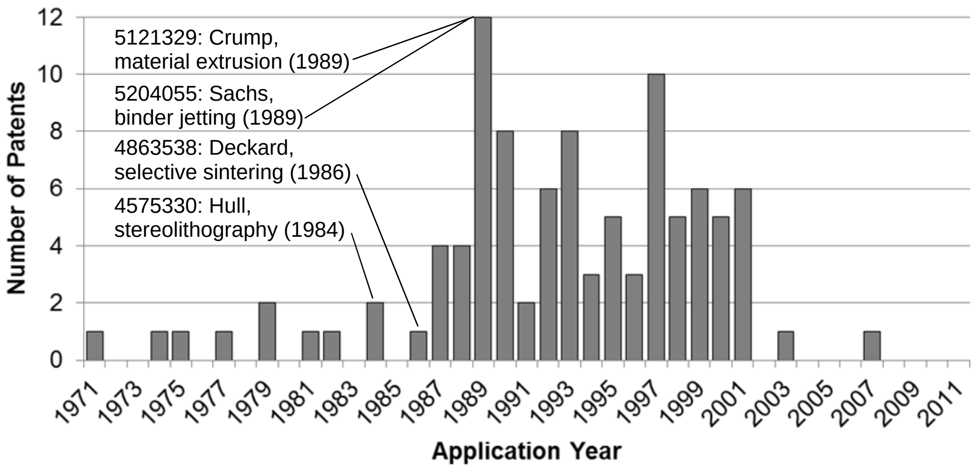

Figure 9. Top 100 Historically Important U.S. AM Patents, Including 4 Patents Identified as Foundational

2. Attribution to Government

Five government agencies or departments played a role in sponsoring 9 (9%) of the top 100 historically important patents (refer to Appendix E for government interest information). The U.S. Navy was an early sponsor of Clyde Brown’s work in directed energy deposition (U.S. Patent No. 4323756, filed in 1979). NSF would play a later role in the early 1990s, sponsoring work at MIT on binder jetting and its application in biomedical devices and tissue regeneration by professors Michael Cima and Linda Griffith (U.S. Patent Nos. 5387380, 5490962, and 5518680). DOE-supported patents from Los Alamos National Laboratory (U.S. Patent No. 5837960) and Sandia National Laboratories on Optomec’s LENS (U.S. Patent No. 6046426) were important discoveries filed in the mid-1990s. The U.S. Air Force and NASA have also contributed to sponsoring the top 100 historically important patents (U.S. Patent No. 6833234 on fabrication of photo-resistant layers and U.S. Patent No. 7168935 on the use of electron beam technology, respectively).

3. Interconnections and Diffusion of Knowledge over Time

Using publicly available software, we mapped the interconnections between the top 100 patents and produced four additional maps that show their role in citing the four foundational patents (see Figures 10–12 and Appendix G). These maps show relationships between patents through their citations, as well as connections that identify the diffusion of knowledge among the top-cited patents over time.

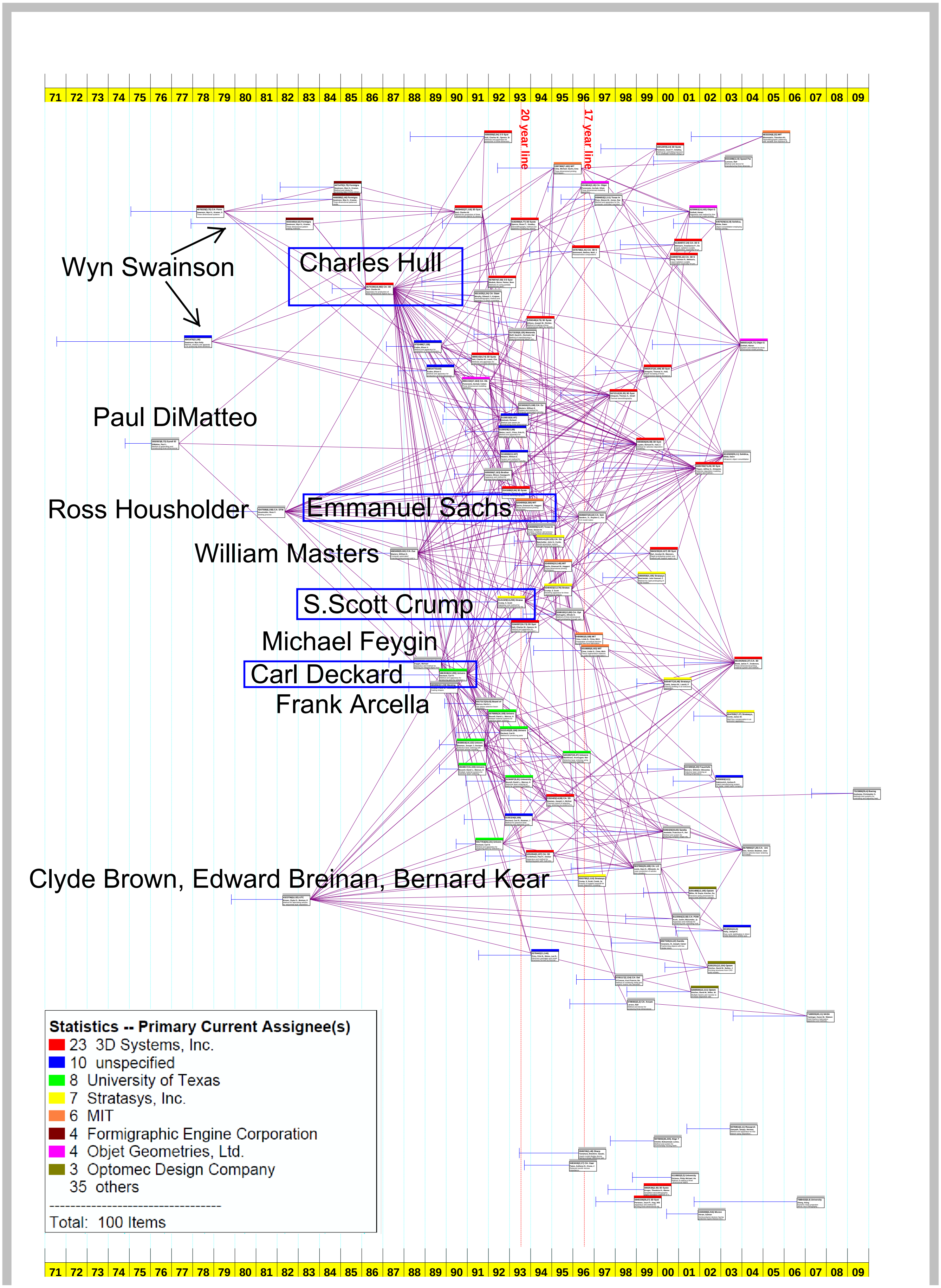

Figure 10. Top 100 Historically Important Patents and Relationships Between Patents Based on Citations, showing 4 Foundational Patents (boxes) and Inventors with Patents Issued Prior to the 4 Patents.

Figure created using patent analytics software from IPVision (http://www.see-the-forest.com)

Note: The location of the box indicates the patent issue year while the left whisker indicates the patent application year.

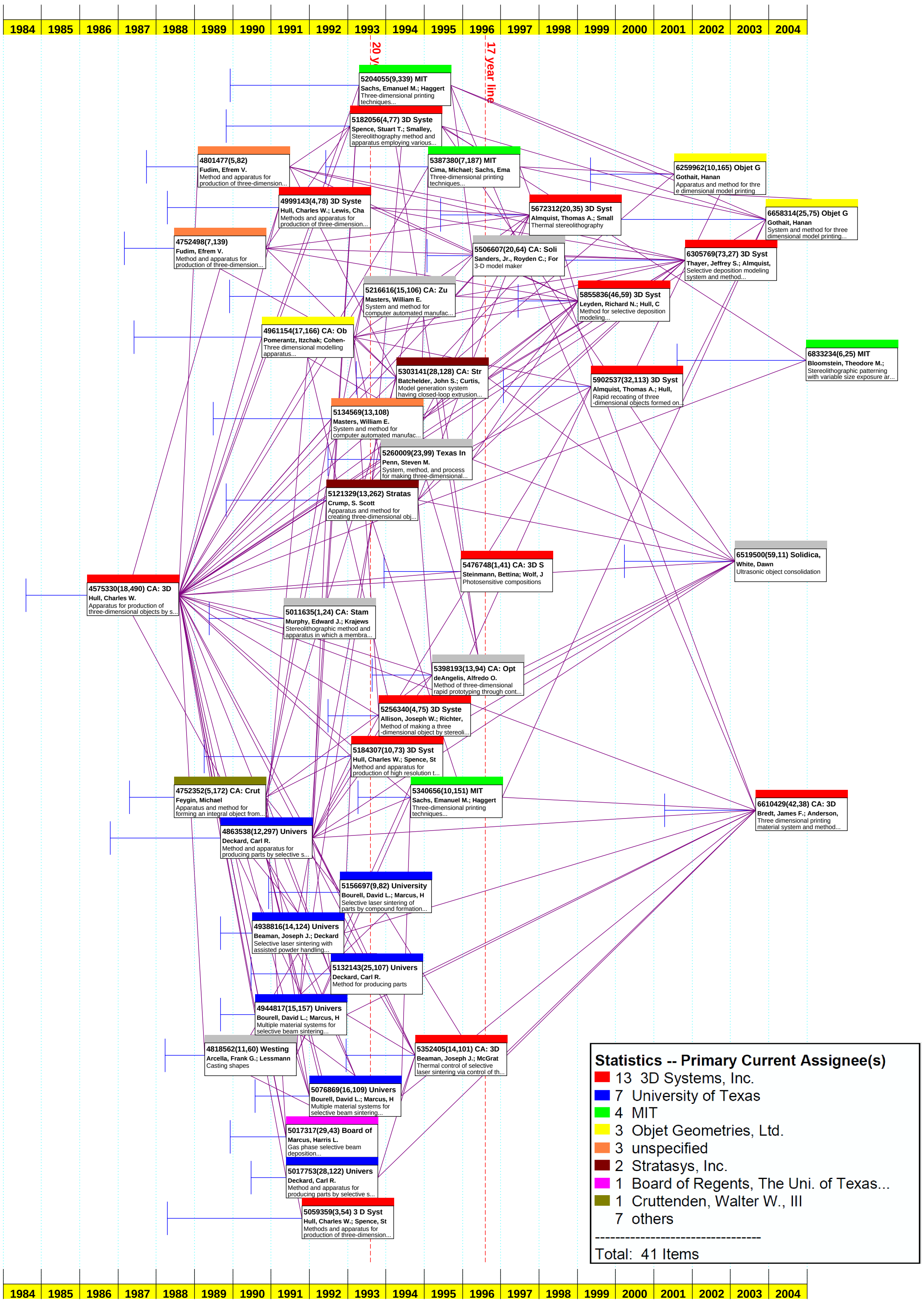

Figure 11. 40 Historically Important Patents Citing U.S. Patent No. 4575330 and Relationships Between Patents Based on Citations.

Figure created using patent analytics software from IPVision (http://www.see-the-forest.com)

Note: The location of the box indicates the patent issue year while the left whisker indicates the patent application year.

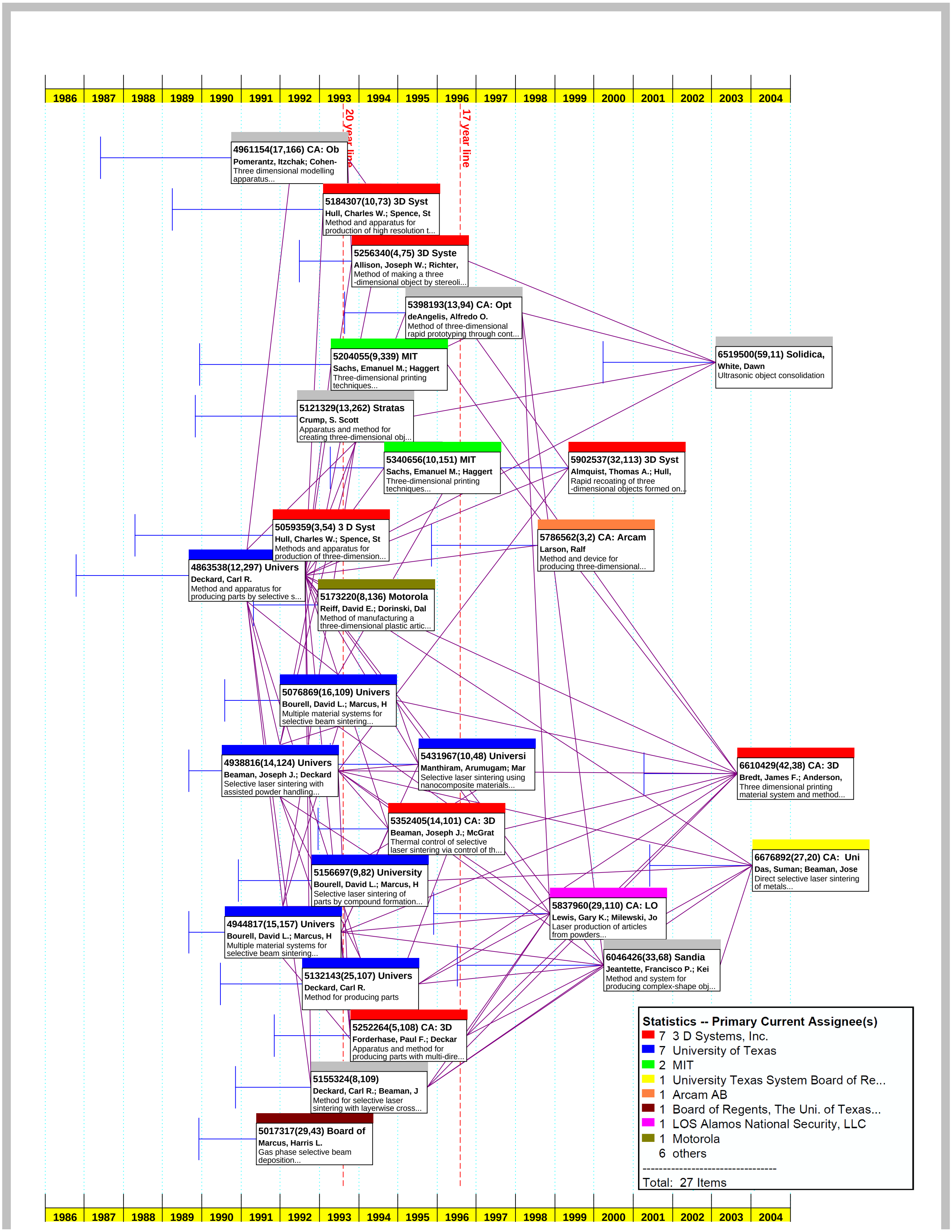

Figure 12. 26 Historically Important Patents Citing U.S. Patent No. 4863538 and Relationships Between Patents Based on Citations.

Figure created using patent analytics software from IPVision (http://www.see-the-forest.com)

Note: The location of the box indicates the patent issue year while the left whisker indicates the patent application year.

The overview map for the top 100 patents indicates that AM patent activity was particularly strong during the early to mid-1990s. The four maps on foundational patents also confirm that this time period was significant in the development of important technologies in the field, many of which were commercially successful. The maps also show that the terms for some important patents have already expired, with many more soon to expire.

Forty-four of the top 100 patents cite U.S. Patent No. 4575330, Hull's invention of stereolithography. These include the three other foundational patents and Feygin's sheet lamination patent. Notably, nine (20%) are from UT on selective laser sintering; four (9%) are from MIT researchers on binder jetting; and two (5%) are from Stratasys on material extrusion, indicating that Hull's patent was significantly influential in developing these processes (see Appendix G for further details on the cited MIT patents). Other important technologies influenced by several of Hull's and 3D Systems patents are Solidica's ultrasonic object consolidation, William Masters' ballistic particle manufacturing (BPM), and material jetting from Solidscape (formerly Sanders Prototypes Inc.) and Objet. The largest fraction of the 44 patents (13, 30%) was issued to 3D Systems as the company expanded its patent portfolio and acquisitions (e.g., purchase of DTM).

Twenty-nine of the top 100 patents cite U.S. Patent No. 4863538, Deckard's patent on selective laser sintering (SLS). These include two other foundational patents on material extrusion and binder jetting.20 Other citing patents include eight from UT (28%) and eight from 3D Systems (28%), which indicates the influence of UT-sponsored inventions on 3D Systems' commercial strategies and industry competitiveness.21 The map also shows that the development of the Optomec LENS process at Sandia National Laboratories , electron beam technology by Ralf Larsson at Arcam, and direct metal laser sintering by Das (a UT graduate student) were key technologies influenced by several of UT's seminal SLS patents.

Sixteen of the top 100 patents cite U.S. Patent No. 5121329, Crump's material extrusion patent. These include one foundational patent on binder jetting.[22] Five of the 16 patents (31%) are issued to Stratasys, 3 (19%) to 3D Systems, and 3 (19%) to MIT researchers on binder jetting. Crump's patent also influenced ultrasonic technology and BPM.

Eight of the top 100 patents cite U.S. Patent No. 5304055, Sachs et al.'s binder jetting patent. Three patents (38%) are assigned to MIT researchers who continued development of the technology for biomedical applications. Two patents are also assigned to Objet (25%)

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[20] The third foundational patent preceded U.S. Patent No. 4863538.

[21] Some of the patents currently assigned to 3D Systems have been acquired through the purchase of DTM, the initial assignee.

[22] The two other foundational patents preceded U.S. Patent No. 5121329.

and one to Sanders Prototype Inc. (13%), indicating the influence of Sachs et al.'s patent on the early development of material jetting and two commercially successful companies.

4. International Patents in the List of Top 100

The 14 international patents that were identified through the patent tally were issued by several countries, the European Patent Office (Table 17), and the World Intellectual Property Organization from 1973 to 2009 (Table 18).

Table 17. Issuing Country or Patent Organization of 14 International Patents in the AM Field

Country/Patent Office	No. of Patents
Finland	1
France	2
Germany	2
Japan	2
United Kingdom	2
European Patent Office	4
World Intellectual Property Organization	1
Total	**14**

Pierre Ciraud's German patent for manufacturing objects from melted material from 1973 is widely recognized as the origin of directed energy deposition, one of the seven ASTM standard AM processes. Note that because we did not conduct an exhaustive search of international literature or ask experts about important international patents, the 14 international patents that were identified through these sources are not claimed to represent the most historically important international patents in the AM field.

Table 18. Fourteen International Patents, Applications, and Disclosures in the AM Field

Patent Number	Issue Year	Inventor(s) and Patent Title
German Patent DE 2263777	1973	Ciraud, P., “Process and Device for the Manufacture of any Objects Desired from any Meltable Material”
Japanese Patent Application, Sho 51 [1976]-10813	1974 (Filed)	Matsubara, K., “Molding Method of Casting Using Photocurable Substance”
French Patent (not found)	1984	Andre, J –C., Le Mehaute, A., and De Witte, O., “Apparatus for making a model of an industrial part”
Japanese Patent JP02153722	1984	Marutani, Y., “Optical molding method”
Finnish Patent 91725	1990	Nyrhilä, O. and Syrjälä, S., “Manufacture of dimensionally precise pieces by sintering”
Great Britain 2307439 B	1997	Dickens, P.M and Hague, R.J.M, “Method Of Making A Three-Dimensional Article”
European Patent 0738584	1997	Mattes et al., “Method and Apparatus for Producing a Three-Dimensional Object”
European Patent 0758952	1998	Serbin et al, “Process and device for manufacturing three-dimensional objects”
German Patent DE19649865	1998	Meiners, Wissenbach and Gasser, “Selective Laser Sintering at melting temperature”
French Patent FR2790 418-A1	1999	Allanic A.-L., P. Schaeffer
European Patent 1144146	2000	Meiners et al., “Vorrichtung für das selektive Laser-Schmelzen zur Herstellung eines Formkörpers”
European Patent 1234625	2002	Lindemann and Graf, “Verfahren und Vorrichtung zur Herstellung eines Formkörpers durch selektives Laserschmelzen”
WO 02/36331 A2	2002	Herzog F. and Herzog K., “Device for Sintering, Removing Material and/or Labelling by Means of Electro magnetically Bundled Radiation and methods for Operating the Device”
Great Britain 0317387	2003	Hopkinson, N., “Method and apparatus for selective sintering of particulate material”

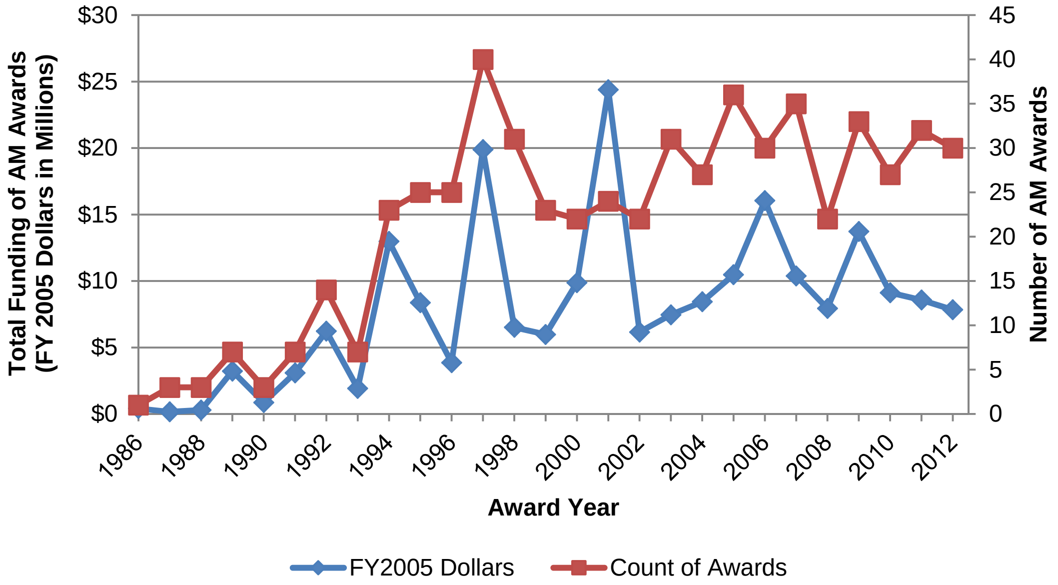
5. Analysis of NSF Awards for Additive Manufacturing

As discussed in Chapter 2, a corpus of relevant NSF awards in the AM field was identified using a keyword-based approach. This approach was necessary because awards relevant to AM are spread throughout several different programs across multiple Directorates at NSF, partly due to the structure of NSF itself and partly because NSF has never had a program dedicated to AM-related technology development and research. Chapter 2, Section C describes the method used to select these awards, and this chapter presents our analysis of the NSF awards database created for this study.

A. Funding by Directorate and Division

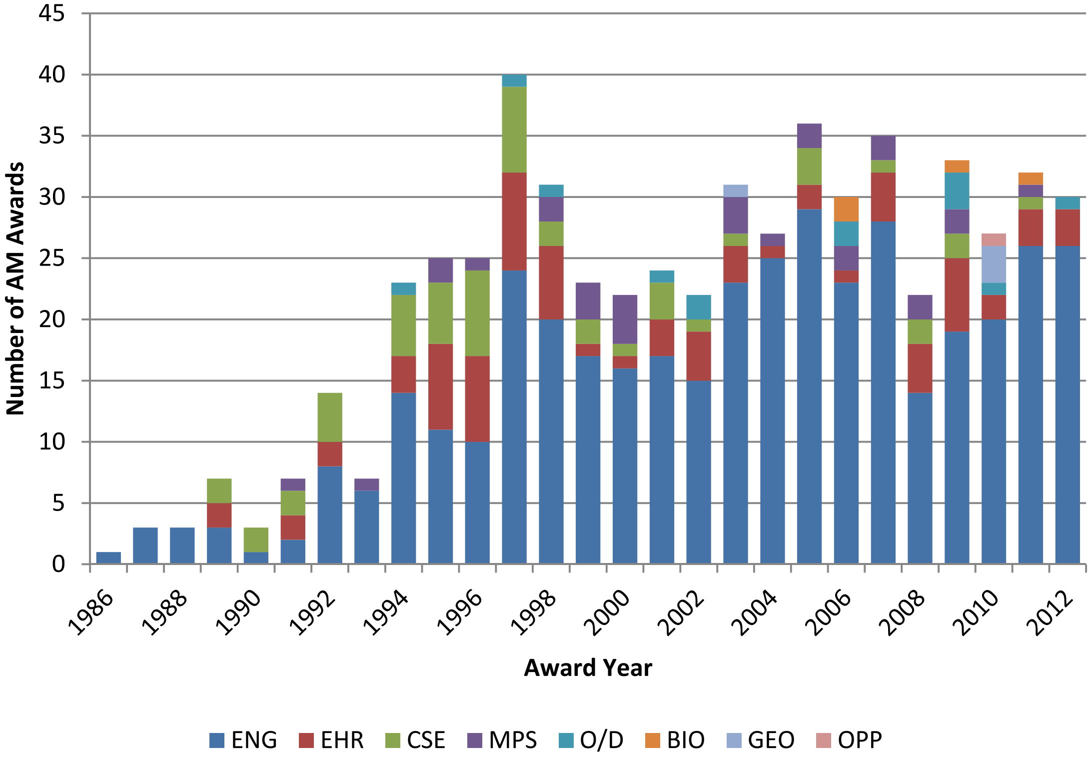
The first NSF award in the AM field was granted in 1986, and a total of 583 awards were granted from 1986 to 2012. Only a handful of awards were given each year in the early years up through 1993, followed by a marked and sustained increase from 1994 onward. Funding for NSF AM awards has increased over time on average; however, funding levels have oscillated on a year-to-year basis. The peak for AM funding was 2001, due in large part to a $15.6 million grant for MIT's Center for Bits and Atoms. Figure 13 displays the number of awards and funding levels over the duration of the field. All the funding amounts in this and the other figures in this section have been deflated to FY 2005 dollars using OMB Deflators—Historical Table 10.1, GDP Chained Price Index (standard deflators used in U.S. Government budgeting).

Figure 14 provides descriptive data for each NSF directorate's or office's involvement over time. NSF's Engineering Directorate's (ENG) share of both the number of awards and the funding amounts has ranged from ~40% to 70% in most years. In total, as Table 19 shows, ENG has funded approximately 53% of the total cumulative funding for AM, with Computer Science (CISE) funding 21% and Education and Human Resources (EHR) funding 14%, representing the majority of the rest. Note that the single award for MIT's Center for Bits and Atoms represents nearly 8% of total NSF funding.



Note: The AM award set spans six Directorates and two Offices at NSF, with the Directorate for Engineering (ENG) granting the majority of awards and funding, followed by Computer and Information Science and Engineering (CISE) and Education and Human Resources (EHR) directorates.

Figure 13. NSF AM Awards over Time



Note: Table 19 provides the full names of the NSF Directorate/Office abbreviated here.

Figure 14. NSF AM Awards by Directorate/Office

Table 19. Aggregate AM Awards per NSF Division, 1986–2012

NSF Division, by Directorate/Office	Total Awards	Total Funding (FY 2005 Dollars)
ENG—Engineering	**404**	**$113,647,546**
CMMI—Civil, Mechanical and Manufacturing Innovation	253	$75,914,167
IIP—Industrial Innovation and Partnerships	101	$20,335,025
ECCS—Electrical, Communications and Cyber Systems	12	$5,949,443
CBET—Chemical, Bioengineering, Environmental, and Transport Systems	25	$5,753,783
EEC—Engineering Education and Centers	11	$3,805,000
EFRI—Emerging Frontiers in Research and Innovation	2	$1,890,129
EHR—Education and Human Resources	**75**	**$27,939,524**
DUE—Undergraduate Education	68	$23,723,269
DRL—Research on Learning in Formal and Informal Settings	5	$3,799,783
HRD—Human Resource Development	2	$416,472
CSE—Computer and Information Science and Engineering	**53**	**$49,642,954**
CCF—Computing and Communication Foundations	24	$25,896,467
EIA—Experimental and Integrative Activities	16	$13,451,916
IIS—Information and Intelligent Systems	6	$5,403,582
CNS—Computer and Network Systems	7	$4,890,988
MPS—Mathematical and Physical Sciences	**29**	**$10,917,559**
DMR—Materials Research	24	$9,890,618
DMS—Mathematical Sciences	4	$607,410
CHE—Chemistry	1	$419,531
O/D—Director	**13**	**$10,578,687**
EPS—Experimental Program to Stimulate Competitive Research	1	$7,052,363
OCI—Cyberinfrastructure	2	$2,892,649
OISE—International Science and Engineering	10	$633,676
GEO—Geosciences	**4**	**$538,435**
EAR—Earth Sciences	2	$447,146
OCE—Ocean Sciences	2	$91,289
BIO—Biological Sciences	**4**	**$915,574**
DEB—Environmental Biology	1	$481,147
DBI—Biological Infrastructure	1	$220,456
IOS—Integrative Organismal Systems	2	$213,971
OPP—Polar Programs	**1**	**$90,122**
ARC—Arctic Research Commission	1	$90,122
Grand Total	**583**	**$214,270,401**

Note: Some division names have changed within the time period represented by the data. These assignments are per the NSF Award Database at the time of writing.

An important set of awards is related to NSF’s Strategic Manufacturing (STRATMAN) Initiative, a program that funded manufacturing technology development from 1989 to 1996. Of the 27 relatively large research grants ($600,000–$900,000) made through this program, totaling approximately $20 million (in 2005 dollars), 5 were related to AM. These 5 awards, themselves totaling nearly $5 million (2005 dollars), include two early awards in 1989 to leading innovators in the field—Joseph Beaman et al. of the University of Texas and Emanuel Sachs et al. of MIT. As Chapter 7 explores in greater detail, these early grants were highly influential in the creation of laser sintering (powder bed fusion in the F42 nomenclature) and 3D printing (binder jetting), some of the initial technologies in the field.

Within the 8 larger NSF Directorates and Offices, 25 different divisions have granted AM awards. Table 19 lists the total number of awards and award dollars for each division. The Division of Civil, Mechanical, and Manufacturing Innovation (CMMI)[23] within ENG has historically been the most involved in the field, with the Division of Industrial Innovation and Partnerships (IIP) within ENG, the Division of Undergraduate Education (DUE) within EHR, and Computing and Communication Foundations (CCF) within CISE also having large roles. The broad coverage of AM-relevant awards is notable—although some divisions like CMMI, IIP, and DUE are the highest contributors, divisions from other diverse areas like materials (DMR in the Math and Physical Sciences Directorate) and computing (CCF) have also contributed significant sums.

Within the largest division (CMMI), two programs have historically covered most AM technology awards—Materials Processing and Manufacturing (MPM) and Manufacturing Machines and Equipment (MME). Around 2000, the core of AM funding was shifted from MPM to MME, mostly to balance workload due to declining applications in the MME program and increasing applications in MPM.

