Competitive Strategic Advantage Through Disruptive Innovation

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Submitted to the Sloan School of Management on May 17, 1996
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ABSTRACT
Technological innovations fall into two broad: those innovations which are introduced
prior to the establishment of a standard product type or “dominant design” and those
innovations introduced after the emergence of a dominant design.

The establishment of a dominant design is a consequence of testing for fit between product
feature variants and market needs. This experimentation is often expensive, problematic,
prone to failure, and generally not pleasant. The strategies a firm might employ in pursuing
successful innovations are unique to the post-dominant design phase of innovation, and to
the pre-dominant design phase. An application of post-dominant design innovation strategy
to a pre-dominant design market may not only be ineffective, but damaging to the firm as
well.

Firms define their innovation strategy based on their knowledge and familiarity with
existing markets. Firms rarely innovate in technologies which do not serve the needs of
mainstream customers. Yet successful innovation other than incremental involves
substantial market innovation as well. It has been found that new entrants firms le·4 in
innovating technologies which addressed non mainstream markets and that those new
entrants often grew to displace existing mainstream firms.

This paper examines a firms competing in an emerging. Of particular focus will be the
firm’s evolving strategic focus in product innovation as the market matures. The
framework of a Value Network is used along with that of a dominant design to help
structure the observations.

Thesis Supervisor: James M. Utterback
Title: Professor of Management
# TABLE OF CONTENTS

## ABSTRACT

## INTRODUCTION

### CHAPTER 1  The Nature of Competition Among Firms

1.0 Differentiation  
1.1 Price  
1.2 Externalities  
1.3 Performance

### CHAPTER 2  The Nature of Technological Innovation

2.0 Competition Through Innovation  
2.1 The Study of Innovation  
2.2 Innovation Life Cycle  
2.3 Linking Innovation and Core Competencies  
2.4 Linking Innovation and Markets

### CHAPTER 3  Disruptive Technological Innovation

3.0 The Established Technology: Model Making  
3.1 A Disruptive Innovation: StereoLithography  
3.1.1 StereoLithography and 3D Systems  
3.1.2 Lead Users  
3.1.3 Commercialization  
3.2 An Emerging Industry  
3.2.1 Du Pont  
3.2.2 Stratasys  
3.2.3 DTM  
3.2.4 MIT/Soligen  
3.2.5 Helisys  
3.3 2X Disruptive Innovation: Convenience Modelers  
3.3.1 Sanders  
3.3.2 Ballistic Particle Manufacturing  
3.4 Traditional Technology Response  
3.4.1 Incremental Improvements  
3.4.2 Hybrid

### CHAPTER 4  Next Generation of Disruptive Innovation

4.0 IBM and Rapid Prototyping  
4.1 3D Systems Responds:  
4.1.1 Component Innovation  
4.1.2 Modular Innovation  
4.1.3 Architectural Innovation  
4.1.4 Marketing  
4.1.5 Results
<table>
<thead>
<tr>
<th>CHAPTER 5</th>
<th>A Framework for Disruptive Innovation</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>Customer Context</td>
<td>50</td>
</tr>
<tr>
<td>5.1</td>
<td>Emerging Markets</td>
<td>51</td>
</tr>
<tr>
<td>5.3</td>
<td>Technology Trajectory</td>
<td>51</td>
</tr>
<tr>
<td>5.4</td>
<td>The Value Network</td>
<td>53</td>
</tr>
<tr>
<td>5.5</td>
<td>Rapid Prototyping and Value Networks</td>
<td>54</td>
</tr>
<tr>
<td>5.5.1</td>
<td>Context</td>
<td>54</td>
</tr>
<tr>
<td>5.5.2</td>
<td>RP Initial