B. AM Topic Areas

NSF’s involvement in the AM field has covered a range of topics, including materials development, process development, education, and design tools. To consistently classify the NSF AM award set, the study team developed a set of major topic areas and manually labeled each award with the topic areas using the award’s abstract or final report if available. The awards naturally split into eight major groups:

- *Machine processes*—developing AM systems; producing proof-of-concept parts

  Example: “Part Generation by Layerwise Selective Sintering”

- *Materials processing*—developing or adapting AM processes for new materials; researching AM materials science and materials processing

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[23] Formerly known as Division of Design, Manufacture, and Industrial Innovation (DMII).

Example: “Design and Fabrication of Graded Materials with the Laser Engineered Net Shaping Process”

- *CAD/solid modeling*—awards that contribute to the functionality of AM-relevant CAD systems and solid modeling research

  Example: “Toward Super-Robust Geometric Computation for Complex Component Design”

- *Design tools*—applying and adapting traditional CAD to the AM sphere as a design tool; developing AM design methodologies

  Example: “Design Automation for Solid Freeform Fabrication”

- *Medical*—applying AM for biomedical use

  Example: “SBIR Phase I: Automatic Fabrication of Custom-Fit Hearing Instruments Using Rapid Prototyping Technology”

- *Education*—implementing, employing, or promoting AM for any education level

  Example: “Teaching Concurrent Engineering Principles Using a Rapid Prototype Machine”

- *Strategy/implementation*—exploring broad feasibility, application areas, and/or implementation strategy for AM

  Example: “National Center For Rapid Prototyping and Additive Manufacturing Technologies (RAPIDTECH)”

- *Conference*—supporting conferences, workshops, and other forums

  Example: “Solid Freeform Fabrication Symposium; Austin, Texas”

Within these topic areas, machine processes and materials processing received the first and second largest amounts of NSF funding and number of NSF awards, respectively. Figure 15 shows the total number of NSF awards each topic area has received, and Figure 16 shows the total amount NSF funded each topic area. The charts present a similar picture of the overall breakdown of funding, with the exception of conferences and strategy/implementation awards. Here, the pattern is opposite, with strategy/implementation representing fewer awards than conference but a greater share of the funding due to the larger average award size.

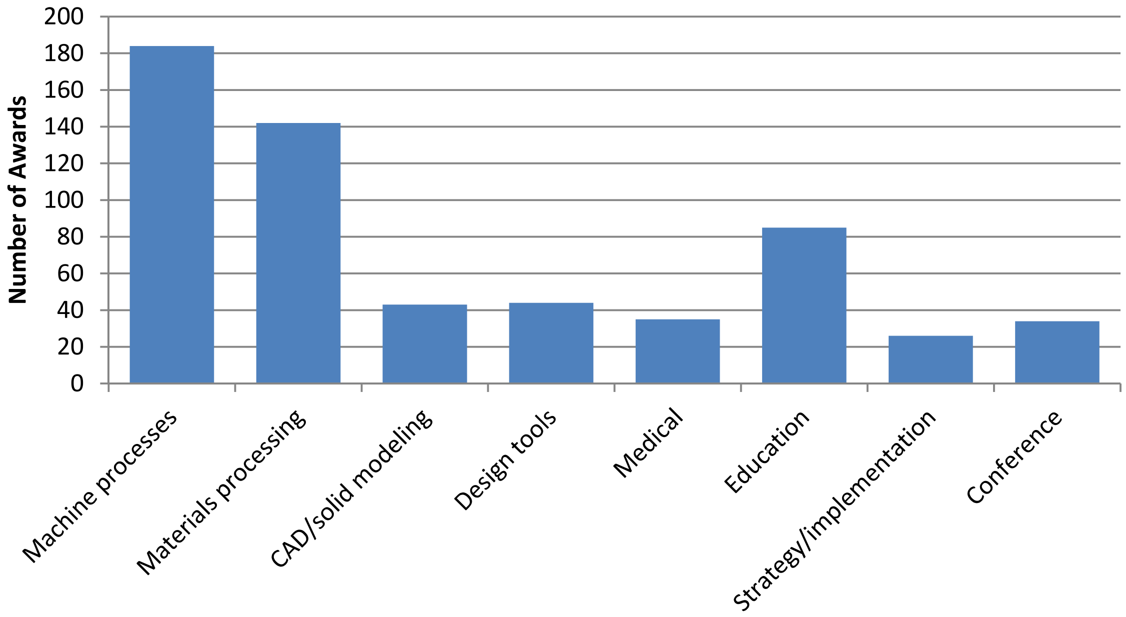


Figure 15. Total Number of NSF AM Awards (1986–2012) by Award Topic Area

The breakdown of funding by type over time is also relevant. Figure 17 shows this breakdown of total funding provided each year for each award topic area. The shares of different topical areas have seen substantial year-to-year variability. This variability is intuitive given that NSF has never had a program specific to AM. Machine processes and materials processing have seen relatively steady support since the mid-1980s, generally accounting for around half of total funding. Design tools represented the next largest portion of the portfolio in the earlier years of the field, but have declined over time as more awards and funds have been granted for strategy/implementation and education awards. Although this apparent shift was not purposefully planned, it does make sense given that AM technologies were maturing through the 1990s and early 2000s toward the point of application and implementation in new fields, which in turn requires education of new designers and researchers.

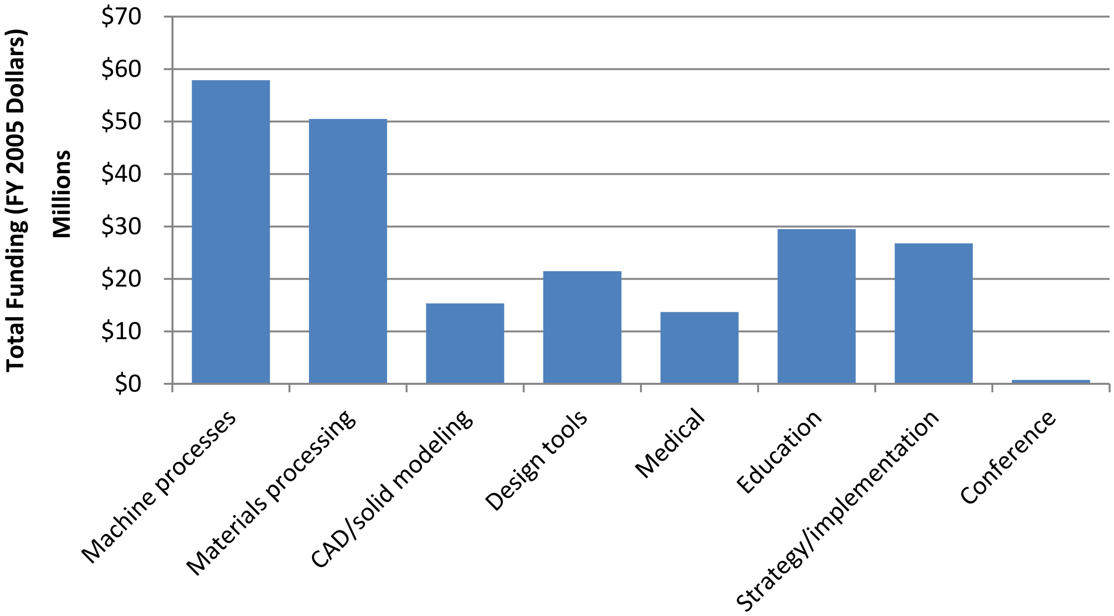


Figure 16. Total NSF AM Funding by Award Topic Area (1986–2012)

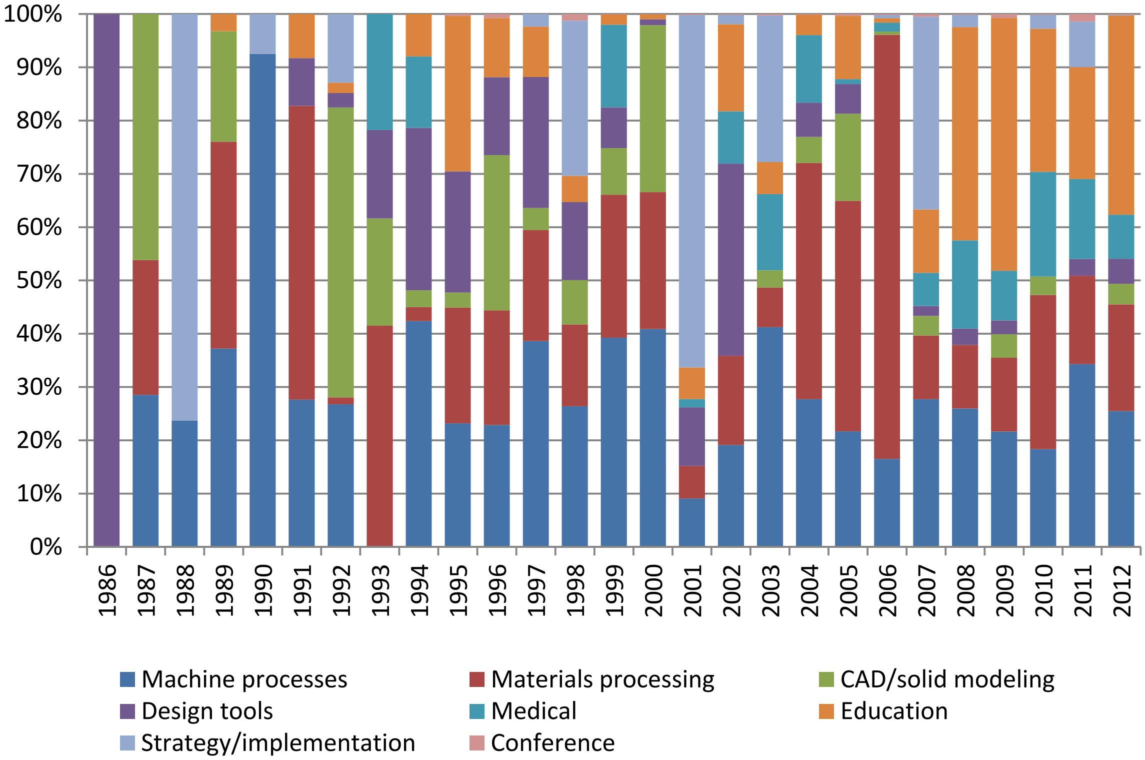


Figure 17. Total NSF Funding Support for AM since 1986, Separated into Eight Award Categories

C. Types of Awards and Programs

The different NSF programs that have supported AM are also relevant. Table 20 shows the various programs and types of awards supporting AM research. The largest number of awards has been single investigator standard research grants, representing approximately half the awards. The next largest awards are Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) awards. They are around 15% of the total, which shows the commercial nature of the field. Smaller portions of the awards were for conference support (discussed in Chapter 3), academic-industry interactions through the Grant Opportunities for Academic Liaison with Industry (GOALI) and Industry/University Cooperative Research Center (I/UCRC) programs, instrumentation purchase (often academic researchers purchasing AM machines), and exploratory Small Grant for Exploratory Research (SGER) grants.

Table 20. Number of Selected Types of Awards Present within NSF Award Set

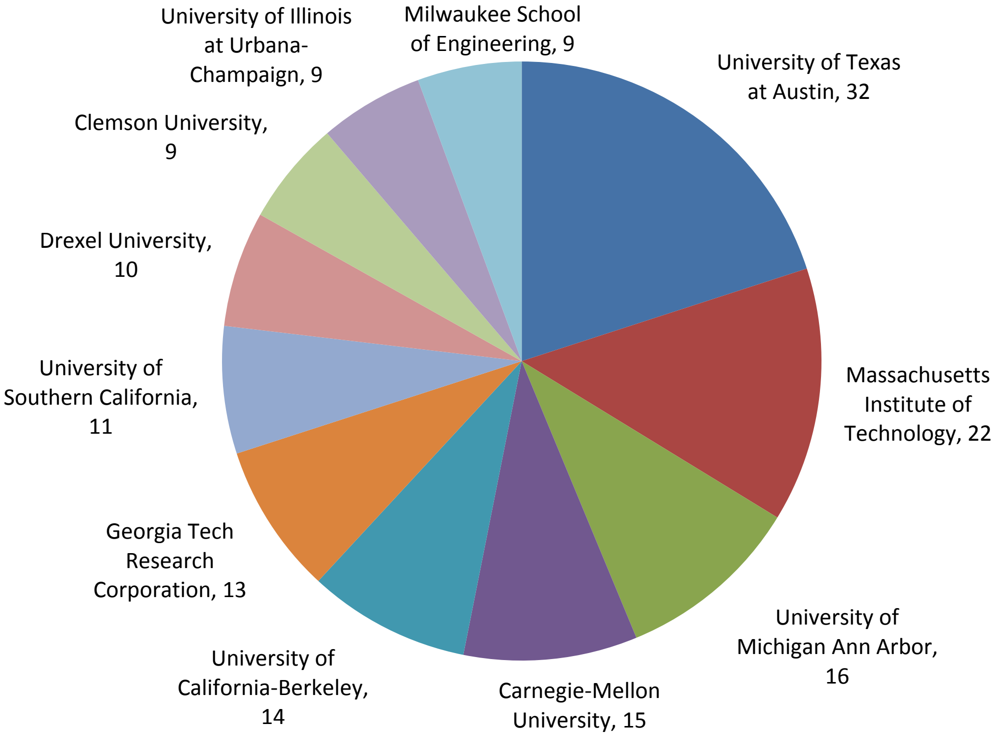
NSF Program/Type of Award	Total Awards	Total Funding (FY 2005 Dollars)
Conferences	32	$731,511
SGER—Small Grant for Exploratory Research	13	$1,041,163
I/UCRC—Industry/University Cooperative Research Center	7	$1,488,035
STRATMAN—Strategic Manufacturing	5	$4,746,441
MRI—Major Research Instrumentation	25	$7,867,372
GOALI—Grant Opportunities for Academic Liaison with Industry	26	$9,149,228
SBIR/STTR—Small Business Innovation Research/ Small Business Technology Transfer	86	$16,701,995
Other Centers	14	$26,772,794
Other including individual research awards	375	$145,771,862
Total	**583**	**$214,270,401**

D. Distribution among Institutions

NSF has funded 234 organizations with AM awards, and a majority (132) of these organizations have received only one AM-related award. Table 21 shows the number of organizations and number of awards to organizations that have received different levels of NSF support. The majority of awards have gone to institutions with few other AM awards; however, a smaller number of institutions have received substantial numbers of NSF AM awards. For example, the top 8 organizations have received as many awards (133) as all institutions with only one award (132 awards). Figure 18 shows a pie chart of the number of awards that the top 10 awardee organizations have received. The top universities performing AM research align well with the institutions identified by experts as the top research universities in the field: the University of Texas, MIT, Carnegie Mellon University, Georgia Tech, and the University of Southern California.

Table 21. NSF Awards per Organization

No. of Awards Received	No. of Organizations	No. of Awards Granted
>9	8	133
9	3	27
8	2	16
7	3	21
6	7	42
5	5	25
4	12	48
3	25	75
2	37	74
1	132	132



Note: Eleven organizations are shown due to a three-way tie for ninth place.

Figure 18. Top 10 NSF Awardee Organizations by Number of Awards

6. Case Studies in Additive Manufacturing

A. Overview and Structure of the Case Studies

The six case studies presented in this chapter provide information on how several major processes in the AM field came to be invented and commercialized. They also serve to highlight the government's role in supporting the initial concepts, research, development, and commercialization of significant technologies and companies in the AM field. We analyze the four U.S. patents identified as foundational to the field (see Chapter 4) and which have reached commercial success. The case studies include structured discussions with the inventors and other experts, as well as a patent citation analysis to highlight the diffusion of important knowledge contributing to the patents. To further explore the role of NSF funding in the field, two additional case studies are presented. These case studies represent a significant volume of material and thus are summarized in this chapter, with further detail available in Appendixes G and H.

B. Foundational Patents in the Additive Manufacturing Field

1. Patent 4575330: Apparatus for Production of 3-Dimensional Objects by Stereolithography

Charles Hull began his work in the AM field while at Ultra Violet Products Inc. (UVP), a developer and manufacturer of ultraviolet products.[24] While at UVP, he filed for his stereolithography[25] patent in 1984 and founded 3D Systems two years later, the same year his patent was issued. Today, 3D Systems remains at the forefront of the AM industry and has made multiple acquisitions of AM companies that have expanded its market share.[26]

Discussions with Hull and other experts, as well as an analysis of the government interest clause in Hull's patent, reveal that U.S. Patent No. 4575330 was sponsored solely by UVP with no support from the Federal Government. Further, Hull did not receive any public funding to develop the technology or grow 3D Systems. However, citation analysis does reveal a role of the Federal Government through Defense Advanced Research Projects Agency (DARPA) sponsorship of Wyn Kelly Swainson's body of work, which is heavily referenced in Hull's stereolithography patent. Forward citations

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[24] See http://www.uvp.com/.

[25] Stereolithography is also referred to as vat photopolymerization.

[26] 3D Systems has made 25 acquisitions since August 2009. See Wohlers (2012).

also show that federally sponsored researchers was able to leverage Hull's invention through further technology development, primarily the binder jetting process developed at MIT (see Section 7.B.3). In particular, NSF sponsored two awards to MIT's research group that led to eight citing patents filed from 1992 to 2004.[27]

2. Patent 4863538: Method and Apparatus for Producing Parts by Selective Sintering

The patent for Carl Deckard's invention of selective laser sintering (SLS)[28] was filed in 1986, the same year Hull's seminal patent was issued. Deckard's invention came about from collaborations among students and professors at the University of Texas (UT) at Austin. Deckard was a graduate student supervised by Joseph Beaman, a professor in the Department of Mechanical Engineering. After completing his master's degree, Deckard, along with Beaman, Paul McClure, the Assistant Dean of Engineering, and Harold Blair, a local business owner, established Nova Automation (later DTM Corporation) to commercialize the technology (Lou and Grosvenor 2012). The UT team and DTM received support to commercialize SLS from various avenues, including UT, NSF, and private investments from BFGoodrich. Table 22 summarizes the main events and support received during the commercialization of SLS.

UT supported DTM through the Austin Technology Incubator,[29] which provided guidance and infrastructure support. NSF also played a role in providing seed funding for SLS research,[30] supporting DTM through a Small Business Innovation Research (SBIR) award to commercialize SLS[31] and the scale-up and further development of SLS through a Directorate of Engineering Strategic Manufacturing (STRATMAN) Initiative award.[32] The investments from BFGoodrich significantly expanded DTM's intellectual property portfolio and led to its competitiveness in the AM market.

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[27] NSF Awards #8913977 and #9215728 through ENG/CMMI's Strategic Manufacturing (STRATMAN) Initiative.

[28] Selective laser sintering is also referred to as *powder bed fusion*.

[29] "About the Austin Technology Incubator," http://ati.utexas.edu/about.

[30] NSF Award #8707871: "Part Generation by Layerwise Selective Sintering," through ENG/CMMI Materials Processing and Manufacturing program, http://www.nsf.gov/awardsearch/showAward?AWD_ID=8707871.

[31] NSF Awards #8761237 and #8896180: "Selective Laser Sintering," through NSF's SBIR, http://www.nsf.gov/awardsearch/showAward?AWD_ID=8761237, http://www.nsf.gov/awardsearch/showAward?AWD_ID=8896180.

[32] NSF Award #8914212: "Solid Freeform Fabrication: Ceramics," through ENG/CMMI's Strategic Manufacturing Initiative, http://www.nsf.gov/awardsearch/showAward?AWD_ID=8914212.

Table 22. Academic, Commercial, and Financial Support Timelines Related to Selective Laser Sintering from 1986 to 1989

Academic	Commercial	Financial Support
May 1986: Carl Deckard receives master’s degree with data from first academic prototype machine “Betsy” October 1986: Carl Deckard filed U.S. Patent No. 4863538 through the University of Texas, Austin	End-1986: Deckard forms Nova Automation	
1987: Design of additional academic machines “Godzilla” and “Bambi”	End-1987: License to Nova Automation is signed under a condition of raising $300,000 by 1988	March 1987: Joseph Beaman receives seed funding ($30,000) from NSF
December 1988: Carl Deckard completes his Ph.D. using the first prototype machine (“Betsy”)	1988: McClure seeks partnerships with potential investors, DuPont and General Motors	Early-1988: Nova Automation receives a NSF Small Business Innovation Research (SBIR) (~$50,000) End-1988: Nova Automation establishes proposal for funding from BFGoodrich
1989: Deckard works as a post-doctoral student with graduate student Paul Forderhase to complete and test a third prototype machine (“Bambi”)	February 1989: Nova Automation becomes DTM Corporation; DTM designs and builds the first commercial machines, Mod A and Mod B Mid-1989: DTM presents machine at the Autofact annual trade show (Detroit, MI); DTM sells its first machine to Sandia National Laboratories	October 1989: Joseph Beaman receives NSF STRATMAN award for more than $870,000 1989: DTM receives BFGoodrich investment; Becomes a member of the Austin Technology Incubator; unable to accept SBIR (Phase 2: $250,000) as BFGoodrich subsidiary

Source: Modified from Lou and Grosvenor (2012).

In total, there are 14 patents in the same family as Deckard’s seminal SLS patent. According to the government interest clause of the patents, none received government support that directly led to the patent. However, many of the patents in the family were filed around the same time frame as Beaman’s STRATMAN award. Similarly, NSF funding to UT and DTM from 1987 to 1989 could have been used to support Deckard’s original SLS patent and the research group more generally. Direct attribution is unclear, but discussions with Beaman, his colleague David Bourell, and other AM experts confirm NSF’s early role in the research and development of SLS. NSF award reports were not available to identify contributors, in particular graduate students, involved in the early NSF awards.

A backward citation analysis of Deckard's SLS patent and patent family shows other Federal Government support from DOD, including the U.S. Navy, U.S. Air Force, and the Department of Commerce. DOD supported the work of Jan VanWyk on bearing lubrication for wear-resistant surfaces, such as ceramics, while he was at Boeing. The U.S. Navy supported research cited by the patent family in three areas:

- Clyde Brown, Edward Breinan, and Bernard Kear's work in directed energy deposition.
- Robert Schaefer and Jack Ayers' work in laser spraying a surface to fabricate protective molten coatings and obtain an alloyed surface.
- Douglas Miller's work in coating a surface with electrostatically charged powder and irradiating it until the surface melts and solidifies.

This analysis confirms the role of several Federal agencies in producing knowledge used in the development of methods, testing, and processes for SLS.

Deckard's original SLS patent has been highly influential in the AM field and stimulated various new areas of research, including Optomec's LENS technology[33] through DOE-sponsored research at Sandia National Laboratories. Other agencies that supported the patents stemming from SLS are DOD (including the U.S. Navy's Office of Naval Research and the U.S. Air Force), DARPA, NSF, NASA, and NIST:

- ONR and the U.S. Air Force supported several UT researchers in the 1990s who were significantly involved in developing SLS.
- NSF awards were used to manufacture ceramic parts[34] and improve understanding of the physical behavior of the powder and liquid phases during the 3D printing process.[35] One NSF award supported James Bredt's early research in binder jetting at MIT, perhaps useful in securing his company's (Z Corporation) position as a market leader in desktop machines. These awards

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[33] LENS technology functions with four nozzles that direct a stream of metal powder to form a three-dimensional product (documented in U.S. Patent No. 6046426). See Sandia National Laboratories (2012).

[34] NSF Award #8913977: "Three Dimensional Printing; Rapid Tooling and Prototypes Directly from a Computer Aided Design Model," through ENG/CMMI's STRATMAN Initiative and program manager Kevin Sewell, awarded $784,700 from October 1989 to March 1993 to principal investigator Emanuel Sachs, and co-principal investigators Michael Cima and James Cornie, http://nsf.gov/awardsearch/showAward?AWD_ID=8913977.

[35] NSF Award #9215728: "Micro-constructive Manufacturing," through ENG/CMMI's STRATMAN Initiative () and program manager Bruce Kramer, awarded $615,000 from October 1992 to March 1996 to principal investigator Emanuel Sachs and co-principal investigators David Gossard, Michael Cima, and James Cornie. http://www.nsf.gov/awardsearch/showAward?AWD_ID=9215728.

also supported other MIT researchers critical to binder jetting process improvements (see Case Study 4 on binder jetting).

- NASA and NIST sponsored work in composite reinforcement preforms and methods for carbohydrate binders, respectively.

3. Patent 5121329: Apparatus and Method for Creating 3-Dimensional Objects

S. Scott Crump invented the material extrusion[36] process in 1988 and founded Stratasys in that same year to commercialize the technology. For the past decade, Stratasys has held the largest market share in the AM industry by number of machines sold (Wohlers 2012). Crump's invention of material extrusion is influenced by several AM processes existent at the time: Hull (stereolithography), Deckard (SLS), Clyde Brown (directed energy deposition), and Michael Feygin (laminated object manufacturing), among others (see Figure 11 in Chapter 4). Crump's material extrusion patent was sponsored solely by Stratasys with no other direct support from the Federal Government. Of the 106 U.S. patents produced by staff at Stratasys since 1989, only one had clear Federal support. Patent 5900207 was co-invented with researchers from Rutgers University and sponsored by DARPA and ONR.[37] One of these researchers, Mukesh Agarwala, was a UT graduate student and influenced by the technology developments in SLS.[38] As discussed in section 3.B.1, Agarwala is first author on two of the most highly cited publications in the leading journal of the field, *Rapid Prototyping Journal*. This example shows one of the dominant influences of government support on private sector innovation—the training of qualified undergraduate and graduate students who go on to work in industry. No other government entity supported any other Stratasys patents. This was also confirmed in discussions with the Stratasys staff.

The backward patent citation analysis highlights the importance of Deckard's work through patent references. Given the strong connections between NSF and UT researchers, it is possible that NSF had an indirect role supporting knowledge used by Crump for developing the material extrusion process. Other government support found through a publication analysis shows research supported by DARPA[39] and a master's

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[36] Material extrusion is also referred to as fused deposition modeling.

[37] U.S. Patent No. 5900207 was filed in 1997 and issued in 1999. Inventors named on the patent are Mukesh Agarwala, Amit Bandyopadghyay, Stephen C. Danforth, Vikram R. Jamalabad, Noshir Langrana, R. Priedeman William Jr., Ahmad Safari, and Remco van Weeren.

[38] Mukesh Agarwala studied synthesis selective laser sintering and post processing of metal and ceramic composites and received his Ph.D. in mechanical engineering in 1994 (Lou and Grosvenor 2012).

[39] The publication is Clark, "Designing Surfaces in 3-D," *Communications of the ACM* 19, No. 8 (Aug. 1976): 454–460, supported by DARPA Contract No. F30602-70-C-0300.

thesis authored by Deckard that may have been supported by NSF seed money, as discussed above.[40]

The forward citation analysis shows that NSF was influential in supporting new technologies that spurred from Crump's material extrusion patent, in particular the work of MIT researchers related to 3D printing (see Case Study 4).

4. Patent 5204055: Three-Dimensional Printing Techniques

The binder jetting process[41] was influenced by the previous three foundational patents and AM processes. Similar to SLS, development of the binder jetting process was also a research effort involving professors and graduate students. Several researchers from MIT were instrumental in developing the binder jetting process, including Emmanuel Sachs, John Haggerty, Michael Cima, and Paul Williams. In 1986, Sachs and Cima were new faculty in the Departments of Mechanical Engineering and Materials Science and Engineering, respectively. Graduate students supported this research, including Paul Williams, who received his master's in Mechanical Engineering in 1990 and was supervised by Sachs (Williams 1990). According to the acknowledgments in Williams' thesis, his research was supported by NSF and MIT.

Four other patents in the same patent family as the Sachs et al. binder jetting patent include other MIT graduate students as co-inventors. NSF's role in funding the binder jetting process through graduate student support is further validated from the thesis acknowledgements of two co-inventors on these patents. According to the government interest clause, NSF supported two of the patents through Sachs's STRATMAN award.[42] No other government entity is attributed in these patents. The NSF award was distributed around the same time frame as the original and family patents were filed. NSF also supported research collaborations to produce two publications co-authored by Sachs and graduate student co-inventors Alain Curodeau[43] and David Brancazio.[44] This analysis

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[40] Carl Deckard, "Part Generation by Layerwise Selective Sintering," May 1986. This thesis may be related to NSF Award DMC-870781 project titled with the same name and awarded to principal investigator Joseph Beaman in 1987.

[41] Binder jetting is also referred to as 3D printing.

[42] NSF Award #8913977 is a Strategic Manufacturing Initiative award listed in the government interest clause of the patent. The project is "Three Dimensional Printing; Rapid Tooling and Prototypes Directly from a Computer Aided Design Model," awarded to principal investigator Emanuel Sachs, and co-principal investigators Michael Cima and James Cornie, from 1989 to 1993. http://nsf.gov/awardsearch/showAward?AWD_ID=8913977.

[43] NSF Award # 9420365 (1995-1999) from the Directorate for Computer and Information Science and Engineering (CISE) Division of Experimental and Integrative Activities was titled "Design Automation for Solid Freeform Fabrication," which supported a journal publication submission: A. Curodeau, E. Sachs, M. Cima, and S. Caldarise, "Design and Fabrication of Cast Parts with Freeform Surface Textures

shows that NSF supported graduate research into the development of the original invention, and it likely supported later developments given the dates of the NSF STRATMAN award and their proximity to filing dates of the patent family.

NSF may have also influenced the knowledge used by Sachs et al. in their binder jetting patent. A citation analysis shows references to the work of Friedrich Prinz and Daniel Siewiorek from 1991 to 1993. Both were former principal investigators of a NSF Engineering Research Center award to create Carnegie Mellon's Engineering Design Research Center.[45] Their referenced patents were filed in the same time frame that they received their NSF award, which suggests that this funding may have played a role in supporting their research. NSF may have had a role in other influential references from Sachs et al., including Deckard's work on SLS and Harris Marcus and Udaykumar Lakshminarayan's work in ceramic powder materials. Deckard has a history of funding from the NSF, although the referenced patent predates any of his NSF awards (see Case Study 2 for further details on the Federal Government's role in supporting SLS). Marcus also received NSF funding, but the funding was provided a decade or more before the patent was filed.

The U.S. Navy also supported two patents influential to Sachs et al.: Brown et al.'s work on directed energy deposition and Douglas Miller's work in melt-coating surfaces.[46]

An analysis of the publication citations shows other government support from the U.S. Army[47] and DARPA[48] into research later used by Sachs et al. No other government entity was identified as supporting other referenced publications.

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from 3D Printed Ceramic Shell," *Journal of Biomedical Materials Research*, http://www.nsf.gov/awardsearch/showAward?AWD_ID=9420365&HistoricalAwards=false.

[44] NSF Award # 9617750 (1997–1999) is a jointly funded award with DARPA titled "The Distributed Design and Fabrication of Metal Parts and Tooling by 3D Printing," which supported a manuscript in an NSF proceeding: E. M. Sachs, N. M. Patrikalakis, M. J. Cima, D. Brancazio, W. Cho, T. R. Jackson, H. Liu, H. Wu, R. Resnick, "The Distributed Design and Fabrication of Metal Parts and Tooling by 3D Printing," *NSF Design & Manufacturing Grantees Conference Proceedings*, 1999, http://www.nsf.gov/awardsearch/showAward?AWD_ID=9617750&HistoricalAwards=false.

[45] NSF Award #8943164 Engineering Research Center for Engineering Design was awarded from 1989 to 1997. http://nsf.gov/awardsearch/showAward?AWD_ID=8943164.

[46] Frank Arcella and Gerald Lessmann, Casting shapes, U.S. Patent 4818562, filed March 24, 1988, and issued: April 4, 1989. The assignee is Westinghouse Electric Corporation, and the patent references another patent: Douglas L. Miller, U.S. Patent No. 4615903, Method for melt-coating a surface, filed July 1, 1985, and issued October 7, 1986. The assignee is The United States of America as represented by the Secretary of the Navy (Washington, DC).

[47] Two patents, U.S. Patent Nos. 5807437 and 6036777, cite Richard G. Sweet, "High Frequency with Electrostatically Deflected Ink Jets," *The Review of Scientific Instruments* 36: 2 (1965): 131–136, supported by U. S. Army Electronics Research and Development Laboratory (currently the Communications-Electronics Research, Development and Engineering Center) under Contracts DA 36(039) SC-87300 and DA 36(039) AMC-03761(E).

Forward citation analysis shows that many of the family patents are highly cited. About 10% or fewer of the citing patents have government support, and about 5% or fewer were supported by NSF. Sachs and MIT researchers produced all the NSF-supported patents. This suggests that NSF may have had an important role in supporting the later development of binder jetting by MIT researchers. A discussion with Cima confirms that NSF played a significant role in the development stages of the technology; however, this was only after a prototype was already established and the foundational patent was submitted.

Interconnections among the four foundational patents are highlighted in Figure 10 in Chapter 4. This map and others in Appendix G show that the four foundational patents build upon each other and influenced several important technologies and commercially successful companies. These technologies include BPM, direct metal laser sintering, electron beam melting, LENS, material jetting, and ultrasonic object consolidation. Table 23 is a summary of the four foundational patent cases and their government support.

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[48] U.S. Patent No. 5204055 cites U.S. Patent No. 4665492 (computer automated manufacturing process and system), which cites Clark, “Designing Surfaces in 3-D,” *Communications of the ACM* 19, No. 8 (Aug. 1976): 454–460, supported by DARPA Contract No. F30602-70-C-0300.

Table 23. Summary of Four Foundational Patents in Additive Manufacturing and Government Role

Patent No.	4575330	4863538	5121329	5204055
Patent Title	Apparatus for production of three-dimensional objects by stereolithography	Method and apparatus for producing parts by selective sintering	Apparatus and method for creating three-dimensional objects	Three-dimensional printing techniques
Inventor(s)	Charles Hull	Carl Deckard	S. Scott Crump	Emanuel Sachs John Haggerty Michael Cima Paul Williams
Year patent filed/issued	1984/1986	1986/1989	1989/1992	1989/1993
Assignee	Ultra Violet Products Inc.	University of Texas	Stratasys Inc.	MIT
Government interest	No Federal Government attribution in the patent or family			NSF attributed in two patents in same patent family
Knowledge flows and government role	Influenced by Wyn Kelly Swainson, sponsored by DARPA DOD, U.S. Navy/ONR, U.S. Air Force, DOE, HHS, and NSF have a strong role in supporting diffusion of invention, particularly in binder jetting	Influenced by work sponsored by DOD, U.S. Navy, U.S. Air Force, and DOC DOE, DOD, U.S. Navy/ONR, U.S. Air Force, DARPA, NSF, NASA, and NIST supported diffusion of invention	Influenced by work sponsored by DARPA and Deckard (possibly NSF supported) DOD, U.S. Navy/ONR, NSF, NIH, and NASA supported diffusion of invention, particularly in binder jetting	Influenced by work sponsored by NSF (e.g., Friedrich Prinz, Carl Deckard, Harris Marcus), U.S. Navy, U.S. Army, and DARPA U.S. Army, U.S. Navy/ONR, DARPA, DOE, NSF, NASA, NIST, and NIH supported diffusion of invention, particularly in binder jetting and tissue engineering
NSF funding history	None	Seed funding ($30,000) in 1987 SBIR (~$50,000) in 1988 STRATMAN award for more than $870,000 in 1989	None	Funding for MIT graduate students and acknowledgment in theses Several awards closely align with the time period of filing patent family
Further details of NSF role	None	Early funding for UT and Nova and later awards provided initial technology development and improvements over time	None	Significant role in early development; but only after prototype established Notable support in later developments and improvements (1990s to 2000s)

C. Additional Case Studies

Two further case studies of NSF support show additional ways that public funding has affected the field. The first case involves laminated object manufacturing, a technology that reached commercialization but then failed to compete in the AM market after several years of success before recently reemerging in a different form.

The second case study involves contour crafting, a technology that has not yet been commercialized at scale but shows an entirely different side of the potential future applications of AM. This represents only one of the many pre-commercial technologies that apply AM techniques in innovative ways, highlighting the potential future impact of the technology and the unanticipated role played by NSF.

1. Laminated Object Manufacturing

Michael Feygin developed the first commercial sheet lamination technology, referred to as laminated object manufacturing (LOM), in 1987 (documented in U.S. Patent No. 4752352). He was motivated to improve automated manufacturing that used computer assisted design and rapid prototyping processes existent at that time, and also influenced by Hull’s work on stereolithography patented in 1986. Feygin recognized the need to diversify materials, reduce process times, and increase accuracy in the internal geometry of intricate manufactured parts. Feygin’s LOM patent is cited 170 times and, according to citation analysis, influenced the development of SLS and binder jetting, among other AM processes today (refer to Case Study 2 on SLS, and Case Study 4 on binder jetting).

Feygin founded Hydronetics Inc. in the mid-1980s (the company later changed its name to Helisys) to commercialize the technology. Helisys produced full-size, inexpensive models for visualization, styling, functional and assembly testing, mold creation, and fit verification and packaging studies (DOE 1999). Feygin’s intellectual property consists of five patents filed between 1987 and 1997 (see Table 24). The first commercial LOM machine was introduced in 1991, and the company controlled a small but growing portion of the market until the mid-1990s, reaching more than 15% at its peak in 1994 (Wohlers 1998–2012).

Although none of the patents attribute government funding, Feygin received early funding support to develop LOM from DOE and NSF (see Table 25). DOE’s Inventions and Innovation program, now in the Advanced Manufacturing Office, supported Feygin’s early ideas with a $70,000 award. According to their abstracts, two NSF SBIR awards also supported the design, development, and testing of a fully automated LOM machine. This support was provided before the introduction of Helisys’ first commercial machine, and it likely had a significant role in speeding the development and launch of the machine.

Table 24. Patents by Michael Feygin on Laminated Object Manufacturing*

Patent	Title	Inventors	File Date	Issue Date	Citing Patents^
4752352	Apparatus and method for forming an integral object from laminations	Feygin, Michael	Apr 17, 1987	Jun 21, 1988	170
5354414	Apparatus and method for forming an integral object from laminations	Feygin, Michael	Apr 4, 1991	Oct 11, 1994	72
5637175	Apparatus for forming an integral object from laminations	Feygin, Michael; Pak, Sung S.	Oct 7, 1994	Jun 10, 1997	85
5730817	Laminated object manufacturing system	Feygin, Michael; Shkolnik, Alexandr; Diamond, Michael N.; Dvorskiy, Emmanuil	Apr 22, 1996	Mar 24, 1998	31
5876550	Laminated object manufacturing apparatus and method	Feygin, Michael; Pak, Sung Sik	Feb 21, 1997	Mar 2, 1999	70

* Feygin's patents are identified by searching the USPTO database for inventor "Feygin; Michael."

^ Citing patents are from July 2, 2013.

Table 25. Federal Government Support of Laminated Object Manufacturing

Agency	Award Number	Program	Start Date	Expiration Date	Amount
DOE	Not found	Invention and Innovation	Not found	Not found	$70,000
NSF	8861228	Small Business Innovation Research: Phase I	Jan 1, 1989	Sep 30, 1989	$50,000
NSF	8920546	Small Business Innovation Research: Phase II	Jun 15, 1990	Nov 30, 1992	$225,000

By the mid-1990s, the introduction of competitors such as DTM and Z Corporation, as well as the growing market share of proven technologies from 3D Systems, impeded Helisys' growth. In 2000, Helisys shut down its operations, and later that year, Feygin established Cubic Technologies, which provides manufactured parts and service for old Helysis machines.

Over the past decade, there has been a resurgence of companies using the LOM process or new processes that were influenced by it. For instance, companies now using LOM include Stratoconception, a French company that uses LOM for metal and other materials, and Kira Corporation, a Japanese machine manufacturer that launched its $35,000 RapidMockup machine in 2006 (RapidToday.com 2008). Fabrisonic's ultrasonic consolidation process is another process that, although dissimilar in many ways, falls into the ASTM category of sheet lamination. Irish manufacturer Mcor Technologies introduced its LOM-based system in 2007 and launched a new business model that offers fixed-price service plans complete with machine, materials, and maintenance in 2011 (Wohlers 2012). Patents issued to these companies over the past decade have heavily referenced Feygin and his patents, signaling the continued importance of the LOM process.

2. Contour Crafting

Behrokh Khoshnevis, a professor of industrial engineering at the University of Southern California (USC), applied for an initial patent in 1995 (issued in 1996) for contour crafting, an extrusion-based AM technique utilizing trowels to produce with relatively high build speeds a surface finish smoother than available in many AM processes at the time (Khoshnevis 1996). At nearly the same time as this initial patent, Khoshnevis applied for and received NSF funding from the Materials Processing and Manufacturing program in ENG/CMMI (see Table 26) to perform the basic research needed to develop an initial contour crafting machine and associated materials. Khoshnevis also received support from the U.S. Navy/ONR around the time of his second NSF award. ONR funding facilitated collaborations with researchers from Rutgers University and Drexel University on the fabrication of piezoelectric actuators using contour crafting.[49]

Table 26. NSF Support of Contour Crafting through ENG/CMMI Programs

Agency	Award Number	Program	Start Date	Expiration Date	Amount
NSF	9522982	Materials Processing and Manufacturing	Oct 1, 1995	Sep 30, 1996	$100,000
NSF	9634962	Materials Processing and Manufacturing	Mar 1, 1997	Feb 28, 2001	$272,000
NSF	0230398	Structural Materials and Mechanics	Mar 1, 2003	Dec 31, 2005	$250,000

Several years later, after receiving the initial NSF awards, Khoshnevis envisioned using the technology—which for some materials does not require the closed build volumes of other AM processes—to develop much larger scale solid shapes than possible using other AM processes. Khoshnevis approached NSF again in 2002 with the concept of applying contour crafting to large-scale home construction and received an award to pursue this research in 2003, which allowed his research team to apply the knowledge gained in the prior basic research to this new scale. This award provided funds to scale up

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[49] NSF Final Report for Award #9634962.

AM to a multi-meter scale and begin to develop a new automated construction process taking advantage of AM's capabilities for custom production. Khoshnevis also received support from USC's Integrated Media Systems Center,[50] an NSF Engineering Research Center.[51] A series of patents followed, six of which acknowledge NSF funding in the government interest clause (see Table 27).[52]

After receiving this initial funding from NSF, Khoshnevis was able to successfully approach other funding agencies, such as ONR and the Army Corps of Engineers, to further develop the technology. ONR's funding is acknowledged in two patents (Table 27) related to devices to meter and pump fluid and a robotic system for material delivery of contour crafted parts. Recent funding from NASA has further supported the technology's development for the purpose of building structures in space, such as lunar bases. Significant interest also exists in using the technology for commercial construction applications. Additional research funding has been secured from foundations and private industry, such as Caterpillar and Siemens. A start-up company is under development.

In all, the ~$600,000 that NSF invested through its three early grants has been leveraged into a total of over $2.8 million in additional research funding from Federal (ONR, U.S. Army Corps of Engineers, and NASA) and private sources. As additional public and private funding has been granted, the research team has been able to build bigger and bigger machines, to the point of now being able to build whole structures. In discussion with the study team, Khoshnevis claimed that without the initial NSF funding to develop and first scale up the process, the technology could not have proceeded to the point where it is today.

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[50] University of Southern California. "Integrated Media Systems Center," http://imsc.usc.edu.

[51] NSF Award #9529152.

[52] NSF Award #9522982 and #9634962.

Table 27. Set of 17 U.S. Patents by Behrokh Khoshnevis Related to Contour Crafting*

Patent	Title	File Date	Issue Date	Government Interest	Citing Patents^
5529471	Additive fabrication apparatus and method	Feb 3, 1995	Jun 25, 1996	None	23
5656230**	Additive fabrication method	Mar 26, 1996	Aug 12, 1997	None	35
7153454	Multi-nozzle assembly for extrusion of wall	Jan 20, 2004	Dec 26, 2006	NSF (Award #9634962 and #9522982)	14
7452196	Automated plumbing, wiring, and reinforcement	Jan 21, 2005	Nov 18, 2008	NSF (Award #9634962 and #9522982)	5
7495654	Haptic apparatus	Jun 2, 2005	Feb 24, 2009	NSF (Award #9634962 and #9522982)	1
7574925	Metering and pumping devices	Nov 1, 2007	Aug 18, 2009	U.S. Navy, ONR (Contract #N000140510850)	0
7641461	Robotic systems for automated construction	Jan 21, 2005	Jan 5, 2010	NSF (Award #9529152 - Engineering Research Center)	6
7814937	Deployable contour crafting	Oct 25, 2006	Oct 19, 2010	None	1
7837378	Mixer-extruder assembly	Jan 21, 2005	Nov 23, 2010	NSF (Award #9529152 - Engineering Research Center)	3
7841849	Dry material transport and extrusion	Nov 2, 2006	Nov 30, 2010	None	1
7841851	Material delivery system using decoupling accumulator	Nov 2, 2006	Nov 30, 2010	None	1
7850388	Compliant, low profile, independently releasing, non-protruding and genderless docking system for robotic modules	Apr 9, 2007	Dec 14, 2010	NASA - Ames Research Center (Contract #NNA05CS38A)	0
7874825	Nozzle for forming an extruded wall with rib-like interior	Act 25, 2006	Jan 25, 2011	None	0
7878789	Multi-chamber vibrating valve for cementitious material	Oct 30, 2009	Feb 1, 2011	None	0
8029258	Automated plumbing, wiring, and reinforcement	Aug 20, 2010	Oct 4, 2011	NSF (Award #9634962 and #9522982)	0
8029710	Gantry robotics system and related material transport for contour crafting	Nov 2, 2007	Oct 4, 2011	U.S. Navy, ONR (Contract #N000140510850)	0
8308470	Extrusion of cementitious material with different curing rates	Nov 2, 2007	Oct 4, 2011	None	0

* Khoshnevis' patents are identified by searching the USPTO database for inventor "Khoshnevis; Behrokh" and "Khoshevis, Behrokh" (the latter is an error that is not corrected in the database).

^ Citing patents are from July 10, 2013.

** U.S. Patent No. 5656230 is a divisional of Khoshnevis' original contour crafting patent, U.S. Patent No. 5529471.

7. Synthesis of Findings

AM was a $2.2 billion global industry in 2012, and is projected to grow to more than $6 billion by 2017 (Wohlers 2012). While the field has roots dating back to the 1860s, much of the progress has been made since 1980. The field has drawn a great deal from the development of other fields including, in particular, topographic surveying and maps; computers; CAD; CNC machining; and lasers. As this report highlights, a range of institutions, both in the public and private sectors, are responsible for its growth. In this chapter, we bring together insights from the interviews, patent analysis, and NSF data analysis to discuss the role of NSF in the evolution of the field, principal lessons learned, and future areas for public investment.

A. Assessing NSF Impact and Influence

1. Investment

Since 1986, when the first AM award was made, NSF has expended more than $200 million (constant 2005 dollars) on AM research and related activities. Within NSF, the principal funder of AM has been the Engineering Directorate (ENG), providing more than two-thirds of the AM grants and more than half of NSF's total funding support. Within ENG, the CMMI Division and its predecessors funded a total of $75 million in AM research, supporting about 580 awards over a period of 25 years. Within CMMI, its pioneering Strategic Manufacturing (STRATMAN) program played a central role, as two of STRATMAN's five AM awards—one to Joseph Beaman of the University of Texas in Austin and another to a team of researchers at the Massachusetts Institute of Technology (MIT) led by Emanuel Sachs—have had enormous impact on the field.

2. Nature of NSF Support

NSF has been involved with AM since its earliest days, funding several precursors of AM technologies in the 1970s (e.g., funding the research of Herbert Voelcker at the University of Rochester in CAD and CNC machining). While NSF efforts were broad (supporting science, education, conferences, etc.), its research funding made significant advances in three of the seven ASTM standardized processes of AM: binder jetting, powder bed fusion, and sheet lamination. In each of these technology areas, NSF's focus has varied between machine processes, materials processing, CAD/solid modeling, and design tools. In many cases, NSF funding helped convert a patented idea into proof-of-concept or scaled-up machines. Beaman's NSF grant, for example, came after his graduate student Deckard had already applied for a patent. Similarly, Khoshnevis applied for an initial patent in 1995 while simultaneously applying for NSF funding from the Materials Processing and Manufacturing program in ENG/CMMI. NSF supported the exploration of newer ideas, which is fitting with its role, while other entities (both private and public) fine-tuned and further developed these ideas into commercially competitive technologies.

In more recent years, as AM technology have matured, NSF has also supported research efforts related to new processes, new applications for existing processes, and AM education. Further, NSF's (and ONR's) efforts in promoting networks within the AM community through the support of seminal conferences, roadmapping, and benchmarking were all highlighted by experts as critical to the development of the field. Thus, NSF has also shown foresight in understanding the role of its limited (as compared with ONR, DARPA, and others) research funds and mission and has leveraged the ecosystem of technology development by funding not just academic research but also innovative small firms, conferences, roadmaps, and training.

Compared with other government agencies that support AM (principally DARPA and ONR but also NASA, DOE, and NIST), NSF support has been at the fundamental end of the science and engineering spectrum, while other agencies have emphasized application and development in the aerospace and defense sectors, consistent with their missions. According to the experts we consulted, NSF collaborated well with DARPA, ONR, and the other agencies, co-sponsoring research, events, and activities. NSF PIs seem especially adept in turning smaller streams of funding from NSF into larger ones from industry and defense-oriented agencies.

3. Outcomes

Nevertheless, discussions with stakeholders and patent analysis revealed that the AM field, while still evolving, is dominated by the private sector. Only about 7% of the more than 3,800 identified patents related to AM, for example, recognize government support (2% recognize NSF). When the names of NSF-funded PIs are mapped onto the NSF-sponsored patents, fewer than 3% of the patents include current or former NSF PIs as inventors. Among the top 100 historically important patents, a slightly higher fraction recognizes government support, but the total is still only 9% (with 3% recognizing NSF). It is notable that AM-related technologies in the top 100 patents, whether sponsored by government or industry, tended to build upon each other, improving upon or combining existent technologies and processes in new ways and signaling the importance of this synergy in the development of the AM field.

The importance of government support became clearer after we examined the four foundational patents in the field. In-depth case studies reveal that two of the four foundational patents received direct support from NSF early in their development, facilitating the successful commercialization of the technologies. While industry dominates in terms of the sheer number of patents, in terms of their importance to the field, NSF support played a strong role in moving ideation to initial prototype and eventually to technology commercialization through SBIR awards. For Carl Deckard's work on selective laser sintering, for example, NSF provided a series of awards—seed funding at the idea stage, a subsequent SBIR when a start-up had been established, and a larger-than-average award to scale up technology to collaborators at the University of Texas. Similarly, for Sachs' work in binder jetting, NSF supported a broad array of research activities.

As to NSF's role in the evolution of the field, the case studies of four foundational patents and two additional NSF-funded technologies showcased that success can rarely be traced to a single factor; multiple funding sources and infrastructure support from Federal and State governments and private markets often must be mobilized simultaneously. The case studies also highlighted the role of supporting students and training the next generation of AM innovators. Last, the cases demonstrated the effects of latency and unanticipated consequences. As with Khoshnevis' work in contour crafting, particularly in emerging technology applications, research that may seem less useful initially may turn out to be relevant to applications that emerge later.

NSF funding directly affected the private sector as well. Through its research funding, including that of the SBIR program, NSF supported—both directly and indirectly—three of the most important early firms in the AM field: DTM, Z Corporation, and Helisys. While all three firms have been acquired by others or transformed, the technologies they developed remain core to the field.

Nearly all interviewees acknowledged NSF's role in the origin and evolution of the field; a small number, however, viewed its impact as somewhat limited. Reasons cited were lack of consistent funding, lack of strategy in the portfolio, lack of consistent partnering with industry, and lack of focus on practical research compared with other funding agencies This final issue, of course, is natural given NSF's mission. It is worth underscoring, though, that NSF's role has often gone unrecognized. This may be due to lack of awareness or a lack of dissemination on the part of the NSF or the researchers. It may further be due to the industry's growing global footprint and the limited focus of this study on the United States. On the other hand, it may be that the question simply has not been asked until now.

The recent surge in AM has been related less to technological breakthroughs and more to other factors (e.g., expiration of early patents, market demand, and standardization); however, it is clear that NSF was influential in supporting some of the most seminal researchers, roadmaps, conferences, networks, standards, patents, and firms. Table 28 summarizes NSF's role in AM developments as it emerged from the interviews, patent analysis, literature, and case studies done for this report.

Table 28. Summary of NSF's Role in Additive Manufacturing Processes and Key U.S. Firms

	NSF Role Observed?
ASTM AM Process	
Binder jetting	Yes
Directed energy deposition	No
Material extrusion	No
Material jetting	No
Powder bed fusion (laser sintering)	Yes
Sheet lamination	Yes
Vat photopolymerization	No
Establishment of Key Firms	
3D Systems	No
DTM (acquired by 3D Systems)	Yes
Stratasys	No
Z Corporation (acquired by 3D Systems)	Yes
Helisys	Yes
Other U.S. firms (Solidscape, ExOne, others)	No

B. Lessons Learned

The evolution of the AM field in the United States holds important lessons for NSF and other government agencies supporting basic and applied research in science and engineering.

First, while the STRATMAN program was well-received by the academic AM community, some of the experts interviewed were critical of the lack of consistency and strategic focus in NSF's efforts to support AM, especially when compared with government agencies such as ONR. To the extent feasible, providing consistent support with strategic intent would help NSF sustain support for emerging areas of science and technology. This goal of providing a consistent strategy at the individual technology level is a difficult one to execute, because not every new technology merits its own research program. Further, the goal necessitates difficult choices related to uncertain technologies. However, it still merits serious consideration.

Second, with respect to creating breakthroughs, industrial advances in AM have often been more important than academic research. Of the four foundational AM patents, for example, two were developed within firms without any public funding. Furthermore, academic investigators built on industrial research. The interconnections and mutual referencing among the four foundational patents—as well as the top 100 ones—reveal that networking between breakthroughs and application is critical for the development of a field. NSF's support of small businesses through its SBIR program played a strong role in the commercialization of laser sintering and sheet lamination technologies. In the case of laser sintering, a strong collaboration between the University of Texas in Austin and Nova Automation/ (later DTM), both of which were early recipients of NSF funding, shows the large potential for university-industry collaboration to drive innovation. Given the pace of industry developments, and the sometimes unpredictable relationship between academia and industry, NSF should explicitly support these types of interactions and continue to foster research and innovation in collaboration with industry, through a range of programs including but not limited to I-Corps, SBIR, GOALI and I/UCRC.

Third, 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 groundbreaking work in large-scale construction and the growing application of AM in the manufacturing of aerospace, biomedical, and other health devices. Therefore, NSF should continue to support both fundamental research and strategic areas like advanced manufacturing in both the near and long terms.

Fourth, the U.S. Government funded not only AM research but also innovative small firms, conferences, roadmaps, standards development, and student training. Experts suggested the importance of this indirect support, particularly the funding of students who go on to work in the private sector. Graduate students studying AM went on to patent or license the technologies, began start-ups, and successfully commercialized the technologies. In the case of binder jetting, NSF-funded graduate students were often involved in laboratory research, as well as patenting and commercialization efforts. The role of government in supporting the broader "ecosystem" of a technology domain should be recognized as critical in the development of an emerging field.

Despite the perception that AM has "arrived," as Chapter 3 summarizes, several areas would benefit from public support. The final lesson learned in the study therefore relates to areas of research that NSF could potentially fund (summarized in Table 11, Chapter 3). These include design/optimization models, new materials development, and improved materials properties. Further, as the technology continues to evolve, it will be important for public support to take stock of the field (and its still-needed improvements) often to fully capture the benefits and opportunities that many authors have discussed. Last, continued support for retrospective studies, roadmapping exercises such as the recent 2009 AM Roadmap, and conferences such as the 2013 NSF Workshop on Frontiers of AM Research and Education should continue to be sustained to fully comprehend the public's role in the future of the technology.

Appendix A.
List of Experts Interviewed

Table A-1 lists the experts who participated in structured discussions for this study. The interviewees are divided into four categories: U.S. academics, government employees, experts from industry, and foreign researchers.

Table A-1. List of Experts Interviewed, Affiliations, and Categories

Interviewee	Affiliation	Category
Behrokh Khoshnevis	University of Southern California	U.S. Academic
Brent Stucker	University of Louisville	U.S. Academic
David Bourell	University of Texas at Austin	U.S. Academic
Friedrich “Fritz” Prinz	Stanford University	U.S. Academic
Hod Lipson	Cornell University	U.S. Academic
Joseph Beaman	University of Texas at Austin	U.S. Academic
Lee Weiss	Carnegie Mellon University	U.S. Academic
Michael Cima	Massachusetts Institute of Technology	U.S. Academic
Charles Hull	3D Systems	Industry
Hans Langer	EOS GmbH	Industry
Jim Comb	Stratasys	Industry
Terry Wohlers	Wohlers Associates	Industry
Tim Anderson	Z Corp	Industry
Craig Blue	Oak Ridge National Laboratory	Government
Craig Brice	NASA	Government
Kevin Jurrens	NIST	Government
Khershed Cooper	Office of Naval Research	Government
Mary Kinsella	Air Force Research Laboratory	Government
G. Nagesh Rao	USPTO (former)	Government
William Coblenz	DARPA	Government
Ian Gibson	National University of Singapore	Foreign Researcher
Jean-Pierre Kruth	Katholieke Universiteit Leuven	Foreign Researcher
Phill Dickens	Loughborough University	Foreign Researcher

Note: In addition to the experts listed here, we also discussed NSF’s funding portfolio and history with Bruce Kramer, George Hazelrigg, and Z. J. Pei, program managers at NSF that have funded AM over the history of its support.

Appendix B.
Interview Protocol

Additive Manufacturing Discussion Guide

The National Science Foundation asked the IDA Science and Technology Policy Institute to conduct a study to learn how agency-sponsored activities originated and evolved in the field of additive manufacturing.

Analytical input is being sought regarding major research directions, the outcomes from NSF support (major discoveries, new technologies and affected industries and development of an additive manufacturing community), factors affecting innovation, and lessons learned that can be used to help design future activities and initiatives.

Background information

1. What is your title?
2. How long have you been in your current position and what are your responsibilities?
3. How long have you been involved with additive manufacturing and in what capacity?

Important events and literature in additive manufacturing

4. What do you consider to be the top 5 key milestones and events in this history of additive manufacturing that helped shape the field?
5. What do you consider the top 5 publications that have impacted the field of additive manufacturing? Why are these your top 5?
6. What do you consider the top 5 patents that have impacted the field of additive manufacturing? Why are these your top 5?
7. Is there a particular time period that you consider especially important in the development of additive manufacturing? If so, why?
8. If you focus on a sub-field of additive manufacturing, please describe it.
    a. Has your sub-field emerged from developments in a particular area?
    b. What are the key milestones and events in its history?

Additive manufacturing networks

9. Who are the top 5 academic, government, or industry leaders or researchers that have influenced additive manufacturing?
10. Who have you collaborated with on additive manufacturing projects?
11. How did these collaborations develop?
12. What conferences and events have you attended that specifically focused on additive manufacturing and are particularly influential in bringing together research community or have contributed to development of field?

Role of government/industrial/academic organizations in additive manufacturing

13. What Federal Agencies have contributed to the development of additive manufacturing? What has been their contribution?
14. What companies are the key players in additive manufacturing?
15. What universities are the key players in additive manufacturing?

Role of NSF in additive manufacturing

16. Do you believe NSF has contributed to the development of the field, if so how?
17. Have you applied for support from NSF related to additive manufacturing? In what form? Were you awarded funds?
18. Are there key research outcomes, conferences, or advancements in additive manufacturing that you specifically attribute to NSF?
19. Focusing specifically on translational research related to additive manufacturing, what role do you think NSF played in it?

    Note: Translational research is research that moves an idea past the basic discovery stage towards and through proof of concept. It can take many forms but is often characterized by the following features: (*1*) *It leads to technology platforms and often takes the form of engineered systems.* (*2*) *It requires the integration of multiple disciplines.* (*3*) *It is developed in collaboration with industry or other practitioners.*

20. What AM research areas might particularly benefit from future NSF support and through what mechanism (e.g., PI support, infrastructure support, or SBIR grant)? Why?

Other remarks

21. Do you have anything else you would like to add to the discussion?
22. Is there anyone else we should contact to learn more about the history of additive manufacturing or NSF’s role in it?

Appendix C.
Database Table Descriptions

IDA Science and Technology Policy Institute researchers created a relational database using Microsoft Access for the 3,822 U.S. patents and associated bibliographic metadata (refer to Section 2.B). The main sources to build the AM patent database were the following:

- U.S. Rapid Prototyping Database (Patent Museum)—used to create tables PATENT MUSEUM and ABSTRACT
- USPTO Custom Data Extract—used to create tables BASIC, 100 HISTORICALLY IMPORTANT PATENTS, 4 FOUNDATIONAL PATENTS, ASSIGNEE, INVENTOR, PTITLE, NPL CITES, AND UCITES
- USPTO Government Interest Extracts—used to create table GIPATS
- USPTO National Science Foundation Extracts—used to create table NSF GIPATS.

Table	**4 FOUNDATIONAL PATENTS**
Description	Four patents identified by STPI to be foundational to AM using references from the literature review, discussions, event materials, and patent citations.
Source	STPI
Time Period	08/09/1978—01/13/2004
Variables	PATENT (Patent Number; Common ID)

Table	**100 HISTORICALLY IMPORTANT PATENTS**
Description	One hundred patents identified by STPI to be historically important to AM using 66 U.S. patents issued from 1975 to 2011 identified from the literature review, discussions, event materials, and 34 highly cited patents present in Patent Museum.
Source	STPI
Time Period	08/09/1978—01/13/2004
Variables	PATENT (Patent Number; Common ID)

Table	**ABSTRACT**
Description	Abstracts of Patents in the Patent Museum
Source	The Additive Fabrication/Rapid Prototyping U.S. Patent Database (also known as the “Rapid Prototyping “Patent Museum”)
Time Period	1/1/1892—01/22/2013
Variables	PATENT (Patent Number; Common ID)
	Abstract (Abstract of the patent)

Table	**ASSIGNEE**
Description	Assignee information for patents in Table BASIC
Source	USPTO
Time Period	1/1/1975—12/31/2011
Variables	PATENT (Patent Number; Common ID)
	AssigneeCode (A seven-digit numeric code corresponding to the name of the assigned patent owner, assigned by USPTO)
	HAssigneeCode (Harmonized AssigneeCode assigned by USPTO. To help identify patents having ownership assigned to different organizations, the USPTO tries to harmonize the assignee name spelling variations, which facilitates the identification of the patents associated with each assigned owner.)
	AssigneeName (Name of the assignee, which corresponds to the associated AssigneeCode)

Table	**BASIC**
Description	Basic bibliographic patent data associated with U.S. patent grants including patent
Source	USPTO
Time Period	1/1/1975—12/31/2011
Variables	PATENT (Patent Number; Common ID)
	Applied Date (Date of Patent Application)
	Awarded Date (Date of Patent Awarded)
	Assignee Code (Code of Patent Assignee, linked to Table ASSIGNEE)
	State (U.S. State or Country of Inventor; linked to Table INVENTOR)
	Basic Class Code (U.S. Patent Classification System Class)
	Basic Class Subclass (U.S. Patent Classification System Subclass)

Table	**GIPATS**
Description	Patent numbers identified by USPTO using a text search of the Government Interest clause field
Source	USPTO
Time Period	1/1/1975—01/08/2013
Variables	PATENT (Patent Number; Common ID; also ALL_GIPATS_PATENT)

Table	**NSF GIPATS**
Description	Patent numbers identified by USPTO using a text search for “NSF” and “National Science Foundation” on the Government Interest clause field
Source	USPTO
Time Period	1/1/1975—01/08/2013
Variables	PATENT (Patent Number; Common ID; also NSF_GIPATS_PATENT)

Table	**INVENTOR**
Description	Inventor information for patents in Table BASIC
Source	USPTO
Time Period	1/1/1975—12/31/2011
Variables	PATENT (Patent Number; Common ID)
	InvNum (Number assigned to each inventor of the patent; 1 = lead inventor)
	LastName (Last name of the inventor)
	FirstName (First name of the inventor)
	MiddleName (Middle name of the inventor)
	Suffix (Suffix of the inventor)
	Street (Street of the inventor’s address)
	City (City of the inventor’s address)
	State (State or Country of the inventor’s address)
	Zipcode (Five digit zip code of the inventor’s address)

Table	**NPLCITES**
Description	Citations of Non-Patent Literature (NPL) for patents in Table BASIC
Source	USPTO
Time Period	1/1/1975—12/31/2011
Variables	PATENT (Patent Number; Common ID)
	LitRefNum (Number assigned to each reference of the patent)
	LitRef (Non-patent literature citation text)
	LitRef-1 (A continuation of LitRef field, occurs in rare instances due to a Microsoft Access field size limitation)

Table	**PATENT MUSEUM**
Description	Basic bibliographic data for a patent related to AM only.
Source	Additive Fabrication / Rapid Prototyping U.S. Patent Database (also known as the “Rapid Prototyping Patent Museum”
Time Period	1/1/1892—01/22/2013
Variables	PATENT (Patent Number; Common ID)
	Title (Title of the patent)
	Inventor (All inventors assigned to the patent)
	Assignee (Patent’s assignee)
	Class (U.S. Patent Classification System of Class and Subclass)
	STPI Added (Flag to identify a patent added by STPI upon review)

Table	**PTITLE**
Description	Patent titles
Source	USPTO
Time Period	1/1/1975—12/31/2011
Variables	PATENT (Patent Number; Common ID)
	Title (Title of the patent)

Table	**UCITES**
Description	Citations of U.S. patent documents for patents in Table BASIC
Source	USPTO
Time Period	1/1/1975—12/31/2011
Variables	PATENT (Patent Number; Common ID)
	PatRef (Citing patent number; listed under category “References Cited [Referenced By]” on patent document)

Appendix D.
Patent Tally

A tally of the references to AM patents from three sources—a literature review, discussions with experts, and AM event materials—yielded 83 U.S. patents issued from 1870 to 2012. The analysis conducted in the study included 70 of these patents that were issued from 1975 to 2011. It excludes 13 patents for which there was no available data (other than the issue year) through the U.S. Patent and Trademark Office and 1 patent issued in 2012, which was beyond the years scoped for the analysis.

Table D-1 shows the patent number, inventors, patent title, issue year, and number of times the patent was cited, aggregated by the three source types.

Table D-1. Additive Manufacturing U.S. Patents from Three Sources—Literature Review, Discussions, and AM Event Materials

Patent Number	Inventor(s)	Title	Issue Year	Literature Review	Discussions	AM Event Materials
105338*	Hyatt, John	Improvement in treating and molding pyroxyline	1870	1	0	0
473901*	Blanther, Joseph	Manufacture of contour relief maps	1892	4	0	0
774549*	Baese, C.	Photographic process for the reproduction of plastic objects	1904	4	0	0
1516199*	Monteah, F.H.	Photochemical Process for Producing bas reliefs	1924	4	0	0
2015457*	Morioka, Isao	Process for manufacturing a relief of maps	1935	4	0	0
2189592*	Bamunuarchige, Victor P.	Process of making relief maps	1940	4	0	0
2350796*	Morioka, Isao	Process for plastically reproducing objects	1944	4	0	0
2566443*	Elmqvist, Rune	Measuring instrument	1951	1	0	0
2775758*	Munz, Otto J.	Photo-glyph recording	1956	4	0	0
3137080*	Zang, Eugene	Vitavue relief model technique	1964	4	0	0
3683212*	Zoltan, Steven I.	Pulsed Droplet Ejecting System	1972	1	0	0
3751827*	Gaskin, Theodore Alfred	Earth Science Teaching Device	1973	4	0	0
3932923	DiMatteo, Paul L.	Method of generating and constructing three-dimensional bodies	1976	4	0	0
4041476	Swainson, Wyn Kelly	Method, medium and apparatus for producing three-dimensional figure product	1977	5	1	0
4078229	Swanson, Wyn K.; Kremer, Stephen D.	Three dimensional systems	1978	1	0	0
4247508	Housholder, Ross F.	Molding process	1981	10	2	2
4323756	Brown, Clyde O.; Breinan, Edward M.; Kear, Bernard H.	Method for fabricating articles by sequential layer deposition	1982	2	2	0
4333165	Swainson, Wyn K.; Kramer, Stephen D.	Three-dimensional pattern making methods	1982	1	0	0
4466080	Swainson, Wyn K.; Kramer, Stephen D.	Three-dimensional patterned media	1984	1	0	0
4471470	Swainson, Wyn K.; Kramer, Stephen D.	Method and media for accessing data in three dimensions	1984	1	0	0

Patent Number	Inventor(s)	Title	Issue Year	Literature Review	Discussions	AM Event Materials
4575330	Hull, Charles W.	Apparatus for production of three-dimensional objects by stereolithography	1986	12	10	2
4665492	Masters, William E.	Computer automated manufacturing process and system	1987	1	0	0
4752352	Feygin, Michael	Apparatus and method for forming an integral object from laminations	1988	5	0	1
4752498	Fudim, Efrem V.	Method and apparatus for production of three-dimensional objects by photosolidification	1988	3	0	0
4801477	Fudim, Efrem V.	Method and apparatus for production of three-dimensional objects by photosolidification	1989	1	0	0
4818562	Arcella, Frank G.; Lessmann, Gerald G.	Casting shapes	1989	4	0	0
4863538	Deckard, Carl R.	Method and apparatus for producing parts by selective sintering	1989	9	11	1
4929402	Hull, Charles W.	Method for production of three-dimensional objects by stereolithography	1990	3	0	0
4944817	Bourell, David L.; Marcus, Harris L.; Barlow, Joel W.; Beaman, Joseph J.; Deckard, Carl R.	Multiple material systems for selective beam sintering	1990	1	0	0
4961154	Pomerantz, Itzchak; Cohen-Sabban, Joseph; Bieber, Avigdor; Kamir, Josef; Katz, Mathew; Nagler, Michael	Three dimensional modelling apparatus	1990	3	0	0
4999143	Hull, Charles W.; Lewis, Charles W.	Methods and apparatus for production of three-dimensional objects by stereolithography	1991	1	0	0
5011635	Murphy, Edward J.; Krajewski, John J.; Ansel, Robert E.	Stereolithographic method and apparatus in which a membrane separates phases	1991	1	0	0
5017317	Marcus, Harris L.	Gas phase selective beam deposition	1991	1	0	0

Patent Number	Inventor(s)	Title	Issue Year	Literature Review	Discussions	AM Event Materials
5059359	Hull, Charles W.; Spence, Stuart T.; Albert, David J.; Smalley, Dennis R.; Harlow, Richard A.; Steinbaugh, Phil; Tarnoff, Harry L.; Nguyen, Hop D.; Lewis, Charles W.; Vorgitch, Tom J.; Remba, David Z.	Methods and apparatus for production of three-dimensional objects by stereolithography	1991	2	0	0
5076974	Modrek, Borzo; Parker, Brent; Spence, Stuart T.	Methods of curing partially polymerized parts	1991	1	0	0
5121329	Crump, S. Scott	Apparatus and method for creating three-dimensional objects	1992	6	9	2
5126529	Weiss, Lee E.; Prinz, Fritz R.; Gursoz, E. Levent	Method and apparatus for fabrication of three-dimensional articles by thermal spray deposition	1992	1	1	0
5136515	Helinski, Richard	Method and means for constructing three-dimensional articles by particle deposition	1992	1	1	2
5182056	Spence, Stuart T.; Smalley, Dennis R.	Stereolithography method and apparatus employing various penetration depths	1993	1	0	0
5184307	Hull, Charles W.; Spence, Stuart T.; Albert, David J.; Smalley, Dennis R.; Harlow, Richard A.; Stinebaugh, Phil; Tarnoff, Harry L.; Nguyen, Hop D.; Lewis, Charles W.; Vorgitch, Tom J.; Remba, David Z.	Method and apparatus for production of high resolution three-dimensional objects by stereolithography	1993	1	0	0
5204055	Sachs, Emanuel M.; Haggerty, John S.; Cima, Michael J.; Williams, Paul A.	Three-dimensional printing techniques	1993	2	7	2
5252264	Forderhase, Paul F.; Deckard, Carl R.; Klein, Jack M.	Apparatus and method for producing parts with multi-directional powder delivery	1993	1	0	0
5256340	Allison, Joseph W.; Richter, Jan; Childers, Craig M.; Smalley, Dennis R.; Hull, Charles W.; Jacobs, Paul F.	Method of making a three-dimensional object by stereolithography	1993	1	0	0
5260009	Penn, Steven M.	System, method, and process for making three-dimensional objects	1993	1	0	0
5431967	Manthiram, Arumugam; Marcus, Harris L.; Bourell, David L.	Selective laser sintering using nanocomposite materials	1995	1	0	0

Patent Number	Inventor(s)	Title	Issue Year	Literature Review	Discussions	AM Event Materials
5463416	Paton, Anthony D.; Kruse, Jurgen M.	Reduced nozzle viscous impedance	1995	1	0	0
5476748	Steinmann, Bettina; Wolf, Jean-Pierre; Schulthess, Adrian; Hunziker, Max	Photosensitive compositions	1995	1	0	0
5506607	Sanders, Jr., Royden C.; Forsyth, John L.; Philbrook, Kempton F.	3D model maker	1996	0	0	1
5506706	Yamahara, Motohiro; Sasaki, Kei; Hara, Teruyoshi; Kohzaki, Shuichi	Liquid crystal display device having a phase difference plate with one refractive index at an angle to the surface normal	1996	1	0	0
5519816	Pomerantz, Itzchak; Gilad, Shaley; Dollberg, Yehoshua; Ben-Ezra, Barry; Sheinman, Yehoshua; Barequet, Gill; Katz, Matthew	Three dimensional modeling apparatus	1996	1	0	0
5672312	Almquist, Thomas A.; Smalley, Dennis R.	Thermal stereolithography	1997	1	0	0
5786562	Larson, Ralf	Method and device for producing three-dimensional bodies	1998	0	1	0
5840239	Partanen, Jouni P.; Hug, William F.	Apparatus and method for forming three-dimensional objects in stereolithography utilizing a laser exposure system having a diode pumped frequency quadrupled solid state laser	1998	1	0	0
5855836	Leyden, Richard N.; Hull, Charles W.	Method for selective deposition modeling	1999	1	0	0
5866058	Batchelder, John Samuel; Crump, Steven Scott	Method for rapid prototyping of solid models	1999	0	0	1
5902537	Almquist, Thomas A.; Hull, Charles W.; Thayer, Jeffrey S.; Leyden, Richard N.; Jacobs, Paul F.; Smalley, Dennis R.	Rapid recoating of three-dimensional objects formed on a cross-sectional basis	1999	1	0	0
5902538	Kruger, Theodore R.; Manners, Chris R.; Nguyen, Hop D.	Simplified stereolithographic object formation methods of overcoming minimum recoating depth limitations	1999	1	0	0

Patent Number	Inventor(s)	Title	Issue Year	Literature Review	Discussions	AM Event Materials
6001297	Partanen, Jouni P.; Smalley, Dennis R.	Method for controlling exposure of a solidfiable medium using a pulsed radiation source in building a three-dimensional object using stereolithography	1999	1	0	0
6027326	Cesarano, III, Joseph; Calvert, Paul D.	Freeforming objects with low-binder slurry	2000	1	0	0
6046426	Jeantette, Francisco P.; Keicher, David M.; Romero, Joseph A.; Schanwald, Lee P.	Method and system for producing complex-shape objects	2000	2	1	0
6054077	Comb, James W.; Leavitt, Paul J; Rapoport, Edward	Velocity profiling in an extrusion apparatus	2000	0	0	1
6100007	Pang, Thomas H.; Melisaris, Anastasios P.; Renyi, Wang; Fong, John W.	Liquid radiation-curable composition especially for producing cured articles by stereolithography having high heat deflection temperatures	2000	1	0	0
6110602	Dickens, Philip Michael; Hague, Richard James Mackenzie	Method of making a three-dimensional object	2000	0	1	0
6122564	Koch, Justin; Mazumder, Jyoti	Apparatus and methods for monitoring and controlling multi-layer laser cladding	2000	1	0	0
6136497	Melisaris, Anastasios P.; Renyi, Wang; Pang, Thomas H	Liquid, radiation-curable composition, especially for producing flexible cured articles by stereolithography	2000	1	0	0
6215093	Meiners, Wilhelm; Wissenbach, Konrad; Gasser, Andres	Selective laser sintering at melting temperature	2001	1	1	0
6259962	Gothait, Hanan	Apparatus and method for three dimensional model printing	2001	0	1	0
6305769	Thayer, Jeffrey S.; Almquist, Thomas A.; Merot, Christian M.; Bedal, Bryan J. L.; Leyden, Richard N.; Denison, Keith; Stockwell, John S.; Caruso, Anthony L.; Lockard, Michael S.	Selective deposition modeling system and method	2001	1	0	0
6457629	White, Dawn	Object consolidation employing friction joining	2002	0	1	0
6459069	Rabinovich, Joshua E.	Rapid manufacturing system for metal, metal matrix composite materials and ceramics	2002	1	0	0

Patent Number	Inventor(s)	Title	Issue Year	Literature Review	Discussions	AM Event Materials
6518541	Kelly, Joseph K.	Duty cycle stabilization in direct metal deposition (DMD) systems	2003	1	0	0
6519500	White, Dawn	Ultrasonic object consolidation	2003	2	0	0
6531086	Larsson, Ralf	Method and device for manufacturing three-dimensional bodies	2003	1	0	0
6547995	Comb, James W.	Melt flow compensation in an extrusion apparatus	2003	0	0	1
6576861	Sampath, Sanjay; Herman, Herbert; Greenlaw, Robert	Method and apparatus for fine feature spray deposition	2003	1	0	0
6610429	Bredt, James F.; Anderson, Timothy C.; Russell, David B.	Three dimensional printing material system and method	2003	1	0	0
6658314	Gothait, Hanan	System and method for three dimensional model printing	2003	1	0	0
6676892	Das, Suman; Beaman, Joseph J.	Direct selective laser sintering of metals	2004	0	3	0
6833234	Bloomstein, Theodore M.; Kunz, Roderick R.; Palmacci, Stephen T.	Stereolithographic patterning with variable size exposure areas	2004	1	0	0
7088432	Zhang, Xiang	Dynamic mask projection stereo micro lithography	2006	1	0	0
7168935	Taminger, Karen M.; Watson, J. Kevin; Hafley, Robert A.; Petersen, Daniel D.	Solid freeform fabrication apparatus and methods	2007	1	0	0
7515986	Huskamp, Christopher S.	Methods and systems for controlling and adjusting heat distribution over a part bed	2009	2	0	0
8246888*	Hopkins, Paul E.; Priedeman, Jr., William R.; Bye, Jeffrey F.	Support material for digital manufacturing systems	2012	0	0	1

* These patents were outside the scope of the analysis (not issued between 1975 and 2011).

Appendix E.
Top 100 Historically Important U.S. Patents in the Additive Manufacturing Field

Table E-1 presents the top 100 historically important U.S. patents in the AM field, including the patent numbers (with hyperlinks to invention information on Google), inventors, and patent titles, application and issue dates, assignee, government interest, and citations from references in the AM patent database as well as the U.S. Patent and Trademark Office (USPTO) as of July 15, 2013.

The list includes the 70 patents with available data from the patent tally (Appendix D) that were issued in the United States between 1975 and 2011, supplemented with 30 of the most highly cited patents in the patent database and verified by the Patent Museum database.

Table E-1. Top 100 Historically Important U.S. Patents in the AM Field, Organized by Application Date

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
4041476	Swainson, Wyn Kelly	Method, medium and apparatus for producing three-dimensional figure product	Jul 23, 1971	Aug 9, 1977			51	90
3932923	DiMatteo, Paul L.	Method of generating and constructing three-dimensional bodies	Oct 21, 1974	Jan 20, 1976	Dynell Electronics Corporation		55	73
4078229	Swanson, Wyn K.; Kremer, Stephen D.	Three dimensional systems	Jan 27, 1975	Mar 7, 1978	Formigraphic Engine Corporation		48	75
4333165	Swainson, Wyn K.; Kramer, Stephen D.	Three-dimensional pattern making methods	Dec 1, 1977	Jun 1, 1982	Formigraphic Engine Corporation		33	52
4323756	Brown, Clyde O.; Breinan, Edward M.; Kear, Bernard H.	Method for fabricating articles by sequential layer deposition	Oct 29, 1979	Apr 6, 1982	United Technologies Corporation	U.S. Navy (Contract #N00014-77-C-0418)	94	132
4247508	Housholder, Ross F.	Molding process	Dec 3, 1979	Jan 27, 1981	DTM Corporation		142	158
4466080	Swainson, Wyn K.; Kramer, Stephen D.	Three-dimensional patterned media	Apr 15, 1981	Aug 14, 1984	Formigraphic Engine Corporation		29	44
4471470	Swainson, Wyn K.; Kramer, Stephen D.	Method and media for accessing data in three dimensions	Feb 22, 1982	Sep 11, 1984	Formigraphic Engine Corporation		32	75
4665492	Masters, William E.	Computer automated manufacturing process and system	Jul 2, 1984	May 12, 1987	Zucker, Jerry		144	181
4575330	Hull, Charles W.	Apparatus for production of three-dimensional objects by stereolithography	Aug 8, 1984	Mar 11, 1986	3D Systems Inc.		399	482
4863538	Deckard, Carl R.	Method and apparatus for producing parts by selective sintering	Oct 17, 1986	Sep 5, 1989	University of Texas System Board of Regents		243	295
4752498	Fudim, Efrem V.	Method and apparatus for production of three-dimensional objects by photosolidification	Mar 2, 1987	Jun 21, 1988			113	138

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
4752352	Feygin, Michael	Apparatus and method for forming an integral object from laminations	Apr 17, 1987	Jun 21, 1988	Cruttenden, Walter W., III		139	169
4961154	Pomerantz, Itzchak; Cohen-Sabban, Joseph; Bieber, Avigdor; Kamir, Josef; Katz, Mathew; Nagler, Michael	Three dimensional modelling apparatus	Jun 2, 1987	Oct 2, 1990	Objet Geometries Ltd.		127	164
4801477	Fudim, Efrem V.	Method and apparatus for production of three-dimensional objects by photosolidification	Sep 29, 1987	Jan 31, 1989			67	82
4818562	Arcella, Frank G.; Lessmann, Gerald G.	Casting shapes	Mar 24, 1988	Apr 4, 1989	Westinghouse Electric Corp.		46	59
4999143	Hull, Charles W.; Lewis, Charles W.	Methods and apparatus for production of three-dimensional objects by stereolithography	Apr 18, 1988	Mar 12, 1991	3D Systems Inc.		63	74
5059359	Hull, Charles W.; Spence, Stuart T.; Albert, David J.; Smalley, Dennis R.; Harlow, Richard A.; Steinbaugh, Phil; Tarnoff, Harry L.; Nguyen, Hop D.; Lewis, Charles W.; Vorgitch, Tom J.; Remba, David Z.	Methods and apparatus for production of three-dimensional objects by stereolithography	Apr 18, 1988	Oct 22, 1991	3D Systems Inc.		43	54
5076974	Modrek, Borzo; Parker, Brent; Spence, Stuart T.	Methods of curing partially polymerized parts	Nov 8, 1988	Dec 31, 1991	3D Systems Inc.		39	50
5184307	Hull, Charles W.; Spence, Stuart T.; Albert, David J.; Smalley, Dennis R.; Harlow, Richard A.; Stinebaugh, Phil; Tarnoff, Harry L.; Nguyen, Hop D.; Lewis, Charles W.; Vorgitch, Tom J.; Remba, David Z.	Method and apparatus for production of high resolution three-dimensional objects by stereolithography	Mar 31, 1989	Feb 2, 1993	3D Systems Inc.		62	73
4929402	Hull, Charles W.	Method for production of three-dimensional objects by stereolithography	Apr 19, 1989	May 29, 1990	3D Systems Inc.		98	118

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
5011635	Murphy, Edward J.; Krajewski, John J.; Ansel, Robert E.	Stereolithographic method and apparatus in which a membrane separates phases	May 18, 1989	Apr 30, 1991	Stamicarbon B. V., a Netherlands Co.		21	24
5134569	Masters, William E.	System and method for computer automated manufacturing using fluent material	Jun 26, 1989	Jul 28, 1992			91	107
4944817	Bourell, David L.; Marcus, Harris L.; Barlow, Joel W.; Beaman, Joseph J.; Deckard, Carl R.	Multiple material systems for selective beam sintering	Sep 5, 1989	Jul 31, 1990	University of Texas System Board of Regents; The University of Texas System, 201 West 7TH Street, Austin, TX 78701 Board of Regents		124	155
4938816	Beaman, Joseph J.; Deckard, Carl R.	Selective laser sintering with assisted powder handling	Sep 5, 1989	Jul 3, 1990	University of Texas System Board of Regents; The University of Texas System, 201 West 7TH Street, Austin, TX 78701 Board of Regents		110	122
5182056	Spence, Stuart T.; Smalley, Dennis R.	Stereolithography method and apparatus employing various penetration depths	Oct 27, 1989	Jan 26, 1993	3D Systems Inc.		58	77
5121329	Crump, S. Scott	Apparatus and method for creating three-dimensional objects	Oct 30, 1989	Jun 9, 1992	Stratasys Inc.		203	259
5136515	Helinski, Richard	Method and means for constructing three-dimensional articles by particle deposition	Nov 7, 1989	Aug 4, 1992			130	147
5216616	Masters, William E.	System and method for computer automated manufacture with reduced object shape distortion	Dec 1, 1989	Jun 1, 1993	Zucker, Jerry		95	106

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
5017317	Marcus, Harris L.	Gas phase selective beam deposition	Dec 4, 1989	May 21, 1991	Board of Regents, University of Texas System; University of Texas System Board of Regents		31	43
5204055	Sachs, Emanuel M.; Haggerty, John S.; Cima, Michael J.; Williams, Paul A.	Three-dimensional printing techniques	Dec 8, 1989	Apr 20, 1993	Massachusetts Institute of Technology		247	330
5059266	Yamane, Mitsuo; Kawaguchi, Takashi; Kagayama, Shigeru; Higashiyama, Shunichi; Suzuki, Keiko; Sakai, Jun; Imaeda, Mikio; Inaishi, Kouji	Apparatus and method for forming three-dimensional article	May 23, 1990	Oct 22, 1991	Brother Kogyo Kabushiki Kaisha		116	163
5132143	Deckard, Carl R.	Method for producing parts	Jun 21, 1990	Jul 21, 1992	University of Texas System Board of Regents		96	106
5017753	Deckard, Carl R.	Method and apparatus for producing parts by selective sintering	Jun 22, 1990	May 21, 1991	University of Texas System Board of Regents		104	121
5076869	Bourell, David L.; Marcus, Harris L.; Barlow, Joel W.; Beaman, Joseph J.; Deckard, Carl R.	Multiple material systems for selective beam sintering	Jul 30, 1990	Dec 31, 1991	University of Texas System Board of Regents		93	108
5141680	Almquist, Thomas A.; Smalley, Dennis R.	Thermal stereolighography	Oct 4, 1990	Aug 25, 1992	3D Systems Inc.		86	94
5155324	Deckard, Carl R.; Beaman, Joseph J.; Darrah, James F.	Method for selective laser sintering with layerwise cross-scanning	Nov 9, 1990	Oct 13, 1992			88	106

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
5126529	Weiss, Lee E.; Prinz, Fritz R.; Gursoz, E. Levent	Method and apparatus for fabrication of three-dimensional articles by thermal spray deposition	Dec 3, 1990	Jun 30, 1992			52	68
5156697	Bourell, David L.; Marcus, Harris L.; Weiss, Wendy L.	Selective laser sintering of parts by compound formation of precursor powders	Dec 7, 1990	Oct 20, 1992	University of Texas System Board of Regents; University of Texas System, an Institution of Texas Board of Regents		73	81
5173220	Reiff, David E.; Dorinski, Dale W.; Hunt, Stephen D.	Method of manufacturing a three-dimensional plastic article	Apr 26, 1991	Dec 22, 1992	Motorola Inc.		127	135
5278442	Prinz, Fritz B.; Weiss, Lee E.; Siewiorek, Daniel P.	Electronic packages and smart structures formed by thermal spray deposition	Jul 15, 1991	Jan 11, 1994			101	144
5252264	Forderhase, Paul F.; Deckard, Carl R.; Klein, Jack M.	Apparatus and method for producing parts with multi-directional powder delivery	Nov 8, 1991	Oct 12, 1993	3D Systems Inc.		94	107
5387380	Cima, Michael; Sachs, Emanuel; Fan, Tailin; Bredt, James F.; Michaels, Steven P.; Khanuja, Satbir; Lauder, Alan; Lee, Sang-Joon J.; Brancazio, David; Curodeau, Alain; Tuerck, Harald	Three-dimensional printing techniques	Jun 5, 1992	Feb 7, 1995	Massachusetts Institute of Technology	NSF (Award #8913977 (DDM))	149	182
5340433	Crump, S. Scott	Modeling apparatus for three-dimensional objects	Jun 8, 1992	Aug 23, 1994	Stratasys Inc.		123	176
5260009	Penn, Steven M.	System, method, and process for making three-dimensional objects	Jun 24, 1992	Nov 9, 1993	Texas Instruments Incorporated		75	97

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
5256340	Allison, Joseph W.; Richter, Jan; Childers, Craig M.; Smalley, Dennis R.; Hull, Charles W.; Jacobs, Paul F.	Method of making a three-dimensional object by stereolithography	Jun 25, 1992	Oct 26, 1993	3D Systems Inc.		69	75
5352405	Beaman, Joseph J.; McGrath, Joseph C.; Prioleau, Frost R. R.	Thermal control of selective laser sintering via control of the laser scan	Dec 18, 1992	Oct 4, 1994	3D Systems Inc.		90	99
5303141	Batchelder, John S.; Curtis, Huntington W.; Goodman, Douglas S.; Gracer, Franklin; Jackson, Robert R.; Koppelman, George M.; Mackay, John D.	Model generation system having closed-loop extrusion nozzle positioning	Mar 22, 1993	Apr 12, 1994	Stratasys Inc.		94	125
5431967	Manthiram, Arumugam; Marcus, Harris L.; Bourell, David L.	Selective laser sintering using nanocomposite materials	Apr 8, 1993	Jul 11, 1995	University of Texas System Board of Regents		24	47
5340656	Sachs, Emanuel M.; Haggerty, John S.; Cima, Michael J.; Williams, Paul A.	Three-dimensional printing techniques	Apr 9, 1993	Aug 23, 1994	Massachusetts Institute of Technology		119	148
5506706	Yamahara, Motohiro; Sasaki, Kei; Hara, Teruyoshi; Kohzaki, Shuichi	Liquid crystal display device having a phase difference plate with one refractive index at an angle to the surface normal	Jun 18, 1993	Apr 9, 1996	Sharp Kabushiki Kaisha		0	40
5398193	deAngelis, Alfredo O.	Method of three-dimensional rapid prototyping through controlled layerwise deposition/extraction and apparatus therefor	Aug 20, 1993	Mar 14, 1995	Optomec Inc.		71	90
5463416	Paton, Anthony D.; Kruse, Jurgen M.	Reduced nozzle viscous impedance	Sep 13, 1993	Oct 31, 1995	Xaar Technology Limited		7	17
5490962	Cima, Linda G.; Cima, Michael J.	Preparation of medical devices by solid free-form fabrication methods	Oct 18, 1993	Feb 13, 1996	Massachusetts Institute of Technology	NSF (Award #8913977 (DDM))	90	189

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
5476748	Steinmann, Bettina; Wolf, Jean-Pierre; Schulthess, Adrian; Hunziker, Max	Photosensitive compositions	Dec 14, 1993	Dec 19, 1995	3D Systems Inc.		29	41
5518680	Cima, Linda G.; Cima, Michael J.	Tissue regeneration matrices by solid free form fabrication techniques	Feb 23, 1994	May 21, 1996	Massachusetts Institute of Technology	NSF (Award #8913977 (DDM))	85	163
5503785	Crump, S. Scott; Comb, James W.; Priedeman, Jr., William R.; Zinniel, Robert L.	Process of support removal for fused deposition modeling	Jun 2, 1994	Apr 2, 1996	Stratasys Inc.		77	110
5519816	Pomerantz, Itzchak; Gilad, Shaley; Dollberg, Yehoshua; Ben-Ezra, Barry; Sheinman, Yehoshua; Barequet, Gill; Katz, Matthew	Three dimensional modeling apparatus	Oct 26, 1994	May 21, 1996	Objet Geometries Ltd.		14	18
5506607	Sanders, Jr., Royden C.; Forsyth, John L.; Philbrook, Kempton F.	3D model maker	Jan 26, 1995	Apr 9, 1996	Solidscape Inc.		50	64
5672312	Almquist, Thomas A.; Smalley, Dennis R.	Thermal stereolithography	Jun 5, 1995	Sep 30, 1997	3D Systems Inc.		32	35
5594652	Penn, Steven M.; Jones, David N.; Embree, Michael E.	Method and apparatus for the computer-controlled manufacture of three-dimensional objects from computer data	Jun 7, 1995	Jan 14, 1997	Texas Instruments Incorporated		87	111
5786562	Larson, Ralf	Method and device for producing three-dimensional bodies	Nov 9, 1995	Jul 28, 1998	Arcam AB		2	2
5837960	Lewis, Gary K.; Milewski, John O.; Cremers, David A.; Nemec, Ronald B.; Barbe, Michael R.	Laser production of articles from powders	Nov 30, 1995	Nov 17, 1998	Los Alamos National Security, LLC	DOE (Contract #W-7405-ENG-36)	73	108
5705117	O'Connor, Kurt Francis; Nohns, Dennis Carl; Chattin, William Allen	Method of combining metal and ceramic inserts into stereolithography components	Mar 1, 1996	Jan 6, 1998	Delphi Technologies Inc.		127	134
6046426	Jeantette, Francisco P.; Keicher, David M.; Romero, Joseph A.; Schanwald, Lee P.	Method and system for producing complex-shape objects	Jul 8, 1996	Apr 4, 2000	Sandia Corporation	DOE (Contract #DE-AC04-94AL85000)	38	65

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
5943235	Earl, Jocelyn M.; Manners, Chris R.; Kerekes, Thomas A.; Marygold, Paul H.; Thayer, Jeffrey S.	Rapid prototyping system and method with support region data processing	Sep 27, 1996	Aug 24, 1999	3D Systems Inc.		102	127
5902537	Almquist, Thomas A.; Hull, Charles W.; Thayer, Jeffrey S.; Leyden, Richard N.; Jacobs, Paul F.; Smalley, Dennis R.	Rapid recoating of three-dimensional objects formed on a cross-sectional basis	Jan 28, 1997	May 11, 1999	3D Systems Inc.		91	109
5840239	Partanen, Jouni P.; Hug, William F.	Apparatus and method for forming three-dimensional objects in stereolithography utilizing a laser exposure system having a diode pumped frequency quadrupled solid state laser	Jan 31, 1997	Nov 24, 1998	3D Systems Inc.		23	27
6001297	Partanen, Jouni P.; Smalley, Dennis R.	Method for controlling exposure of a solidfiable medium using a pulsed radiation source in building a three-dimensional object using stereolithography	Apr 28, 1997	Dec 14, 1999	3D Systems Inc.		11	14
5866058	Batchelder, John Samuel; Crump, Steven Scott	Method for rapid prototyping of solid models	May 29, 1997	Feb 2, 1999	Stratasys Inc.		84	105
5855836	Leyden, Richard N.; Hull, Charles W.	Method for selective deposition modeling	Jun 12, 1997	Jan 5, 1999	3D Systems Inc.		53	58
6305769	Thayer, Jeffrey S.; Almquist, Thomas A.; Merot, Christian M.; Bedal, Bryan J. L.; Leyden, Richard N.; Denison, Keith; Stockwell, John S.; Caruso, Anthony L.; Lockard, Michael S.	Selective deposition modeling system and method	Jun 13, 1997	Oct 23, 2001	3D Systems Inc.		18	26
5902538	Kruger, Theodore R.; Manners, Chris R.; Nguyen, Hop D.	Simplified stereolithographic object formation methods of overcoming minimum recoating depth limitations	Aug 29, 1997	May 11, 1999	3D Systems Inc.		33	35

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
5975893	Chishti, Muhammad; Lerios, Apostolos; Freyburger, Brian; Wirth, Kelsey; Ridgley, Richard	Method and system for incrementally moving teeth	Oct 8, 1997	Nov 2, 1999	Align Technology Inc.		150	235
6027326	Cesarano, III, Joseph; Calvert, Paul D.	Freeforming objects with low-binder slurry	Oct 28, 1997	Feb 22, 2000	Sandia Corporation	DOE (Contract #DE-AC04-94AL85000)	17	22
6136497	Melisaris, Anastasios P.; Renyi, Wang; Pang, Thomas H	Liquid, radiation-curable composition, especially for producing flexible cured articles by stereolithography	Mar 30, 1998	Oct 24, 2000	3D Systems Inc.		19	24
6100007	Pang, Thomas H.; Melisaris, Anastasios P.; Renyi, Wang; Fong, John W.	Liquid radiation-curable composition especially for producing cured articles by stereolithography having high heat deflection temperatures	Apr 6, 1998	Aug 8, 2000	3D Systems Inc.		10	12
6122564	Koch, Justin; Mazumder, Jyoti	Apparatus and methods for monitoring and controlling multi-layer laser cladding	Jun 30, 1998	Sep 19, 2000	POM Group Inc.		39	58
6268584	Keicher, David M.; Miller, W. Doyle	Multiple beams and nozzles to increase deposition rate	Jul 20, 1998	Jul 31, 2001	Optomec Design Company		104	111
6110602	Dickens, Philip Michael; Hague, Richard James Mackenzie	Method of making a three-dimensional object	Oct 26, 1998	Aug 29, 2000	University of Nottingham		3	3
6054077	Comb, James W.; Leavitt, Paul J; Rapoport, Edward	Velocity profiling in an extrusion apparatus	Jan 11, 1999	Apr 25, 2000	Stratasys Inc.		32	48
6259962	Gothait, Hanan	Apparatus and method for three dimensional model printing	May 3, 1999	Jul 10, 2001	Objet Geometries Ltd.		151	163
6251488	Miller, W. Doyle; Keicher, David M.; Essien, Marcelino	Precision spray processes for direct write electronic components	May 5, 1999	Jun 26, 2001	Optomec Design Company		119	145
6215093	Meiners, Wilhelm; Wissenbach, Konrad; Gasser, Andres	Selective laser sintering at melting temperature	Jul 12, 1999	Apr 10, 2001	Fraunhofer-Gesellschaft zur Foerderung der Angewandten Forschung E.V.		12	20

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
6658314	Gothait, Hanan	System and method for three dimensional model printing	Oct 6, 1999	Dec 2, 2003	Objet Geometries Ltd.		64	71
6531086	Larsson, Ralf	Method and device for manufacturing three-dimensional bodies	Oct 27, 1999	Mar 11, 2003	Speed Part RP AB		8	15
6519500	White, Dawn	Ultrasonic object consolidation	Mar 23, 2000	Feb 11, 2003	Solidica Inc.		6	11
6391251	Keicher, David M.; Bullen, James L.; Gorman, Pierrette H.; Love, James W.; Dullea, Kevin J.; Smith, Mark E.	Forming structures from CAD solid models	May 9, 2000	May 21, 2002	Optomec Design Company		117	154
6326698	Akram, Salman	Semiconductor devices having protective layers thereon through which contact pads are exposed and stereolithographic methods of fabricating such semiconductor devices	Jun 8, 2000	Dec 4, 2001	Micron Technology Inc.		75	216
6459069	Rabinovich, Joshua E.	Rapid manufacturing system for metal, metal matrix composite materials and ceramics	Sep 29, 2000	Oct 1, 2002			1	5
6457629	White, Dawn	Object consolidation employing friction joining	Oct 4, 2000	Oct 1, 2002	Solidica Inc.		3	18
6518541	Kelly, Joseph K.	Duty cycle stabilization in direct metal deposition (DMD) systems	Nov 16, 2000	Feb 11, 2003			3	3
6610429	Bredt, James F.; Anderson, Timothy C.; Russell, David B.	Three dimensional printing material system and method	Apr 10, 2001	Aug 26, 2003	3D Systems Inc.		29	37
6576861	Sampath, Sanjay; Herman, Herbert; Greenlaw, Robert	Method and apparatus for fine feature spray deposition	May 23, 2001	Jun 10, 2003	Research Foundation of State University of New York		8	11
6676892	Das, Suman; Beaman, Joseph J.	Direct selective laser sintering of metals	Jun 1, 2001	Jan 13, 2004	University Texas System Board of Regents; University of Texas System Broad of Regents		6	20

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Assignee(s)	Government Interest	AM Database Citations	USPTO Citations (7/15/2013)
6833234	Bloomstein, Theodore M.; Kunz, Roderick R.; Palmacci, Stephen T.	Stereolithographic patterning with variable size exposure areas	Aug 6, 2001	Dec 21, 2004	Massachusetts Institute of Technology	U.S. Air Force (Contract #F19628-95-C-0002)	10	22
6547995	Comb, James W.	Melt flow compensation in an extrusion apparatus	Sep 21, 2001	Apr 15, 2003	Stratasys Inc.		12	27
7088432	Zhang, Xiang	Dynamic mask projection stereo micro lithography	Sep 27, 2001	Aug 8, 2006	Regents of the University of California		4	4
7168935	Taminger, Karen M.; Watson, J. Kevin; Hafley, Robert A.; Petersen, Daniel D.	Solid freeform fabrication apparatus and methods	Aug 1, 2003	Jan 30, 2007	United States of America as represented by Administrator of the National Aeronautics and Space Administration	See Assignee	4	11
7515986	Huskamp, Christopher S.	Methods and systems for controlling and adjusting heat distribution over a part bed	Apr 20, 2007	Apr 7, 2009	Boeing Company		0	4

Appendix F.
Keywords Used in NSF Awards Database Search

Table F-1 shows the 61 keywords out of the set of 165 that yielded the NSF awards database. The table also shows the number of awards associated with each keyword in terms of the keyword's relevance to additive manufacturing (AM).

Table F-1. Keywords that Yielded AM-Related NSF Awards

Keyword	AM-Related Awards	Non-AM-Related Awards
3DP	0	1
adaptive slic*	1	0
additive fabricat*	3	0
additive layer manufactur*	1	0
additive manufactur*	48	1
additive process*	3	12
additive system*	0	7
conformal cool*	1	1
DDM	1	16
deposition model*	5	28
desktop manufactur*	3	0
digital fabricat*	10	1
digital manufactur*	2	1
direct* energy	4	34
direct fabricat*	10	8
direct manufactur*	6	5
direct metal deposit*	4	0
direct metal fabricat*	1	0
DMD	0	19
electron beam melt*	2	1
fab lab*	3	1
FDM	1	7
free form	11	9
freeform	120	60
fused deposition	1	0

Keyword	AM-Related Awards	Non-AM-Related Awards
laminated object	4	0
laser additi*	1	9
laser engineered net shap*	7	0
laser melt*	1	15
laser sint*	22	0
layer deposit*	1	157
layer fabricat*	1	3
layer manufactur*	2	1
layered fabricat*	1	0
layered manufactur*	9	0
LOM	1	7
mass custom*	10	26
metal deposit*	3	77
metallic deposit*	1	3
MLS	2	21
powder bed	1	3
prototype tool*	3	98
rapid manufactur*	15	3
rapid prototyp*	185	141
rapid tool*	3	6
rapid-prototyp*	7	4
RP	0	56
select deposit*	1	1
selective deposit*	0	23
selectively deposit*	4	2
SFF	0	1
shape deposit*	4	0
SLA	0	19
SLS	0	24
stereolithograph*	17	1
STL	0	12
strategic manufactur*	0	14
STRATMAN	3	9
three dimensional print*	2	0
ultrasonic consol*	5	0
ultrasonic fabricat*	1	0
TOTAL	558	948

Note: An asterisk (*) is a wildcard character used in searches.

Appendix G.
Five Patent Landscape Maps to Analyze the Top 100 Historically Important Patents in Additive Manufacturing

We created several patent landscape maps to analyze the top 100 historically important patents and citations associated with the four foundational patents using a visual software tool called IPVision. The distance between the parallel vertical dotted lines on the maps represents 1 year. Each rectangle on the maps represents a single U.S. patent, and its placement on the map indicates the patent's issue year. The left-tail whisker begins when the patent was filed and shows the time lag between the patent's file and issue years.

Figure G-1 through G-2 show the following patent landscape maps, similar to Figures 10–12 in the main text:

- 16 historically important patents citing U.S. Patent No. 5121329 (Crump)
- 8 historically important patents citing U.S. Patent No. 5204055 (Sachs)

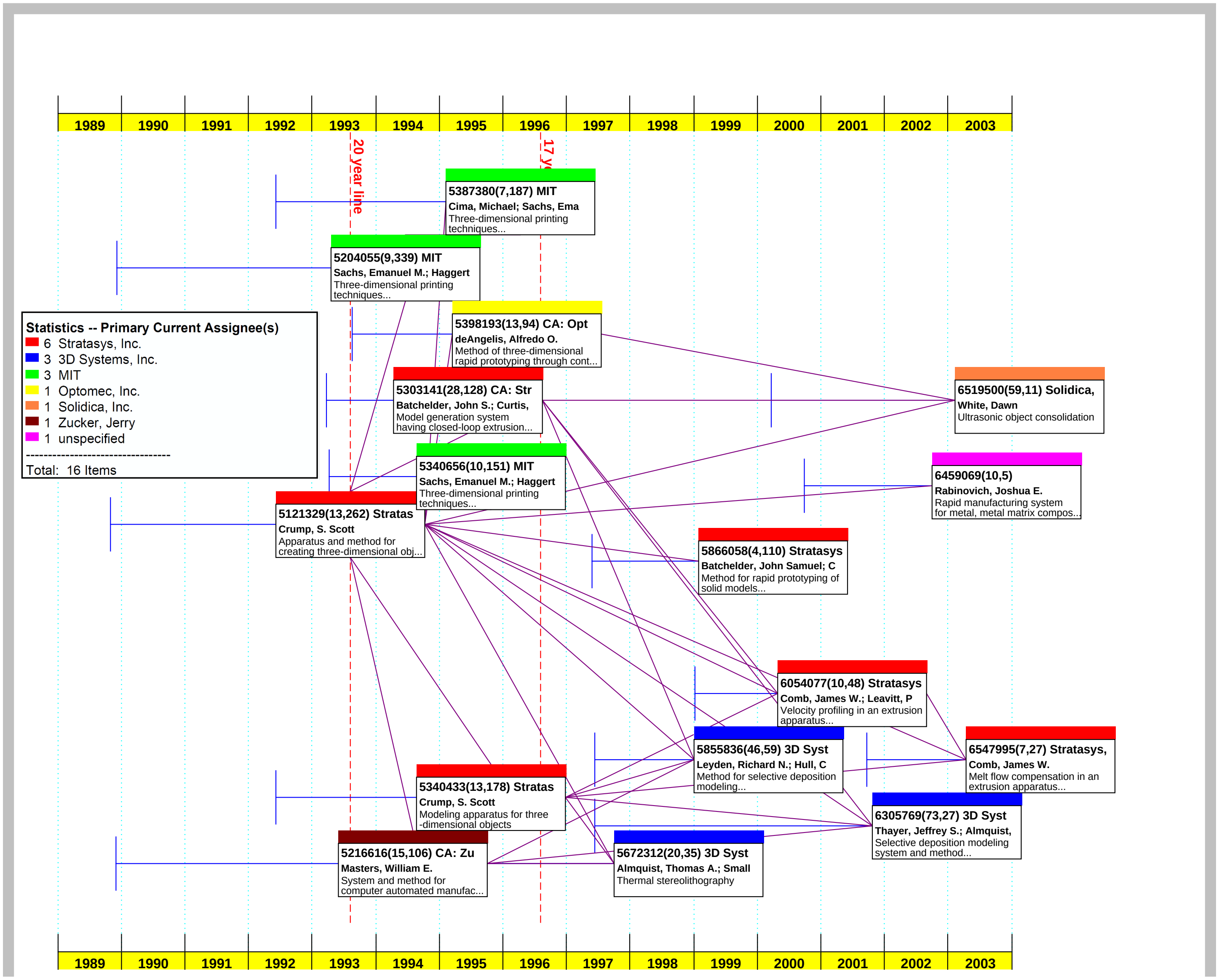

Figure G-1. 15 Historically Important Patents Citing U.S. Patent No. 5121329 and Relationships Between Patents Based on Citations.

Figure created using patent analytics software from IPVision (http://www.see-the-forest.com)

Note: The location of the box indicates the patent issue year while the left whisker indicates the patent application year.

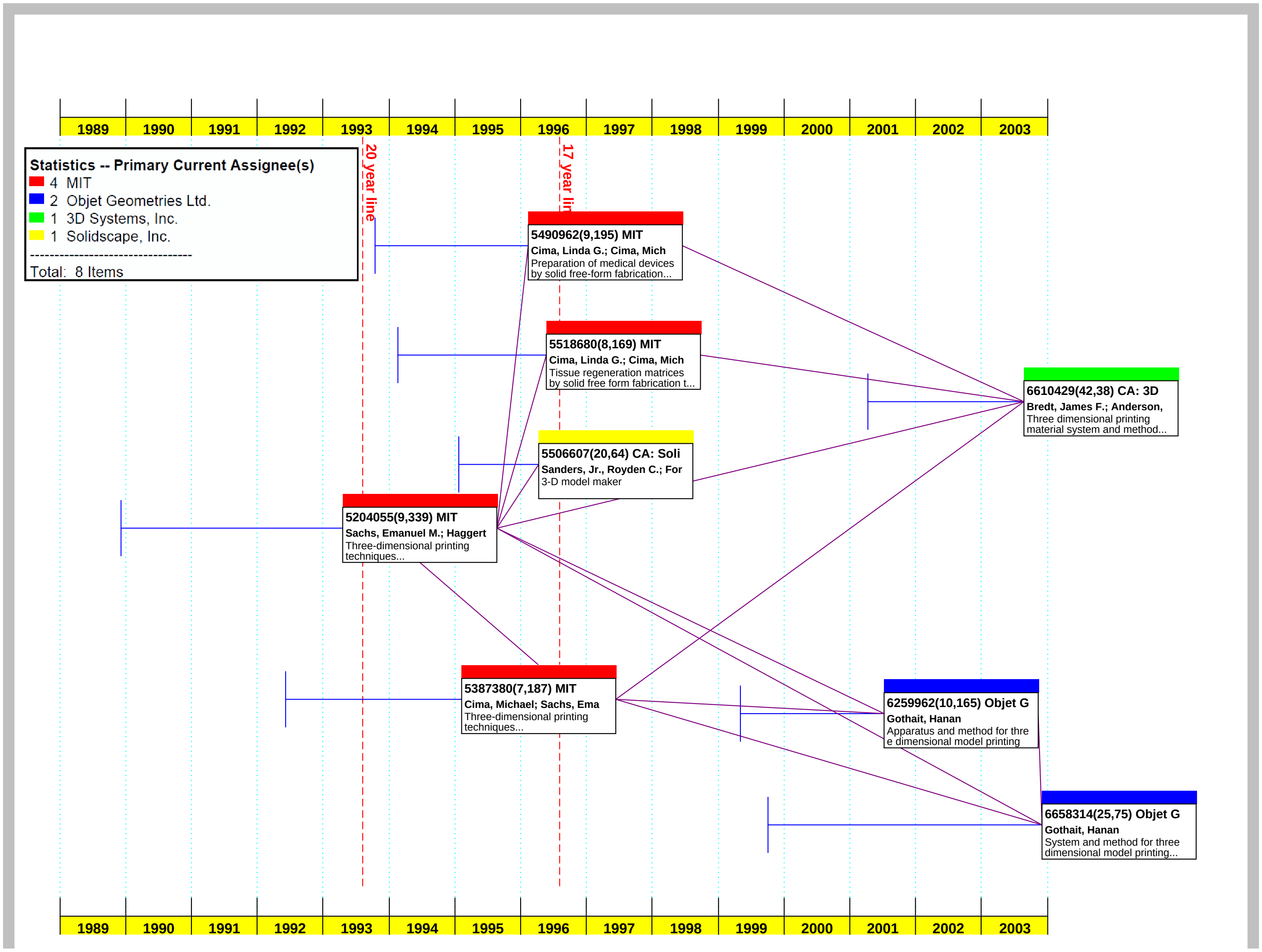

Figure G-2. 7 Historically Important Patents Citing U.S. Patent No. 5204055 and Relationships Between Patents Based on Citations.

Figure created using patent analytics software from IPVision (http://www.see-the-forest.com)

Note: The location of the box indicates the patent issue year while the left whisker indicates the patent application year.

Appendix H.
Case Studies on Four Foundational Patents in the Additive Manufacturing Field

As discussed in Chapter 6, case studies on the following four foundational patents were conducted as part of this study: the case studies for these four foundational patents:

- Patent 4575330—Apparatus for production of 3-dimensional objects by stereolithography.
- Patent 4863538—Method and apparatus for producing parts by selective sintering.
- Patent 5121329—Apparatus and method for creating 3-dimensional objects.
- Patent 5204055—Three-dimensional printing techniques.

This appendix presents details of these four patent case studies as follows:

- *Background*—identifies the motivations, development, and current status of the patent, inventors, and any related companies established to commercialize the technology.
- *Government interest clause*—provides a summary of Federal Government support as stated in the government interest clause of the foundational patent and any patent in the same family.
- *Backward citation analysis*—describes a patent citation analysis of the foundational patent's references (patents and publications) to identify research and technologies that influenced the development of the foundational patent and if any Federal Government support was provided. The patent citations are analyzed at two levels—the first generation and second generation relate to the first set of citations and the citations to those citations, respectively.
- *Forward citation analysis*—describes a first-generation patent citation analysis of the foundational patent's citing references. A patent's citations are used as one indicator of patent value or significance in the field.

Patent 4575330: Apparatus for production of 3-dimensional objects by stereolithography

Background

Charles Hull's invention of stereolithography,[53] documented in U.S. Patent No. 4575330, is considered a major milestone in the field of additive manufacturing. It was the earliest of the foundational additive manufacturing patents.

Hull began his journey in the additive manufacturing field while working for Ultra Violet Products Inc. (UVP), a developer and manufacturer of ultraviolet products.[54] While at UVP, he filed for his stereolithography patent in 1984 and founded 3D Systems 2 years later—the same time his patent was issued in 1986. In 1987, Hull received venture capital funding and was able to expand the company, and over time 3D Systems has become a frontier manufacturer with the largest market share in the industry. Currently, Hull is the Chief Technology Officer at 3D Systems. In the past, he has served in several roles, as Founder, Chief Operating Officer, Executive Officer, and President as well as a member of the Board of Directors.

Government Interest Clause

Discussions with Hull and other experts, as well as an analysis of the government interest clause in Hull's patent, reveal that U.S. Patent No. 4575330 was sponsored solely by UVP with no support from the Federal Government. Hull did not receive any public funding to develop the technology or grow 3D Systems. U.S. Patent No. 4575330 was the first of 72 patents filed by Hull and his co-inventors at 3D Systems. These patents are related to the process of stereolithography and incremental improvements on the technology, as well as to the development of other AM processes obtained through company acquisitions.[55] The 72 patents were filed between 1984 and 2011. None received NSF or government funds.

Backward Citation Analysis

There was some government role in the patents that were cited by the Hull patent. When filing U.S. Patent No. 4575330, Hull was influenced by several patents produced by Wyn Kelly Swainson (Figure H-1). Swainson and his co-inventors have several patents issued starting in the early 1970s that describe the use of photopolymer materials.

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[53] Stereolithography is referred to as vat photopolymerization in the ASTM Standards.

[54] See http://www.uvp.com/.

[55] We searched all USPTO-issued patents for the inventor name "Charles W. Hull" through the USPTO Advanced Search feature: http://patft.uspto.gov/netahtml/PTO/search-adv.htm.

Swainson founded Formigraphic Engine Company to commercialize a dual-laser approach using photopolymers called photochemical machining.[56] Later, Formigraphic partnered with the Battelle Memorial Institute. Battelle researchers, sponsored by DARPA from 1982 to 1984, were working on a similar technology,[57] and the partnership sought to further develop stereolithography, but efforts were abandoned years later due to the complexity of the process.[58] The technology was a precursor to Hull's invention; however, it did not result in a commercial system.

Forward Citation Analysis

Based on the government interest clause, neither Swainson nor any of the other inventors from the U.S. Patent No. 4575330 patent citations were directly funded by the Federal Government. But the Federal Government did play a role in leveraging Hull's invention and sponsoring technologies stemming from Hull's invention. After U.S. Patent No. 4575330 was issued in 1986, it became highly influential in developing the AM field. There are 433 U.S. patents that reference the stereolithography patent, and 25 (or about 6%) of these, those filed between 1992 and 2009, had Federal Government sponsorship.

NSF sponsored 8 of these 25 patents, filed from 1992 to 2004 (Figure H-2). Seven of the eight patents were issued to researchers at MIT—Emanuel Sachs, Michael Cima, James Bredt, and others—that developed binder jetting or 3D printing techniques in the early 1990s (see Case Study 4). NSF awarded two grants to MIT researchers from the Strategic Manufacturing (STRATMAN) Initiative, one in 1989 and one in 1992.[59] The eighth patent was issued to several researchers at Georgia Institute of Technology, with funding from the Division of Information and Intelligent Systems (Directorate for Computer Science and Engineering) in 2001. These patents were produced several years after receiving the awards.

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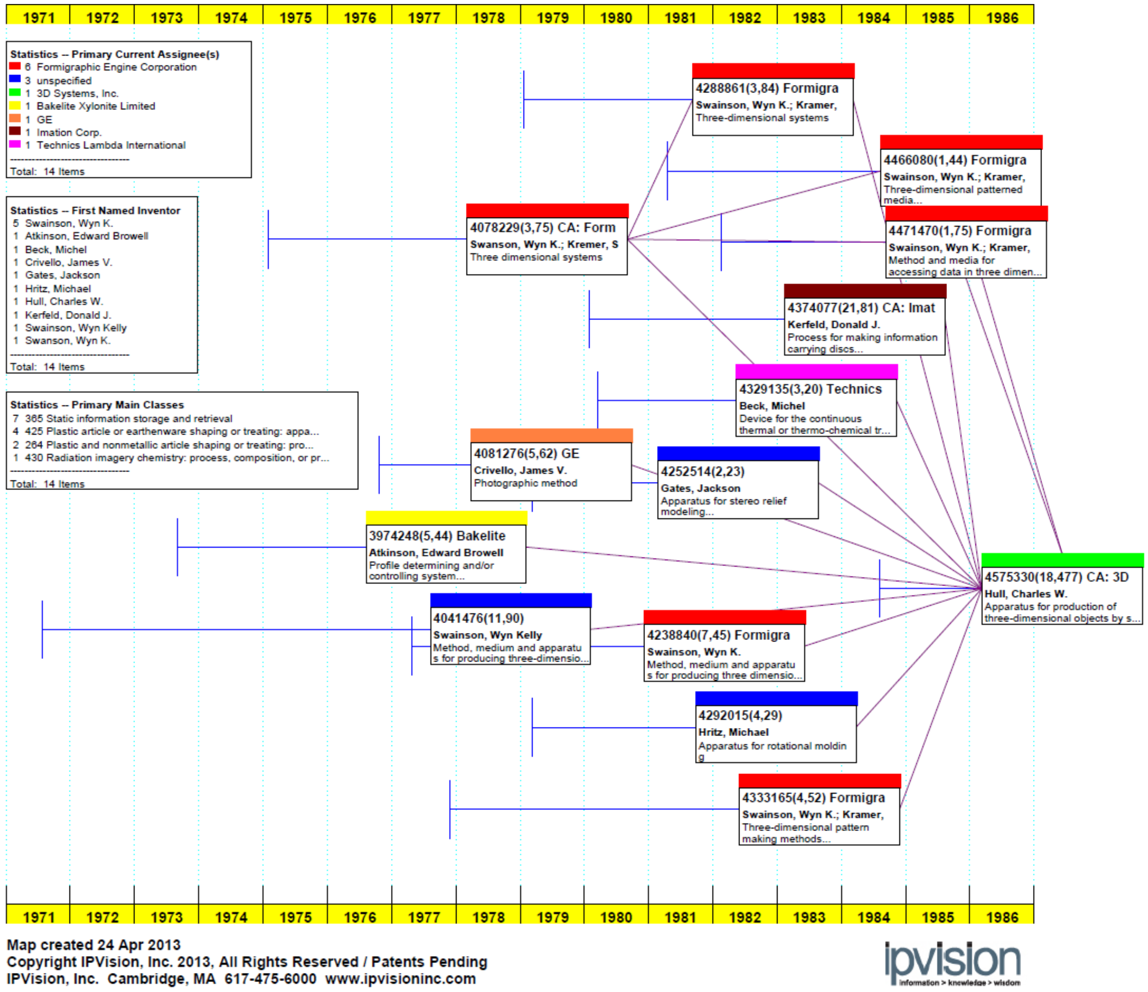
[56] See http://www.wohlersassociates.com/history2011.

[57] The DARPA project "Three-Dimensional Photochemical Machining with Lasers" was funded to principal investigator Dr. Robert E. Schwerzel under contract no. F49620-82-C-0077.

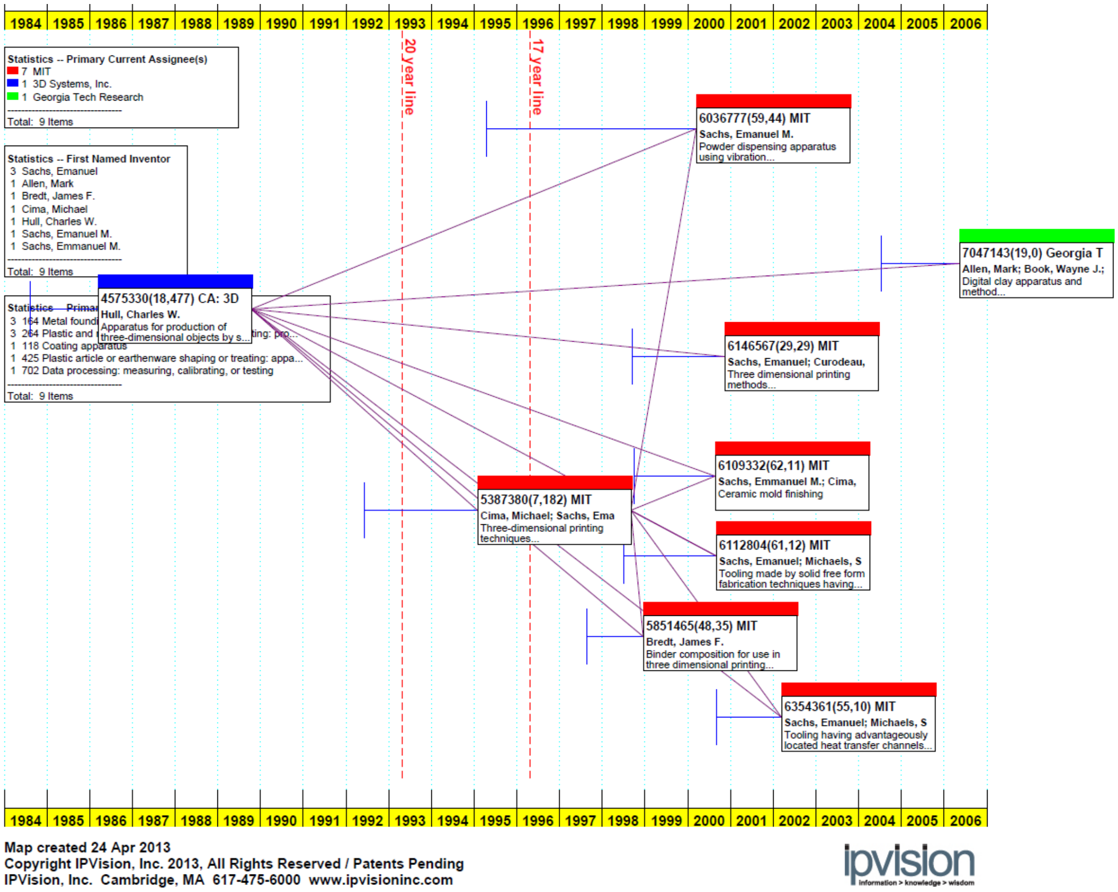
[58] See http://www.additive3d.com/museum/mus_1.htm.

[59] See Case Study 4 for further information on the NSF awards related to binder jetting.



Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com). The location of the box indicates the patent issue year, and the left whisker indicates the patent application year. USPTO data show incorrect spellings and varied abbreviations for W.K. Swainson, last name also shown as Swanson and middle name is shown as K. and Kelly.

Figure H-1. Relationships between U.S. Patent 4575330 and Its References Based on Citations in Each Patent



Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com).The location of the box indicates the patent issue year, and the left whisker indicates the patent application year. USPTO data show incorrect spellings and varied abbreviations for Emanuel Sachs, first name also shown as Emmanuel and middle name is either abbreviated or not included.

Figure H-2. Map Showing the Relationships between U.S. Patent 4575330 and the Eight Citing Patents with NSF Government Sponsorship Based on Citations in each Patent

Patent 4863538: Method and apparatus for producing parts by selective sintering

Background

Carl Deckard's invention of selective laser sintering (SLS,)[60] documented in U.S. Patent No. 4863538 (Method and apparatus for producing parts by selective sintering), was filed in 1986, the same year Hull's seminal patent was issued.

Deckard's invention came about from collaborations with students and professors at the University of Texas (UT) at Austin. Deckard was a graduate student supervised by Joseph Beaman, a professor in the Department of Mechanical Engineering, from 1984 to 1986 for his master's degree and from 1986 to 1988 for his doctorate. The idea for SLS first came to Deckard while he was an undergraduate working at a manufacturing facility that used computer-aided design to make casting patterns. He presented a concept—using an automated machine to make a part from a directed energy beam that melts powder—to Beaman, who accepted the project as Deckard's graduate thesis. After completing his master's degree, Deckard, along with Beaman, Paul McClure, the assistant dean of engineering, and Harold Blair, a local business owner, established Nova Automation (later DTM Corporation) to commercialize the technology (Lou and Grosvenor 2012).

The UT team and DTM received support to commercialize SLS from various avenues. Deckard continued research and development of academic machines with fellow graduate student Paul Forderhase. UT supported the research team during intellectual property disputes, and DTM received support through the Austin Technology Incubator. The Federal Government also contributed to the development of SLS. NSF awarded Beaman seed funding through the Engineering Directorate's Civil, Mechanical and Manufacturing Innovation (CMMI) Division to further develop SLS.[61] While seeking investors, McClure helped secure a NSF Small Business Innovation Research (SBIR) award to commercialize SLS.[62] Beaman later facilitated a deal with DTM's primary investor, BFGoodrich, and was

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[60] Selective laser sintering is referred to as powder bed fusion in ASTM standards.

[61] NSF Award #8707871: "Part Generation by Layerwise Selective Sintering," through ENG/CMMI Materials Processing and Manufacturing program and program manager Bruce Kramer, awarded $30,000 from March 1987 to August 1988 to principal investigator Joseph Beaman and co-principal investigator Alfred Traver from UT. http://www.nsf.gov/awardsearch/showAward?AWD_ID=8707871.

[62] NSF Awards #8761237 and #8896180: "Selective Laser Sintering," through NSF's SBIR program and program manager Ritchie Coryell, awarded a total of $46,670 from January 1988 to January 1989 to principal investigator Carl Deckard. http://www.nsf.gov/awardsearch/showAward?AWD_ID=8761237, http://www.nsf.gov/awardsearch/showAward?AWD_ID=8896180.

awarded one of the first CMMI STRATMAN awards.[63] In 1990, another critical factor bolstered DTM's competitiveness in the market—DTM negotiated the rights to U.S. Patent No. 4247508, a historically influential and highly cited patent in the additive manufacturing field.[64]

By 1993, Deckard had left DTM for a position in academia at Clemson University. In 2001, DTM was acquired by 3D Systems, one of the largest AM companies today.

Government Interest Clause

Deckard's original SLS patent is related to 14 other patents—2 are continuation in parts of the original, while the rest are continuations, continuation in parts, or divisionals of these patents or applications that have now been abandoned (Table H-1).

According to the government interest clause of the patents, none received government support that directly led to the patent. However, many of the patents in the family were filed around the same time frame as Beaman and his colleagues received the STRATMAN award. Similarly, NSF funding from 1987 to 1989 could have been used to support Deckard's original SLS patent and his research more generally. Attribution is unclear, but discussions with Beaman and AM experts confirm NSF's early recognition of their research and its potential to revolutionize manufacturing practices. It is likely that NSF had an early role in the research and development of SLS, but final reports were not available to identify contributors, in particular graduate students, involved in these early NSF awards.

Although several of the patents in the family are filed solely by Deckard, 8 of the 14 patents have co-inventors from UT. Beaman and Deckard recruited colleagues from throughout UT's engineering departments to assist with developing and testing materials for use with the machines they built (Table H-2). Professors David Bourell and Joel Barlow were consultants for DTM and, along with Harris Marcus, were co-principal investigators on the STRATMAN award to develop and expand SLS using both solid powder and gas-based ceramics rather than a polymer-based material. Other co-inventors supported the group's computing needs and furthered work in the use of ceramic powders.

DTM sponsored 14 patents from 1990 to 1998 (the time period prior to their acquisition by 3D Systems). None of these received government support. The NSF SBIR was awarded when the company was first established to conduct research on process control methods and material selection, scale-up issues, and computer integration. The SBIR could

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[63] NSF Award #8914212: "Solid Freeform Fabrication: Ceramics," through ENG/CMMI's STRATMAN Initiative and program manager Bruce Kramer, awarded $871,335 from October 1989 to March 1993 to principal investigator Joseph Beaman and co-principal investigators Harris Marcus, David Bourell, and Joel Barlow. http://www.nsf.gov/awardsearch/showAward?AWD_ID=8914212.

[64] Ross Householder, Molding process, U.S. Patent No. 4247508, filed December 3, 1979, and issued January 27, 1981; assignee: Hico Western Products.

have had some initial impact on the development of DTM’s patent portfolio. BFGoodrich was DTM’s primary investor and funded various technologies to expand DTM’s intellectual property portfolio, leading to important patents on multi-directional powder delivery, sinterable semi-crystalline powder, and thermal control, among others (Lou and Grosvenor 2012).

Table H-1. U.S. Patents in Patent Family of U.S. Patent No. 4863538

Patent	Title	Inventors	File Date	Issue Date	Relationship to U.S. Patent No. 4863538
4938816	Selective laser sintering with assisted powder handling	Beaman, Joseph J.; Deckard, Carl R.	Sep 5, 1989	Jul 3, 1990	Continuation in part of U.S. Patent No. 4863538 (Same Family ID)
4944817	Multiple material systems for selective beam sintering	Bourell, David L.; Marcus, Harris L.; Barlow, Joel W.; Beaman, Joseph J.; Deckard, Carl R.	Sep 5, 1989	Jul 31, 1990	Continuation in part of U.S. Patent No. 4863538
5017753	Method and apparatus for producing parts by selective sintering	Deckard, Carl R.	Jun 22, 1990	May 21, 1991	Continuation of application (now abandoned), a continuation-in-part of U.S. Patent No. 4863538
5053090	Selective laser sintering with assisted powder handling	Beaman, Joseph J.; Deckard, Carl R.	Jul 2, 1990	Oct 1, 1991	Continuation of U.S. Patent No. 4938816, a continuation-in-part of U.S. Patent No. 4863538
5076869	Multiple material systems for selective beam sintering	Bourell, David L.; Marcus, Harris L.; Barlow, Joel W.; Beaman, Joseph J.; Deckard, Carl R.	Jul 30, 1990	Dec 31, 1991	Continuation of U.S. Patent No. 4944817, a continuation-in-part of U.S. Patent No. 4863538
5132143	Method for producing parts	Deckard, Carl R.	Jun 21, 1990	Jul 21, 1992	Divisional of application (now abandoned), which is a continuation-in-part of U.S. Patent No. 4863538
5147587	Method of producing parts and molds using composite ceramic powders	Marcus, Harris L.; Lakshminarayan, Udaykumar	Feb 19, 1991	Sep 15, 1992	Continuation-in-part of U.S. Patent No. 5076869, a continuation of U.S. Patent No. 4944817, which is a continuation-in-part of U.S. Patent No. 4863538
5155324	Method for selective laser sintering with layerwise cross-scanning	Deckard, Carl R.; Beaman, Joseph J.; Darrah, James F.	Nov 9, 1990	Oct 13, 1992	Continuation-in-part of application, which is a continuation of another application, which is a continuation-in-part of U.S. Patent No. 4863538
5296062	Multiple material systems for selective beam sintering	Bourell, David L.; Marcus, Harris L.; Barlow, Joel W.; Beaman, Joseph L.; Deckard, Carl R.	Sep 25, 1992	Mar 22, 1994	Continuation of copending application (now abandoned), which is a continuation of U.S. Patent No. 5076869, which is a continuation of U.S. Patent No. 4944817, which is a continuation-in-part of U.S. Patent No. 4863538
5316580	Method and apparatus for producing parts by selective sintering	Deckard, Carl R.	Jul 10, 1992	May 31, 1994	Divisional of U.S. Patent No. 5132143, which is a divisional of application (now abandoned), which is a continuation-in-part of U.S. Patent No. 4863538

Patent	Title	Inventors	File Date	Issue Date	Relationship to U.S. Patent No. 4863538
5382308	Multiple material systems for selective beam sintering	Bourell, David L.; Marcus, Harris L.; Barlow, Joel W.; Beaman, Joseph J.; Deckard, Carl R.	Mar 21, 1994	Jan 17, 1995	Continuation of U.S. Patent No. 5296062, which is a continuation of application (now abandoned), which is a continuation of U.S. Patent No. 5076869, which is a continuation of U.S. Patent No. 4944817, which is a continuation-in-part of U.S. Patent No. 4863538
5597589	Apparatus for producing parts by selective sintering	Deckard, Carl R.	May 31, 1994	Jan 28, 1997	Continuation of U.S. Patent No. 5376580, which is a divisional of U.S. Patent No. 5132143, which is a divisional of application (now abandoned), which is continuation-in-part of U.S. Patent No. 4863538
5616294	Method for producing parts by infiltration of porous intermediate parts	Deckard, Carl R.	Jun 7, 1995	Apr 1, 1997	Continuation of application, which is a continuation of U.S. Patent No. 5316580, which is a divisional of U.S. Patent No. 5132143,which is a divisional of application (now abandoned), which is a continuation-in-part of U.S. Patent No. 4863538
5639070	Method for producing parts by selective sintering	Deckard, Carl R.	Jun 7, 1995	Jun 17, 1997	Divisional of U.S. Patent No. 5597589, which is a continuation of U.S. Patent No. 5316580, which is a divisional of U.S. Patent No. 5132143, a divisional of application (now abandoned), which is a continuation-in-part of U.S. Patent No. 4863538

Table H-2. Inventors in Patent Family of U.S. Patent No. 4863538

Inventor	About Inventor	Role in SLS Research	Role in Patent Family
Joseph Beaman	University of Texas (UT), Austin, Department of Mechanical Engineering professor Supervised Deckard during master's (1986) and Ph.D. (1988)	Leave of absence (1990–1992) from UT to guide Advanced Development for Nova Automation/DTM (first SLS company)	Co-inventor on 7 of 14 patents in patent family Patents filed from 1989 to 1994
Harris Marcus	UT Department of Mechanical Engineering professor	Developed selective area laser deposition (SALD), a gas-driven technology that was never commercialized	Co-inventor on 5 of 14 patents in patent family Patents filed from 1989 to 1994
David Bourell	UT Department of Mechanical Engineering professor	Starting in 1988, began research in metals and general materials for SLS; Consulted with DTM	Co-inventor on 4 of 14 patents in patent family Patents filed from 1989 to 1994
Joel Barlow	UT Department of Chemical Engineering professor	Late 1980s, began research in polymers synthesis for SLS prototypes developed at UT Consulted with DTM	Co-inventor on 4 of 14 patents in patent family Patents filed from 1989 to 1994
James Darrah	Software engineer	Wrote software for one of the first commercial DTM machines	Co-inventor on 1 of 14 patents in patent family Patent filed in 1990
Udaykumar Lakshminarayan	Supervised by Harris Marcus, Ph.D. (1992) in Mechanical Engineering	Researched ceramic powder materials Worked for DTM after graduating from UT	Co-inventor on 1 of 14 patents in patent family Patent filed in 1991

Backward Citation Analysis

A citation analysis of Deckard's SLS patent and its patent family shows the influence research support from the Department of Defense, including the Department of the Navy and the Department of the Air Force, the Department of Commerce, and, possibly, NSF.

The DOD supported the work of Jan VanWyk at Boeing. His patent filed in 1974 for a process to create bearing lubrication for wear-resistant surfaces, such as ceramics.[65] This was referenced by citations in Deckard's original SLS patent and one family patent.

The work of Clyde Brown, Edward Breinan, and Bernard Kear in directed energy deposition (documented in U.S. Patent No. 4323756) was highly referenced by Deckard's original SLS patent as well as 13 of the 14 family patents (Figure H-3). This patent was funded by the U.S. Navy through United Technologies Corporation almost a decade before Deckard's original SLS patent.[66] Another area funded by the Navy deals with laser spraying a surface to fabricate protective molten coatings and obtain an alloyed surface. This was patented by Robert Schaefer and Jack Ayers in 1978.[67] Yet a third area of support is a patent filed in 1985 by Douglas Miller on coating a surface with electrostatically charged powder and irradiating it until the surface melts and solidifies.[68] This research was referenced by two continuations-in-part patents to Deckard's original patent and was issued after the original patent.

The U.S. Air Force also played a role in supporting MIT researchers who patented technology on depositing material using a direct energy laser beam, primarily for fabrication of semiconductor devices.[69] This technology was invented before Deckard's original patent.

Analyzing the non-patent references of Deckard's SLS patent and the patent family, two of the more recent patents filed in 1994 and 1995 cite articles from the Department of Commerce's National Bureau of Standards/Center for Fire Research.[70] These articles

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[65] A second-generation reference of U.S. Patent Nos. 4863538 and 4944817 in the same patent family as Deckard's SLS patent is U.S. Patent No. 3938868: Jan VanWyk, Bearing lubrication system, filed September 23, 1974, and issued February 17, 1976; assignee: The Boeing Company.

[66] Clyde O. Brown, Edward M. Breinan, and Bernard H. Kear, Method for fabricating articles by sequential layer deposition, U.S. Patent No. 4323756, filed 1979, and issued 1982; assignee: United Technologies Corporation (UTC). The work was sponsored by U.S. Navy Contract No. N00014-77-C-0418.

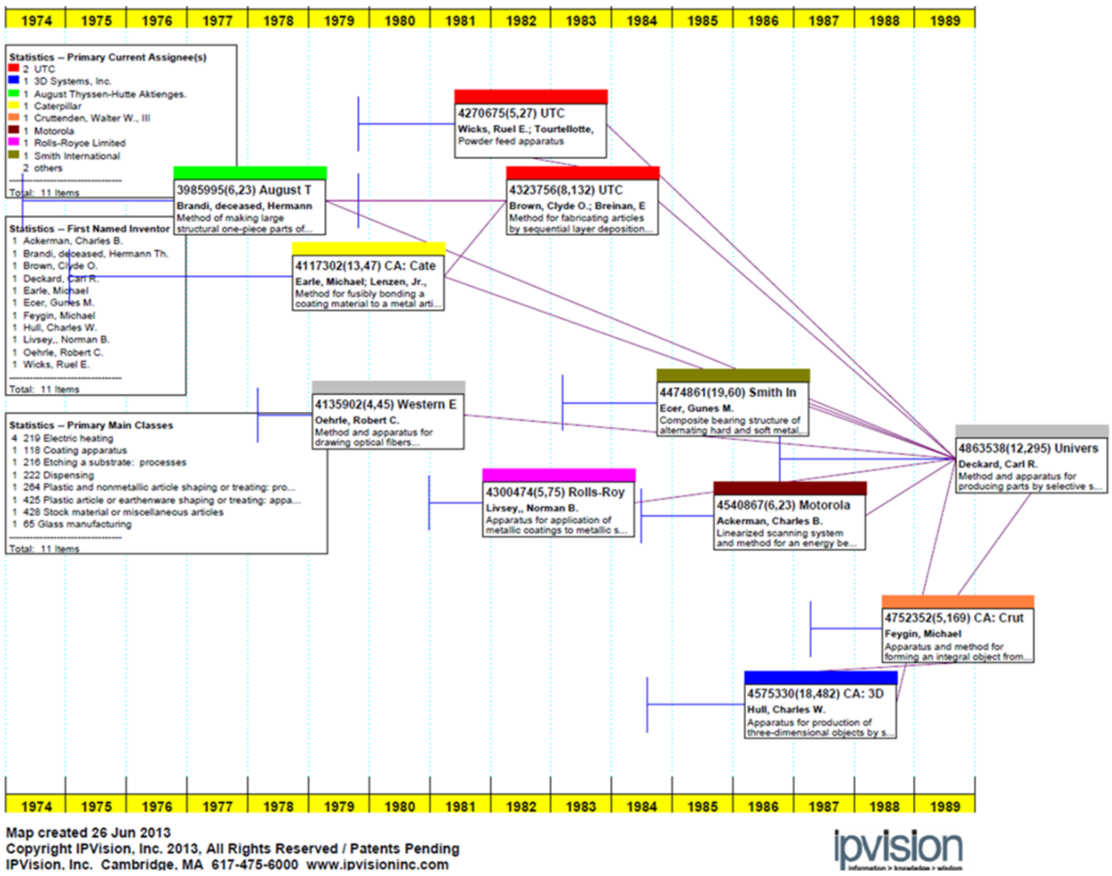
[67] A second-generation reference of U.S. Patent No. 4944817 in the same patent family as Deckard's SLS patent is U.S. Patent No. 4200669: Robert Schaefer and Jack Ayers, Laser spraying, filed November 22, 1978, and issued April 29, 1980; assignee: The United States of America as represented by the Secretary of the Navy (Washington, D.C.).

[68] A second-generation reference of U.S. Patent Nos. 4938816 and 4944817 in the same patent family as Deckard's SLS patent is U.S. Patent No. 4615903: Douglas L. Miller, Method for melt-coating a surface, filed July 1, 1985, and issued October 7, 1986; assignee: The United States of America as represented by the Secretary of the Navy (Washington, DC).

[69] A second-generation reference of U.S. Patent No. 4944817 in the same patent family as Deckard's SLS patent is U.S. Patent No. 4340617: Thomas Deutsch, Daniel Ehrlich, and Richard Osgood, Method and apparatus for depositing a material on a surface, filed May 19, 1980, and issued July 20, 1982; assignee: MIT.

[70] U.S. Patent No. 5597589 in the same patent family as Deckard's SLS patent references Babrauskas, "Development of the Cone Calorimeter—A Bench-Scale Heat Release Rate Apparatus Based on Oxygen Consumption," NBSIR 82-2611 (U.S. Dept. of Commerce, November 1982), and U.S. Patent No. 5639070 in the same patent family as Deckard's SLS patent references Babrauskas, et al., "Ignitability Measurements with the Cone Calorimeter," NBSIR 86-3445 (U.S. Department of Commerce, September 1986).

explain the development of a bench-scale calorimeter to measure rates of heat release developed for use in fire testing and research. Three of the 14 family patents also reference Deckard's Ph.D. thesis or conference proceedings on SLS after he obtained his master's in 1986. Deckard could have been partly supported by NSF funds throughout this period, particularly while pursuing his Ph.D. (1988), which coincides with the SBIR awarded earlier that year. In fact, the SBIR project has the same project name as his thesis title. And Deckard's master's thesis (1986) has the same project title as the NSF award to Beaman in 1987, suggesting the award was used to continue Deckard's research.



Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com). The location of the box indicates the patent issue year, and the left whisker indicates the patent application year. U.S. Patent No. 4863538 references 12 patents, 2 are issued before 1975 and are not included in the map since USPTO does not have publicly available data on patents issued prior to 1975.

Figure H-3. Relationships between U.S. Patent 4863538 and 10 References Based on Citations in Each Patent

Forward Citation Analysis

U.S. Patent No. 4863538 has been cited by 297 patents, 15 (5%) of which were government supported (Table H-3), and 4 (about 1%) of which were funded by NSF (Figure H-4). Deckard's original SLS patent, which was highly influential in the field, is cited by various new areas of research, including Optomec's Laser Engineered Net Shaping (LENS) technology[71] and the binder jetting process (or 3D printing) developed by MIT researchers, which both came about in the early to mid-1990s (see Case Study 4).

Government-supported patents were supported by the U.S. Navy—including ONR, the U.S. Air Force, and DARPA—NASA, NIST, and NSF. ONR and the Air Force supported several UT researchers in the 1990s, including Marcus (U.S. Patent No. 5611883), Barlow (U.S. Patent No. 6048954), and Beaman and Das[72] (U.S. Patent No. 6355086). The NSF awards explored the manufacture ceramic parts[73] and improving the understanding of the physical behavior of the powder and liquid phases during the 3D printing process.[74] One NSF award supported James Bredt's early research in binder jetting at MIT (U.S. Patent No. 5851465). Bredt is co-founder of Z Corporation, a market leader in 3D printing desktop manufacturing machines. These awards also supported other MIT researchers critical to binder jetting process improvements, including Emanuel Sachs and Michael Cima (Case Study 4).

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[71] LENS technology functions with four nozzles that direct a stream of metal powder to form a three-dimensional product (documented in U.S. Patent No. 6046426). See Sandia National Laboratories (2012).

[72] Suman Das received his Ph.D. in mechanical engineering from the University of Texas in 1998 and was supervised by Joseph Beaman. In his research he designed and built two AM machines and co-invented a process using metals. His research was supported by DARPA, ONR, and the U.S. Air Force. In cooperation with Rolls Royce (U.S. Patent No. 6355086), Das helped develop a prototype machine to make nickel superalloy cermet (heat-resistant materials made from ceramic and sintered metal) abrasive tips for engine turbine blades. These activities were precursors to the development of direct metal laser sintering (DMLS) technology.

[73] NSF Award #8913977: "Three Dimensional Printing; Rapid Tooling and Prototypes Directly from a Computer Aided Design Model," through ENG/CMMI's STRATMAN Initiative and program manager Kevin Sewell, awarded $784,700 from October 1989 to March 1993 to principal investigator Emanuel Sachs and co-principal investigators Michael Cima and James Cornie, http://nsf.gov/awardsearch/showAward?AWD_ID=8913977.

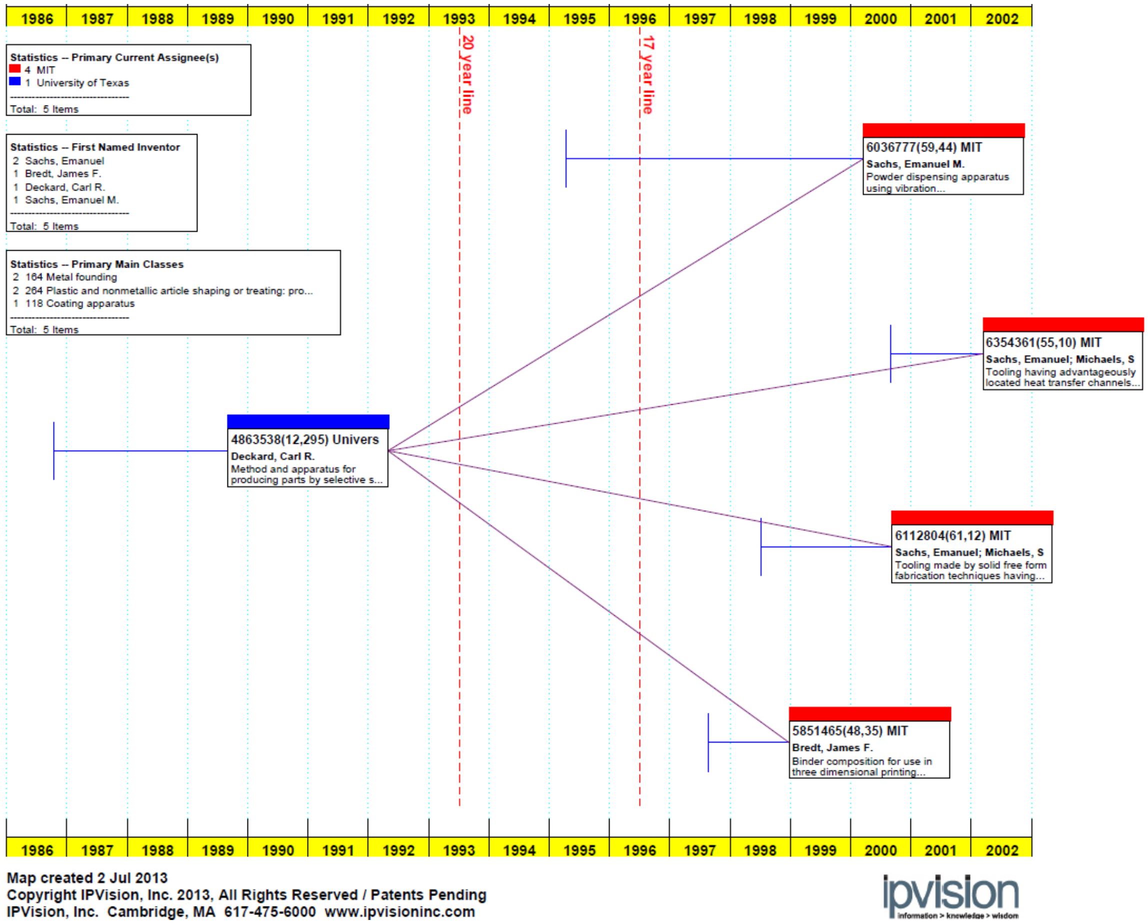
[74] NSF Award #9215728: "Micro-constructive Manufacturing" through ENG/CMMI's STRATMAN Initiative and program manager Bruce Kramer, awarded $615,000 from October 1992 to March 1996 to principal investigator Emanuel Sachs and co-principal investigators David Gossard, Michael Cima, and James Cornie. http://www.nsf.gov/awardsearch/showAward?AWD_ID=9215728.

Table H-3. Fifteen U.S. Patents Citing U.S. Patent 4863538 and Supported by the Federal Government*

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Current Assignee(s)	Government Interest	Citing Patents
5611883	Tompkins, James V.; Birmingham, Britton R.; Jakubenas, Kevin J.; Marcus, Harris L.	Joining ceramics and attaching fasteners to ceramics by gas phase selective beam deposition	Jan 9, 1995	Mar 18, 1997	The University of Texas System Board of Regents	U.S. Navy, ONR (Contract #N00014-92-J-1514)	23
5837960	Lewis, Gary K.; Milewski, John O.; Cremers, David A.; Nemec, Ronald B.; Barbe, Michael R.	Laser production of articles from powders	Nov 30, 1995	Nov 17, 1998	Los Alamos National Security, LLC	DOE (Contract #W-7405-ENG-36)	108
5851465	Bredt, James F.	Binder composition for use in three dimensional printing	Aug 21, 1997	Dec 22, 1998	Massachusetts Institute of Technology	NSF (Award #9215728)	35
6036777	Sachs, Emanuel M.	Powder dispensing apparatus using vibration	Apr 14, 1995	Mar 14, 2000	Massachusetts Institute of Technology	NSF (Award #8913977)	44
6046426	Jeantette, Francisco P.; Keicher, David M.; Romero, Joseph A.; Schanwald, Lee P.	Method and system for producing complex-shape objects	Jul 8, 1996	Apr 4, 2000	Sandia Corporation	DOE (Contract #DE-AC04-94AL85000)	65
6048954	Barlow, Joel W.; Vail, Neal K.	Binder compositions for laser sintering processes	Jun 24, 1997	Apr 11, 2000	The University of Texas System Board of Regents	Defense Advanced Research Projects Agency (DARPA)/U.S. Navy, ONR (Award #N0001492J1394)	5
6112804	Sachs, Emanuel; Michaels, Steven P; Allen, Samuel M.	Tooling made by solid free form fabrication techniques having enhanced thermal properties	Jul 2, 1998	Sep 5, 2000	Massachusetts Institute of Technology	NSF (Awards #8913977 and #9215728)	12
6214279	Yang, Junsheng; Wu, Liangwei; Liu, Junhai; Jang, Bor Z.	Apparatus and process for freeform fabrication of composite reinforcement preforms	Oct 2, 1999	Apr 10, 2001	Nanotek Instruments Inc.	NASA (Johnson Space Center)	56

Patent Number	Inventor(s)	Title	Application Date	Issue Date	Current Assignee(s)	Government Interest	Citing Patents
6354361	Sachs, Emanuel; Michaels, Steven P; Allen, Samuel M.	Tooling having advantageously located heat transfer channels	Sep 1, 2000	Mar 12, 2002	Massachusetts Institute of Technology	NSF (Awards #8913977 and #9215728)	10
6355086	Brown, Lawrence Evans; Fuesting, Timothy Paul; Beaman, Jr., Joseph Jefferson; Das, Suman	Method and apparatus for making components by direct laser processing	Aug 12, 1997	Mar 12, 2002	Rolls-Royce Corporation; The University of Texas Board of Regents	U.S. Air Force (Contract #F33616-C-2424)	16
6429402	Dixon, Raymond D.; Lewis, Gary K.; Milewski, John O.	Controlled laser production of elongated articles from particulates	Jun 2, 2000	Aug 6, 2002	Los Alamos National Security, LLC	DOE (Contract #W-7405-ENG-36)	12
6585930	Liu, Jianxin; Rynerson, Michael	Method for article fabrication using carbohydrate binder	Apr 25, 2001	Jul 1, 2003	The EX ONE Company	NIST (Advanced Technology Program Award #70NANB7H3030)	4
7582004	Schwartz, Brian J.; Davie, Jr., Robert N.; Vaillette, Bernard D.; Hammett, Jon C.; Packman, Allan B.; Brown, Timothy L.; Campbell, Jr., James D.	Coolant nozzle	Jul 11, 2003	Sep 1, 2009	United Technologies Corporation	U.S. Navy (Contract #N0001902C3003)	1
8157948	Maxwell, James L.; Chavez, Craig A.; Black, Marcie R.	Method of fabricating metal- and ceramic- matrix composites and functionalized textiles	Apr 8, 2008	Apr 17, 2012	Los Alamos National Security, LLC	DOE (Contract #DE-AC52-06NA25396)	0
8375581	Romanelli, James; Lin, Wangen; Delisle, Robert P.; Chin, Herbert A.; Moor, James J.; Boyer, Jesse R.	Support structure for linear friction welding	Feb 14, 2011	Feb 19, 2013	United Technologies Corporation	U.S. Air Force (Contract #F33657-03-D-0016-0010)	0

* Government support is identified by the government interest clause of the patent.



Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com). The location of the box indicates the patent issue year, and the left whisker indicates the patent application year. USPTO data show incorrect spellings and varied abbreviations for Emanuel Sachs, middle name is either abbreviated or not included.

Figure H-4. Relationships between U.S. Patent 4863538 and Citing Patents with NSF Government Sponsorship Based on Citations in each Patent

Patent 5121329: Apparatus and method for creating 3-dimensional objects

Background

S. Scott Crump's invention of material extrusion,[75] documented in U.S. Patent No. 5121329 (Apparatus and method for creating 3-dimensional object), built on several areas of knowledge in AM present at that time: work by Hull in stereolithography, Deckard and University of Texas (UT) researchers in selective laser sintering, Michael Feygin in laminated object manufacturing, and Clyde Brown in directed energy deposition, among others (Figure H-5).

Crump invented the material extrusion process in 1988 when he experimented with making a toy frog for his daughter using a glue gun to shape the object layer by layer.[76] He invested in equipment to automate the process and subsequently with his wife founded Stratasys in that same year. Crump has served as both chief executive officer and President of Stratasys. Since the company's merger in 2012 with Object,[77] an Israel-based technology company, Crump has served as the chairman and chief innovation officer.

Government interest clause

U.S. Patent No. 5121329 was awarded in 1992. In the same year, Crump filed for another patent, U.S. Patent No. 5340433 (modeling apparatus for three-dimensional objects), which is in the same patent family as U.S. Patent No. 5121329. In addition to his original patent, Crump is shown as an inventor on nine other patents, of which seven cite U.S. Patent No. 5121329 and are related to the original invention.[78] Many of these patents are improvements of materials and methods used in the extrusion process. An analysis of the government interest clause in U.S. Patent No. 5121329 and Crump's nine other patents reveal that they were sponsored solely by Stratasys with no other direct support from the Federal Government.

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[75] Material extrusion is also referred to as fused deposition modeling.

[76] FundingUniverse, "Stratsys, Inc. History," http://www.fundinguniverse.com/company-histories/stratasys-inc-history.

[77] See http://objet.co.il/.

[78] We searched all USPTO-issued patents for the inventor name "S. Scott Crump" through the USPTO Advanced Search feature: http://patft.uspto.gov/netahtml/PTO/search-adv.htm.

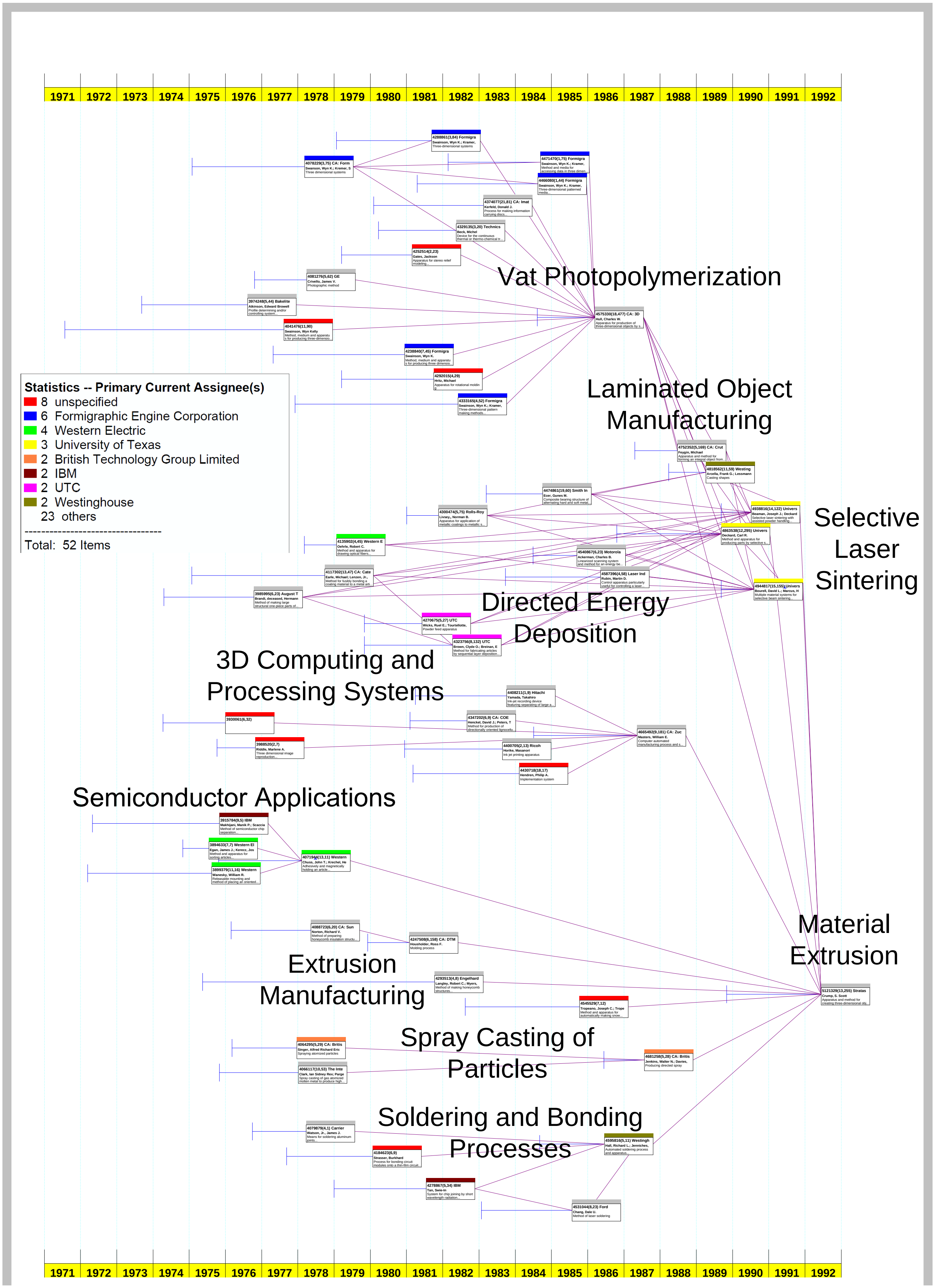

Figure H-5: Map Showing the Relationships between U.S. Patent 5121329 and 1st and 2nd Generation References of Patents Based on Citations

Figure created using patent analytics software from IPVision (http://www.see-the-forest.com)

Note: The location of the box indicates the patent issue year while the left whisker indicates the patent application year.

Other staff at Stratasys have also been active in patenting, with 106 U.S. patents issued since 1989. Of the 106 patents, 89 reference U.S. Patent No. 5121329. One (U.S. Patent No. 5900207—Solid freeform fabrication methods)[79] was co-invented with researchers from the Rutgers State University of New Jersey through sponsorship from a DARPA/ONR award.[80] Some of the co-inventors worked at Rutgers' Center for Ceramic Research on ceramic powder materials.[81] One of these co-inventors was Mukesh Agarwala, a former graduate student at UT who worked with Joseph Beaman, David Bourell, Harris Marcus, and Joel Barlow among others involved in the origins of selective laser sintering (Case Study 2).[82] Because of this relationship and similar connections to work at UT shown through the patent citation analysis, it is likely that Agarwala was highly influenced by the technology developments in selective laser sintering starting from the late 1980s and early 1990s. Due to the influence of NSF on the selective laser sintering field (Case Study 2), NSF may also have indirectly influenced patents produced by staff at Stratasys. From an analysis of the patent's government interest clause, no other government entity directly supported any of Stratasys' other patents. This was confirmed by an interview with two senior researchers at Stratasys.

Backward Citation Analysis

The patent citation analysis shows that Crump's original patent was influenced by Deckard's U.S. Patent No. 4863538 (Figure H-6). We found through Case Study 2 that NSF was involved in supporting Deckard as well as other UT researchers. In this way, it is possible that NSF had an indirect role supporting knowledge used by Crump for developing the material extrusion process.

In addition to the patents cited by Crump's patent, an analysis of non-patent publications referenced by Crump's patent (first generation) and their cited references (second generation)

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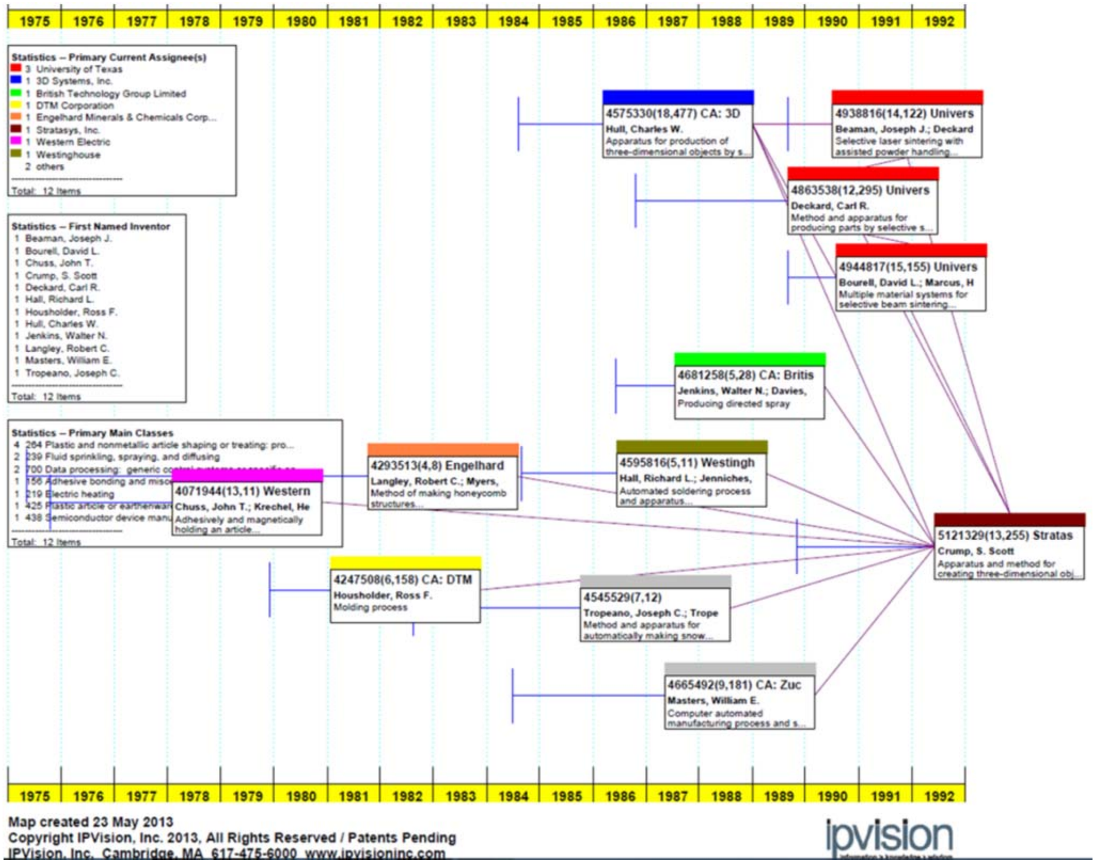
[79] U.S. Patent No. 5900207 was filed in 1997 and issued in 1999. Inventors on the patent are Mukesh Agarwala, Amit Bandyopadghyay, Stephen C. Danforth, Vikram R. Jamalabad, Noshir Langrana, R. Priedeman William Jr., Ahmad Safari, and Remco van Weeren.

[80] DARPA/ONR Contract No. N00014-94-C-0115 is listed in the government interest clause of the patent.

[81] Mukesh Agarwala and Stephen Danforth worked on ceramic powder materials and part prediction tools for fused deposition processing (Yardimci, Guceri, Agarwala, and Danforth 2012).

[82] Mukesh Agarwala studied synthesis selective laser sintering and post processing of metal and ceramic composites and received his Ph.D. in mechanical engineering in 1994 (Lou and Grosvenor 2012).

reveals one publication that was supported in part by DARPA[83] and a master’s thesis authored by Deckard that may have received support from NSF (see Case Study 2).[84]



Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com). The location of the box indicates the patent issue year, and the left whisker indicates the patent application year. U.S. Patent No. 5121329 has 13 patent cited references, 11 are shown since 2 were issued previous to 1975 and data is not available for these patents.

Figure H-6. Relationships between U.S. Patent No. 5121329 and Its References Based on Citations in Each Patent

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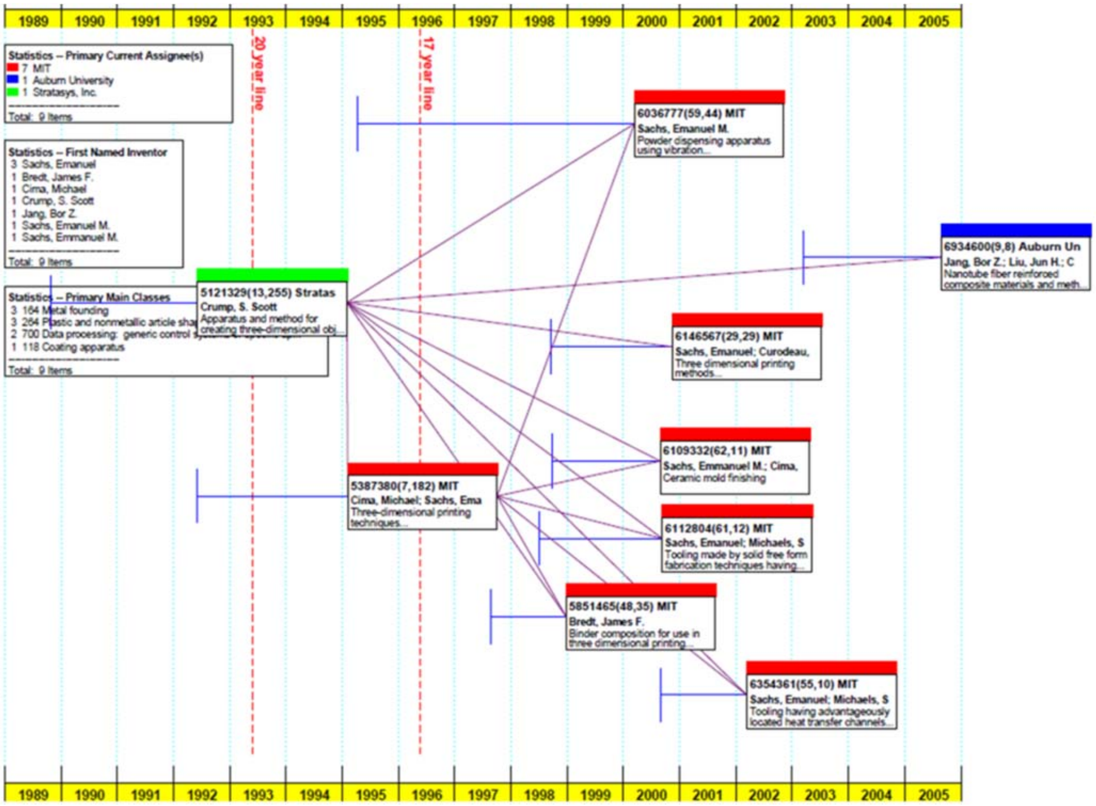
[83] The publication is Clark, “Designing Surfaces in 3-D,” *Communications of the ACM*. 19, No. 8 (August 1976):454–60, supported by DARPA Contract No. F30602-70-C-0300. At the time, the author’s affiliation was at the Department of Information Sciences at the University of California, Santa Cruz. This publication is cited by William Masters’ U.S. Patent No. 4665492, which is a referenced by Crump.

[84] The thesis is by Carl Deckard, “Part Generation by Layerwise Selective Sintering,” May 1986. This thesis may be related to NSF Award DMC-870781 project titled with the same name and awarded to principal investigator Joseph Beaman at the University of Texas in 1987, who was Deckard’s thesis supervisor.

Forward Citation Analysis

U.S. Patent No. 5121329 is referenced by 259 patents, which indicates that this was a highly influential patent to the AM field. Of these, 22 patents (about 8%) were filed from 1992 to 2003 and received government support, and 8 (about 3%) were sponsored by NSF (Figure H-7). The forward citation analysis of the eight NSF-sponsored patents shows that seven patents were issued to MIT researchers related to 3D printing (see Case Study 4) and one to researchers at Auburn University related to the layerwise production of nanotube fiber reinforced composite materials. This shows that NSF was influential in supporting new technologies that spurred from Crump's material extrusion patent.



Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com). The location of the box indicates the patent issue year, and the left whisker indicates the patent application year. USPTO data show incorrect spellings and varied abbreviations for Emanuel Sachs, first name also shown as Emmanuel and middle name is either abbreviated or not included.

Figure H-7. Relationships between U.S. Patent 5121329 and the Citing Patents with NSF Government Sponsorship Based on Citations in each Patent

Patent 5204055: Three-dimensional printing techniques

Background

Several researchers from MIT—Emmanuel Sachs, John Haggerty, Michael Cima, and Paul Williams—invented the binder jetting process,[85] as documented in U.S. Patent No. 5204055 (Three-dimensional printing techniques). The binder jetting process was influenced by the previous three foundational patents and AM processes. Figure H-8 shows the flow of knowledge from stereolithography, selective laser sintering, and material extrusion based on patents cited by Sachs et al.'s patent and their cited references. Other technology applications that influenced Sachs et al.'s patent are 3D computing and processing, material binding processes, and directed energy deposition.

The binder jetting process was a research effort that involved professors and graduate students. Cima arrived at MIT in 1986 as an assistant professor in the Department of Materials Science and Engineering. At that time, Sachs, a professor in the Department of Mechanical Engineering, specialized in the design of manufacturing processes and partnered with Cima shortly after his arrival to develop the materials used in binder jetting. Graduate students supported this research, including Paul Williams, who received his master's in mechanical engineering in 1990 and was supervised by Sachs (Williams 1990). According to the acknowledgements in Williams' thesis, his research was sponsored in part by NSF and the MIT Leaders for Manufacturing Program.[86]

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[85] Binder jetting is also referred to as 3D printing.

[86] The MIT Leaders for Manufacturing Program is coordinated by the School of Engineering and the Sloan School of Management to support educational and research partnerships with the private sector for students interested in manufacturing and operations (See MIT School of Engineering website, "Leaders for Manufacturing Program," http://engineering.mit.edu/education/graduate/lmp.php).

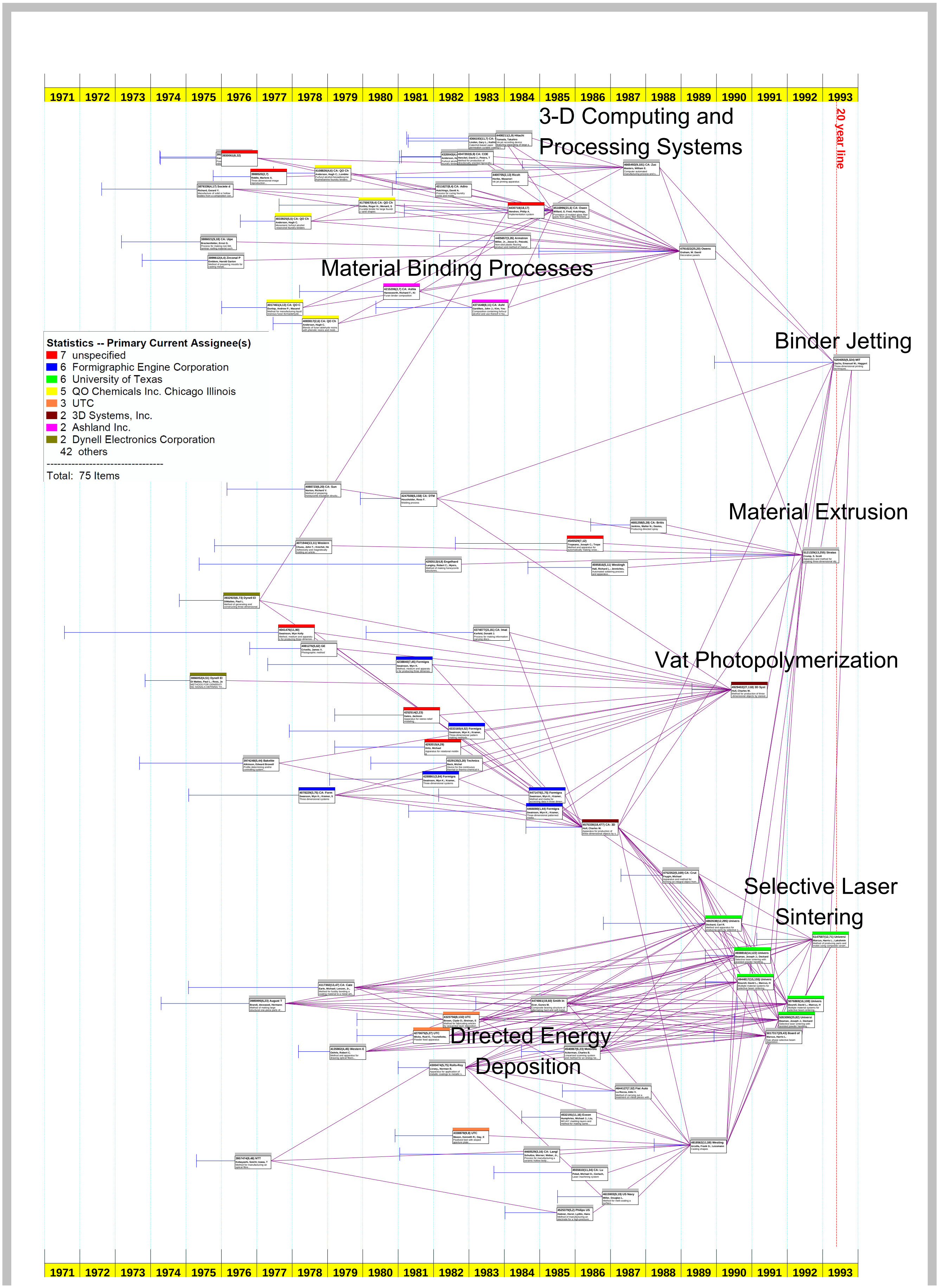

Figure H-8. Map Showing the Relationships between U.S. Patent 5204055 and 1st and 2nd Generation References of Patents Based on Citations

Figure created using patent analytics software from IPVision (http://www.see-the-forest.com)

Note: The location of the box indicates the patent issue year while the left whisker indicates the patent application year.

Four other patents are in the same patent family[87] as the Sachs et al. patent (U.S. Patent Nos. 5340656, 5387380, 5807437, and 6036777; see Table H-4). These were filed from 1992 to 1995 and issued from 1994 to 2000, after the original patent, and include other MIT graduate students as co-inventors. NSF's role in funding the binder jetting process through graduate student support is further validated from the thesis acknowledgements of two co-inventors on these patents (Table H-5). NSF also supported research collaborations to produce two publications co-authored by Sachs and his co-inventors Alain Curodeau[88] and David Brancazio.[89] NSF Award #9420365 was awarded to Sachs from 1995 to 1999, which coincides with the time period he and his co-inventors filed U.S. Patent No. 5807437. This overlap suggests there may have been some influence from NSF funding on graduate students and research that led to U.S. Patent No. 5807437.

The Sachs et al. patent was licensed to James Bredt and Tim Anderson, a graduate student and technician, respectively, who worked with Sachs and Cima in their laboratories. Bredt and Anderson realized that the complexity of current 3D printers led to mechanical problems. They sought to develop a simplified 3D printer using an ink-jet head as a nozzle and sugar and water as binders. This led to a low-end but functional machine that was further developed in Sachs's laboratory. They later partnered with entrepreneurs Walter Bornhorst and Marina Hatsopoulos to found Z Corporation in 1994, 5 years after the Sachs et al. patent was issued (Lassiter, Lieb, and Clay 2005). Z Corporation has become one the leading 3D printing companies in the AM industry and has grown to employ over 100 people.[90]

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[87] Patent families are based on patents that are assigned the same Family ID by the USPTO. USPTO incorrectly lists the original patent in the parent case text of U.S. Patent No. 5387380 as U.S. Patent No. 5204053, rather than U.S. Patent No. 5204055.

[88] NSF Award # 9420365 (1995–1999) from the Directorate for Computer and Information Science and Engineering (CISE) Division of Experimental and Integrative Activities was titled "Design Automation for Solid Freeform Fabrication" and supported a journal publication submission: A. Curodeau, E. Sachs, M. Cima, and S. Caldarise, "Design and Fabrication of Cast Parts with Freeform Surface Textures from 3D Printed Ceramic Shell," *Journal of Biomedical Materials Research*, http://www.nsf.gov/awardsearch/showAward?AWD_ID=9420365&HistoricalAwards=false.

[89] NSF Award # 9617750 (1997-1999) is a jointly funded award with DARPA titled "The Distributed Design and Fabrication of Metal Parts and Tooling by 3D Printing" that supported a manuscript in an NSF proceeding: E. M. Sachs, N. M. Patrikalakis, M. J. Cima, D. Brancazio, W. Cho, T. R. Jackson, H. Liu, H. Wu, R. Resnick, "The Distributed Design and Fabrication of Metal Parts and Tooling by 3D Printing," *NSF Design & Manufacturing Grantees Conference Proceedings*, 1999, http://www.nsf.gov/awardsearch/showAward?AWD_ID=9617750&HistoricalAwards=false.

[90] See http://www.zcorp.com/.

Table H-4. U.S. Patents in the U.S. Patent No. 5204055 Patent Family

Patent	Title	Inventors	File Date	Issue Date
5340656*	Three-dimensional printing techniques	Emanuel Sachs; John S. Haggerty; Michael J. Cima; Paul A. Williams	Apr 9, 1993	Aug 23, 1994
5387380	Three dimensional printing techniques	Michael Cima; Emanuel Sachs; Tailin Fan; James F. Bredt; Steven Michaels; Satbir Khanuja; Alan Lauder; Sang-Joon Lee; David Brancazio; Alain Curodeau; Harald Tuerck	Jun 5, 1992	Feb 7, 1995
5807437	Three dimensional printing system	Emanuel Sachs; Alain Curodeau; Tailin Fan; James F. Bredt; Michael Cima; David Brancazio	Feb 5, 1996	Sep 15, 1998
6036777	Powder dispensing apparatus using vibration	Emanuel Sachs	Apr 14, 1995	Mar 14, 2000

Note: The Family ID 23777294 was used to identify relevant patents in the same family.

* U.S. Patent No. 5340656 is a divisional patent of U.S. Patent No. 5204055, meaning the original parent application describes more than one invention and the patent must be split into one or more divisional patents that each claims one invention.

Table H-5. MIT Co-Inventors on Patents in the U.S. Patent No. 5204055 Patent Family

Inventor	Degree/Year	Thesis Supervision	Thesis Title	Funding Acknowledgements in Thesis
Alain Curodeau	MSc Mechanical Engineering in 1991	Supervised by Emanuel Sachs	Three dimensional printing: machine control from CAD model to nozzles	NSF Strategic Manufacturing (STRATMAN) Initiative & MIT Leaders for Manufacturing Program
Tailin Fan	Ph.D. Mechanical Engineering in 1995	Supervised by Emanuel Sachs	Droplet—powder impact interaction in three dimensional printing	No funding acknowledgement
James F. Bredt	MSc Mechanical Engineering in 1987, Ph.D. in 1995	MSc supervised by George Chryssolouris; Ph.D. supervised by Emanuel Sachs	1987: Laser machining of ceramics and metals: development of a laser lathe 1995: Binder stability and powder/binder interaction in three dimensional printing	1987: Ford Motor Company and Coherent General Inc. 1995: No funding acknowledgement
David Brancazio	MSc Mechanical Engineering in 1991	Supervised by Emanuel Sachs,	Development of a robust electrostatically deflecting printhead for three dimensional printing	NSF Strategic Manufacturing (STRATMAN) Initiative & MIT Leaders for Manufacturing Program

Government Interest Clause

U.S. Patent No. 5204055 was filed in 1989 and was the first in the patent family of four patents invented or co-invented by Sachs and his colleagues at MIT. According to the government interest clause of these patents, NSF is listed as supporting U.S. Patent Nos. 5387380 and 6036777.[91] These were filed several years after the original binder jetting patent. The NSF award was from the Strategic Manufacturing (STRATMAN) Initiative discussed previously. This NSF award was provided to Sachs and Cima in October 1989, 2 months before U.S. Patent No. 5204055 was submitted. It expired in March 1993, about 1 month before U.S. Patent No. 5340656 was submitted and more than 2 years before U.S. Patent Nos. 5807437 and 6036777 were submitted. NSF is attributed in two patents and likely supported the refinement of the original invention or later developments, given the dates of the NSF award and their proximity to filing dates of the other patents. A discussion with Cima confirmed that the initial STRATMAN award and further NSF awards were instrumental in advancing the initial prototype machine and process into more functional and eventually commercializable machines and processes.

Backward citation analysis

A citation analysis of the four patents in the U.S. Patent No. 5204055 family shows U.S. Patent No. 6036777 references six patents filed from 1991 to 1993 by Friedrich Prinz and Daniel Siewiorek. Both were former principal investigators of an NSF Engineering Research Center award to create Carnegie Mellon's Engineering Design Research Center.[92] Their six patents were filed in the same time frame that they received the NSF award, which suggests that this funding may have played a role in supporting their research that was later used in their inventions and in U.S. Patent 6036777.[93]

When analyzing the second-generation cited references of U.S. Patent No. 5204055, we observe that the Navy had a role to play in supporting two patents influential to Sachs

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[91] NSF Award #8913977 is listed in the government interest clause of the patents. NSF Award #8913977 is a Strategic Manufacturing Initiative award listed in the government interest clause of the patent. The project is "Three Dimensional Printing; Rapid Tooling and Prototypes Directly from a Computer Aided Design Model," awarded to principal investigator Emanuel Sachs, and co-principal investigators Michael Cima and James Cornie, from 1989 to 1993. http://nsf.gov/awardsearch/showAward?AWD_ID=8913977

[92] In 1997, the Engineering Design Research Center was rolled into the Institute for Complex Engineered Systems. Friedrich (Fritz) Prinz was director of the ERDC from 1989 to 1994 (now Chair of the Mechanical Engineering Department at Stanford University), and Daniel P. Siewiorek from 1994 to 1997 (now Director of the Human-Computer Interaction Institute at Carnegie Mellon). Carnegie Mellon University, 2013. "ICES," http://www.ices.cmu.edu/history.asp.

[93] NSF Award #8943164 Engineering Research Center for Engineering Design was awarded from 1989 to 1997. http://nsf.gov/awardsearch/showAward?AWD_ID=8943164.

et al. One patent, related to directed energy deposition, was funded by the U.S. Navy.[94] This patent was cited by several patents referenced by Sachs et al.: Deckard's patent on selective laser sintering and a patent on ceramic powders by Harris Marcus and Udaykumar Lakshminarayan (see Case Study 2).[95] Deckard has a history of funding from the NSF, although this patent predates any of his NSF awards. Marcus also received NSF funding; however, the funding was provided a decade or more before they filed their patent. The U.S. Navy also sponsored another patent that was influential to Frank Arcella, founder of AeroMet, and which was later cited by Sachs et al.[96]

An analysis of the non-patent citations from the four patents reveals two publications that acknowledge government support. One was supported by the U.S. Army[97] and another was supported by DARPA.[98] No other government entity was identified as supporting the other non-patent publications.

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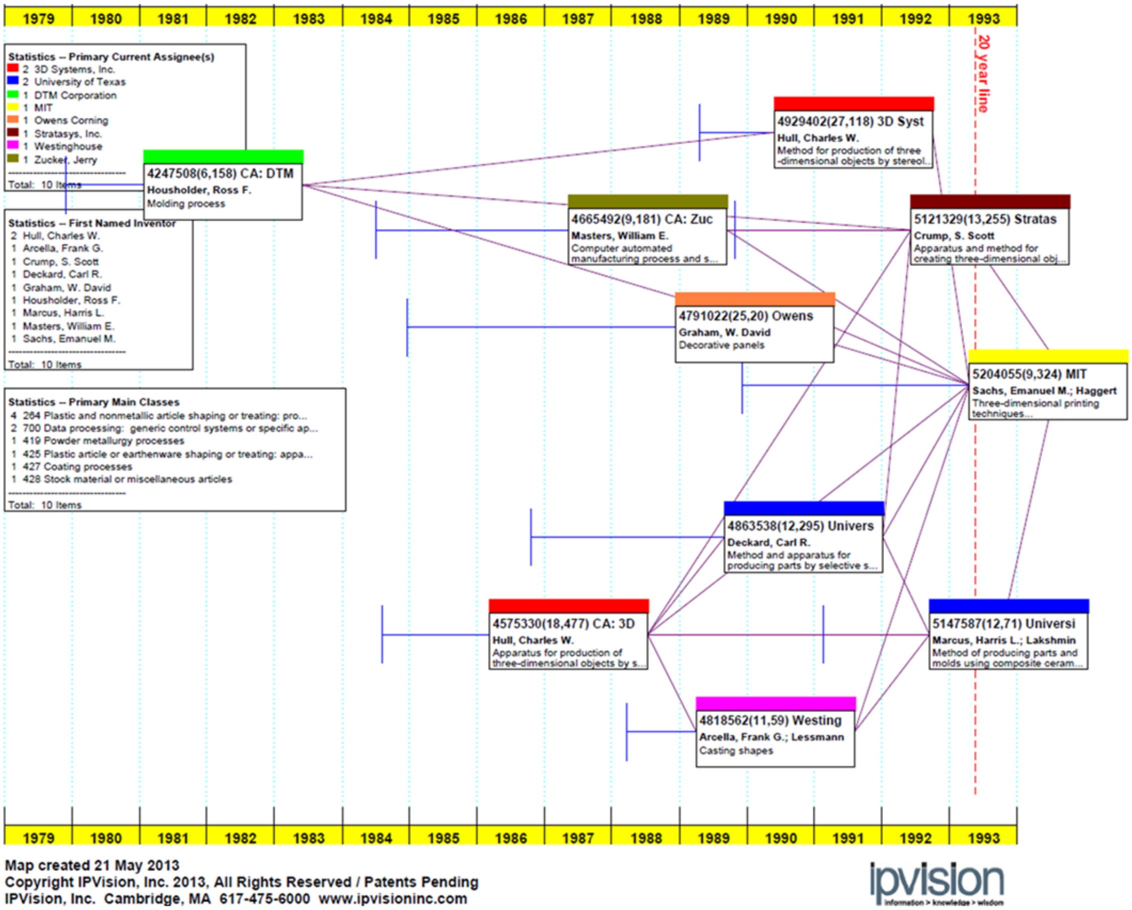
[94] Clyde O. Brown, Edward M. Breinan., Bernard H. Kear, Method for fabricating articles by sequential layer deposition, U.S. Patent No. 4323756, filed 1979 and issued 1982; assignee: UTC. This patent was sponsored by U.S. Navy Contract No. N00014-77-C-0418.

[95] Carl Deckard, Method and apparatus for producing parts by selective sintering, U.S. Patent No. 4863538, filed October 17, 1986, and issued September 5, 1989; assignee: University of Texas and Harris Marcus and Udaykumar Lakshminarayan, Method of producing parts and molds using composite ceramic powders, U.S. Patent No. 5147587, filed: February 19, 1991, and issued: September 15, 1992; assignee: University of Texas.

[96] Frank Arcella and Gerald Lessmann, Casting shapes, U.S. Patent 4818562, filed March 24, 1988, and issued April 4, 1989; assignee: Westinghouse Electric Corporation; this patent references U.S. Patent No. 4615903: Douglas L. Miller, Method for melt-coating a surface, filed July 1, 1985, and issued October 7, 1986; assignee: The United States of America as represented by the Secretary of the Navy (Washington, DC).

[97] Two patents, U.S. Patent Nos. 5807437 and 6036777, cite Richard G. Sweet, "High Frequency with Electrostatically Deflected Ink Jets," *The Review of Scientific Instruments* 36:2 (1965): 131–136, supported by U. S. Army Electronics Research and Development Laboratory (currently the Communications-Electronics Research, Development and Engineering Center) under Contracts DA 36(039) SC-87300 and DA 36(039) AMC-03761(E).

[98] U.S. Patent No. 5204055 cites U.S. Patent No. 4665492 (Computer automated manufacturing process and system), which cites Clark, "Designing Surfaces in 3-D," *Communications of the ACM* 19, No. 8 (August 1976), 454–60, supported under Contract No. F30602-70-C-0300.



Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com). The location of the box indicates the patent issue year, and the left whisker indicates the patent application year.

Figure H-9. Relationships between U.S. Patent 5204055 and its References Based on Citations in Each Patent

Forward Citation Analysis

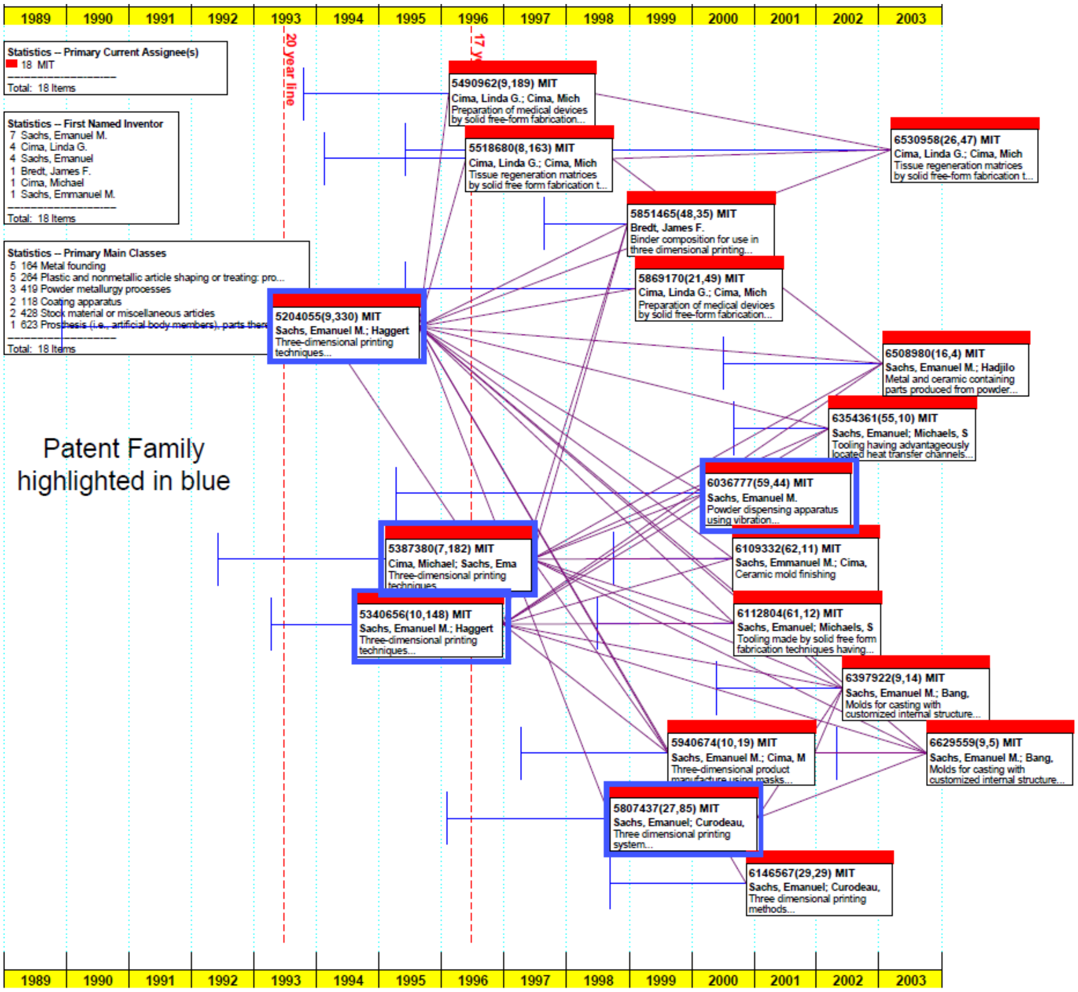
The Sachs et al. original patent has been cited by 324 patents. Although the three patents in the same family have not yet received as many citations, these patents were produced several years after the original and thus have had less time for citation (Table H-6). For all four patents, 10% or less of the citing patents have some government support as stated in the government interest clause of the patent. Of these, about 6% or less of the citing patents are supported by NSF.

All the patents supported by NSF that cite the Sachs et al. original or family of patents were produced by Sachs and MIT researchers (Figure H-10). This analysis shows that NSF may have had a greater role in supporting the later development of binder jetting by MIT researchers. A discussion with Cima confirms that NSF played a significant role in the early development stages of binder jetting, but only after a prototype of the technology was already established.

Table H-6. U.S. Patent No. 5204055 Patent Family, Citing Patents, and Government Interest

Patent	No. of Citing Patents	No. with Government Interest Clause (% of Total)	No. with NSF in the Government Interest Clause (% of Total)
5204055	324	33 (10%)	15 (5%)
5387380	186	16 (9%)	9 (5%)
5340656	148	12 (8%)	9 (6%)
5807437	85	5 (6%)	3 (4%)
6036777	44	2 (5%)	0 (0%)

Note: The Family ID 23777294 was used to identify relevant patents in the same family.



Map created 24 Jun 2013

IPVision, Inc. Cambridge, MA 617-475-6000 www.ipvisioninc.com

Notes: Figure created using patent analytics software from IPVision (http://www.see-the-forest.com). The location of the box indicates the patent issue year, and the left whisker indicates the patent application year. USPTO data show incorrect spellings and varied abbreviations for Emanuel Sachs, first name also shown as Emmanuel and middle name is either abbreviated or not included.

Figure H-10. Relationships between U.S. Patent Nos. 5204055, 5387380, 5340656, 5807437, and 6036777 and 14 Citing Patents with NSF Government Sponsorship Based on Citations in Each Patent

References

Additive Manufacturing Special Interest Group. 2012. *Shaping our National Competency in Additive Manufacturing: A Technology Innovation Needs Analysis Conducted by the Additive Manufacturing Special Interest Group for the Technology Strategy Board*. UK Technology Strategy Board.

Agarwala, M., D. Bourell, J. Beaman, H. Marcus, and J. Barlow. 1995a. “Direct Selective Laser Sintering of Metals.” *Rapid Prototyping Journal* 1 (1): 26–36.

———. 1995b. “Post-Processing of Selective Laser Sintered Metal Parts.” *Rapid Prototyping Journal* 1 (2): 36–44.

ASTM International. 2010. “Standard Terminology for Additive Manufacturing - Coordinate Systems and Test Methodologies.” ASTM F2921–11.

———. 2012a. “Standard Terminology for Additive Manufacturing Technologies.” ASTM F2792-12a.

———. 2012b. “Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1.” ASTM F2915-12.

Baese, C. 1904. “Photographic Process for the Reproduction of Plastic Objects.”

Bártolo, P. 2011. *Stereolithography Materials, Processes and Applications*. New York: Springer.

Beaman, J. J. 2012. “General Overview of Additive Manufacturing Technologies.” Paper presented at the Additive Manufacturing Symposium, White House Conference Center.

Beaman, J. J., C. Atwood, T. L. Bergman, D. Bourell, S. Hollister, and D. Rosen. 2004. “Additive/Subtractive Manufacturing Research and Development in Europe.” 154. Baltimore: World Technology Evaluation Center Inc.

Blanther, J. E. 1892. “Manufacture of Contour Relief Maps.” U.S. Patent No. 473901.

Bogart, M. 1979. “In Art the End Don’t Always Justify Means.” *Smithsonian*: 104-10.

Bourell, D. L., J. J. Beaman, M. C. Leu, and D. W. Rosen. 2009. “A Brief History of Additive Manufacturing and the 2009 Roadmap for Additive Manufacturing: Looking Back and Looking Ahead.” Paper presented at the RapidTech 2009:US-Turkey Workshop on Rapid Technologies.

Bourell, D. L., M. C. Leu, and D. W. Rosen (eds). 2009. *Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing*. Austin, TX: University of Texas at Austin. http://www.wohlersassociates.com/roadmap2009.pdf.

Brown, C. O., E. M. Breinan, and B. H. Kear. 1982. “Method for Fabricating Articles by Sequential Layer Deposition.” U.S. Patent No. 4323756.

Campbell, T., C. Williams, O. Ivanona, and B. Garrett. 2011. “Could 3D Printing Change the World? Technologies, Potential, and Implications of Additive Manufacturing.” Washington, D.C.: Atlantic Council, October.

Ciraud, P., 1973. “Process and Device for the Manufacture of any Objects Desired from any Meltable Material.”

Crump, S. S. 1992. “Apparatus and Method for Creating Three-Dimensional Objects.” Stratasys Inc.

Deagon, B. 2013. “ExOne IPO Soars in 3D Print Maker’s Stock Debut.” *Investors Business Daily*, February 7. http://news.investors.com/technology/020713-643591-exone-3d-printer-maker-ipo-soars.htm?p=full.

Deckard, C. R. 1989. “Method and Apparatus for Producing Parts by Selective Sintering.” Board of Regents, The University of Texas System.

Department of Energy (DOE). 1999. “Inventions & Innovation Success Story: Laminated Object Manufacturing Improves Rapid Prototyping Process,” http://www.metalcasting.govtools.us/reports/helysis.pdf.

Dickens, P., R. James, and M. Hague. 2000. “Method of Making a Three-Dimensional Object.” In *DE69616585D1, DE69616585T2, EP0865348A1, EP0865348B1, WO1997018933A1*, edited by University of Nottingham.

DiMatteo, P. L. 1976. “Method of Generating and Constructing Three-Dimensional Bodies.”

“Print Me a Stradivarius.” 2011. *The Economist* (February 10).

Feygin, M. 1988. “Apparatus and Method for Forming an Integral Object from Laminations.”

Fisher, W. B., A. A. G. Requicha, N. M. Samuel, and H. B. Voelcker. 1978. “Part and Assembly Description Languages--II: Definitional Facilities in PADL-1.n and Command Facilities in the PADL-1.0/2.n Processor.” https://urresearch.rochester.edu/institutionalPublicationPublicView.action?institutionalItemId=1015.

Frazier, W. E. 2010. “Direct Digital Manufacturing of Metallic Components: Vision and Roadmap.” In *Direct Digital Manufacturing of Metallic Components: Affordable, Durable, and Structurally Efficient Airframes*. Solomons Island, MD.

Gershenfeld, N. 2012. “How to Make Almost Anything: The Digital Fabrication Revolution.” *Foreign Affairs* 91 (6): 43–57.

Gibson, I., D. W. Rosen, and B. Stucker. 2010. Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing. New York: Springer.

Harris, I. 2012. “Additive Manufacturing and Amc.”

Hartke, K. 2011. “Manufacturing Technology Support (Mates).” Wright-Patterson Air Force Base, OH.

Hopkinson, N., R. J. M. Hague, and P. M. Dickens. 2006. *Rapid Manufacturing : An Industrial Revolution for the Digital Age*. Chichester, England: John Wiley.

Hopkinson, N. 2010. "Additive Manufacturing: Technology and Applications." Loughborough, UK: British Educational Communications and Technology Agency.

Housholder, R. F. 1981. "Molding Process."

Hull, C. W. 1986. "Apparatus for Production of Three-Dimensional Objects by Stereolithography."

Jeantette, F., D. Keicher, J. Romero, and L. Schanwald, 2000. "Method and System for Producing Complex-Shape Objects." edited by Sandia Corporation.

Khoshnevis, B. 1996. "Additive Fabrication Apparatus and Method." edited by U.S. Patent and Trademark Office: University Of Southern California.

Kinsella, M. 2011. "Additive Manufacturing Workshop: Results and Plans." 1–14. Washington, DC: Air Force Research Laboratory.

Kruth, J. 1991. "Material Incress Manufacturing by Rapid Prototyping Techniques." *CIRP Annals-Manufacturing Technology* 40, no. 2: 603–14.

Kunieda, M., and T. Nakagawa. 1984. "Development of Laminated Drawing Dies by Laser Cutting." *Bull of JSPE*: 353–54.

Larsson, R. 2003. "Method and Device for Manufacturing Three-Dimensional Bodies." In *DE69806949D1, DE69806949T2, EP1015214A1, EP1015214B1, WO1998051464A1*, edited by Speed Part Rp Ab.

Lassiter, J., M. Lieb, and T. Clay. 2005. "Z Corporation." *Harvard Business School*, no. Case 801-210 (Revised April 2005).

Lipson, H., and M. Kurman. 2011. "Factory @ Home: The Emerging Economy of Personal Fabrication." In *Occasional Papers in Science and Technology Policy*, 1-104. Washington, DC: Science and Technology Policy Institute.

Lipson, H. 2013. *Fabricated: the New World of 3D Printing*. Vol. 1. Indianapolis: Wiley.

Lou, A., and C. Grosvenor. 2012. "Selective Laser Sintering, Birth of an Industry." https://www.me.utexas.edu/news/2012/0712_sls_history.

Matsubara, Y. 1974. "Molding Method of Casting Using Photocurable Substance."

Monteah, F. H. 1924. "Photochemical Process for Producing Bas Reliefs."

Morioka, I. 1935. "Process for Manufacturing a Relief by the Aid of Photography."

Mudge, R. P., and N. R. Wald. 2007. "Laser Engineered Net Shaping Advances Additive Manufacturing and Repair." *Welding* (January): 44–48.

Munz, O. J. 1956. "Photo-Glyph Recording."

Nakagawa, T., et al. 1979 "Blanking Tool by Stacked Bainite Steel Plates." *Press Technique*: 93–101.

Nakagawa, T., M. Kunieda, and S. Liu. 1985. "Laser Cut Sheet Laminated Forming Dies by Diffusion Bonding." *Proceedings of the 25th MTDR Conference*: 505–10.

National Academy of Engineering. 2012. "Frontiers of Engineering 2011: Reports on Leading-Edge Engineering from the 2011 Symposium." Paper presented at the

National Academy of Engineering's 2011 U.S. Frontiers of Engineering Symposium, Mountain View, California.

National Center for Manufacturing Sciences (NCMS). 1998. "The Road to Manufacturing: 1998 Industrial Roadmap for the Rapid Prototyping Industry." Ann Arbor, MI: NCMS.

Oak Ridge National Laboratory (ORNL). "Manufacturing Demonstration Facilituy." ORNL, http://web.ornl.gov/sci/manufacturing/mdf.shtml.

Perera, B. V. 1940. "Process of Making Relief Maps."

Prinz, F. B., C. I. Atwood, R. F. Aubin, J. J. Beaman, R. I. Brown, P. S. Fussell, A. J. Lightman, et al. 1997. *JTEC/WTEC Panel Report on Rapid Prototyping in Europe and Japan*. Baltimore, MD: Rapid Prototyping Association of the Society of Manufacturing Engineers.

RapidToday.com. 2008. "3D Printer Uses Standard Paper." May. http://rapidtoday.com/mcor.html.

Sachs, E. M., M. J. Cima, and J. Cornie. 1989. "Strategic Manufacturing Initiative: Three Dimensional Printing; Rapid Tooling and Prototypes Directly from a Computer Aided Design Model." National Science Foundation,.

Sachs, E. M., J. S. Haggerty, M. J. Cima, and P. A. Williams. 1993. "Three-Dimensional Printing Techniques."

Sandia National Laboratories. 2012. "Creating a Complex Metal Part in a Day Is Goal of Commercial Consortium," http://www.sandia.gov/media/lens.htm.

Scott, J., N. Gupta, C. Weber, S. Newsome, T. Wohlers, and T. Caffrey. 2012. "Additive Manufacturing: Status and Opportunities." IDA Science and Technology Policy Institute..

Shellabear, M., and O. Nyrhilä. 2004. "DMLS-Development History and State of the Art." *Laser Assisted Netshape Engineering 4, Proceedings of the 4th LANE*: 21–24.

Shipp, S., N. Gupta, B. Lal, J. Scott, C. Weber, M. Finnin, M. Blake, S. Newsome, and S. Thomas. 2012. *Emerging Global Trends in Advanced Manufacturing*. IDA Paper P-4603. Alexandria, VA: Institute for Defense Analyses.

Semiconductor Industry Association (SIA). 2013. "Semiconductor Industry Posts near Record Sales Total in 2012." http://www.semiconductors.org/news/2013/02/04/global_sales_report_2013/semiconductor_industry_posts_near_record_sales_total_in_2012/.

Tourtellotte, H. A., and R. E. Wicks. 1981. "Powder Feed Apparatus." United Technologies Corporation. U.S. Patent No. 4270675.

University of Texas at Austin. 2012. "Selective Laser Sintering, from a Texas Idea to a Global Industry." The University of Texas at Austin Mechanical Engineering Department, http://www.me.utexas.edu/news/2012/0612_selective_laser_sintering.php.

Yardimci, M. A., S. I. Guceri, M. Agarwala, and S. C. Danforth. 2012. “Part Quality Prediction Tools for Fused Deposition Processing.” http://utwired.engr.utexas.edu/lff/symposium/proceedingsArchive/pubs/Manuscripts/1996/1996-62-Yardimci.pdf.

Voelcker, H. 1976. “Production Automation Project.” NSF.

Williams, P. 1990. “Three Dimensional Printing: A New Process to Fabricate Prototypes Directly from CAD Models.” Master of Science Thesis in the Department of Mechanical Engineering, MIT.

Wohlers Associates. 2011. Additive Manufacturing Technology Roadmap for Australia. Ft. Collins, CO: Wohlers Associates Inc.

Wohlers, T. 1998. “Wohlers Report 1998: Additive Manufacturing and 3d Printing, State of the Industry.” Ft. Collins, CO: Wohlers Associates.

———. 2002. “Wohlers Report 2002: Additive Manufacturing and 3d Printing, State of the Industry.” Ft. Collins, CO: Wohlers Associates.

———. 2011. “Wohlers Report 2011: Additive Manufacturing and 3d Printing, State of the Industry.” 1–271. Ft. Collins, CO: Wohlers Associates.

———. 2012. “Wohlers Report 2012: Additive Manufacturing and 3d Printing, State of the Industry.” 1–271. Ft. Collins, CO: Wohlers Associates,.

Wohlers, T., and T. Gornet. 2011. “History of Additive Manufacturing.” In *Wohlers Report*. Wohlers Associates Inc.

Wong, K., and A. Hernandez. 2012. “A Review of Additive Manufacturing.” *International Scholarly Research Network* (*ISRN*) *Mechanical Engineering*: 1–10.

Zang, E. E. 1964. “Vitavue Relief Model Technique.”

Abbreviations

2D	two dimensional
3D	three dimensional
3DP	three-dimensional printers
AFRL	Air Force Research Laboratory
AM	additive manufacturing
AMF	Additive Manufacturing File Format
AMUG	Additive Manufacturing Users Group
ARC	Arctic Research Commission
ARL	Army Research Laboratory
ASTM	International (known until 2001 as the American Society for Testing and Materials)
BIO	Directorate of Biological Sciences
BPM	ballistic particle manufacturing
CAD	computer-aided design
CAM	computer-aided manufacturing
CBET	Division of Chemical, Bioengineering, Environmental, and Transport Systems
CCF	Division of Computing and Communication Foundations
CHE	Division of Chemistry
CIRP	College International Pour la Recherche en Productique (International Academy for Production Engineering)
CLAD	construction laser additive directed
CMMI	Civil, Mechanical and Manufacturing Innovation
CNC	computer numerical control
CNS	Division of Computer and Network Systems
CSE	Directorate of Computer and Information Science and Engineering
DARPA	Defense Advanced Research Projects Agency
DBI	Division of Biological Infrastructure
DEB	Division of Environmental Biology
DLP	digital light processing
DMII	Design, Manufacture, and Industrial Innovation
DMLS	direct metal laser sintering
DMR	Division of Materials Research
DMS	Division of Mathematical Sciences
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy

DRL	Division of Research on Learning in Formal and Informal Settings
DTM	Desk Top Manufacturing
DUE	Division of Undergraduate Education
EAR	Division of Earth Sciences
EBM	electron beam melting
ECCS	Division of Electrical, Communications and Cyber Systems
EEC	Division of Engineering Education and Centers
EFRI	Division of Emerging Frontiers in Research and Innovation
EHR	Directorate of Education and Human Resources
EIA	Division of Experimental and Integrative Activities
ENG	Directorate of Engineering
EPS	Experimental Program to Stimulate Competitive Research
EPSRC	Engineering and Physical Sciences Research Council
FDM	fused deposition modeling
GEO	Directorate Geosciences
GmbH	Gesellschaft mit beschränkter Haftung (designates a privately held company)
GOALI	Grant Opportunities for Academic Liaison with Industry
HRD	Division of Human Resource Development
I/UCRC	Industry/University Cooperative Research Center
IDA	Institute for Defense Analyses
IIP	Industrial Innovation and Partnerships
IIS	Division of Information and Intelligent Systems
IOS	Division of Integrative Organismal Systems
JTEC	Japanese Technology Evaluation Center
LENS	Laser Engineered Net Shaping
MIT	Massachusetts Institute of Technology
MLS	MicroLightSwitch
MME	Manufacturing Machines and Equipment
MPM	Materials Processing and Manufacturing
MPS	Directorate of Mathematical and Physical Sciences
MRI	Major Research Instrumentation
NAMII	National Additive Manufacturing Innovation Institute
NASA	National Aeronautics and Space Administration
NCMS	National Center for Manufacturing Sciences
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
O/D	Office of the Director
OCE	Division of Ocean Sciences
OCI	Office of Cyberinfrastructure
OISE	Office of International Science and Engineering

ONR	Office of Naval Research
OPP	Office of Polar Programs
ORNL	Oak Ridge National Laboratory
PADL	Part and Assembly Description Language
POM	Precision Optical Manufacturing
R&D	research and development
SBIR	Small Business Innovation Research
SFF	solid freeform fabrication
SGER	Small Grant for Exploratory Research
SIA	Semiconductor Industry Association
SLA	stereolithography
SLM	selective laser melting
SLS	selective laser sintering
SME	Society of Manufacturing Engineers
STL	Standard Triangulation Language
STPI	Science and Technology Policy Institute
STRATMAN	Strategic Manufacturing Initiative
STTR	Small Business Technology Transfer
USPTO	U.S. Patent and Trademark Office
VRAP	Virtual and Rapid Prototyping
WTEC	World Technology Evaluation Center

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14. ABSTRACT

The rapidly growing research field of additive manufacturing is an emerging technology that is proving to have the potential to revolutionize manufacturing. The IDA Science and Technology Policy Institute (STPI) undertook a study to examine the role of the National Science Foundation (NSF) and other U.S. Government agencies in the development and commercialization of additive manufacturing within the United States. The goal was to discover what lessons can be learned about identifying, nurturing, and promoting emerging science and engineering at NSF. The study found that NSF played an important role, together with industry and such agencies as the Defense Advanced Research Projects Agency, the Office of Naval Research, and NASA, in creating and maturing the field.

15. SUBJECT TERMS

additive manufacturing, 3D printing, history of technology, historical tracing, patent analysis, bibliometrics, case studies, historiography, technology transfer, expert assessment

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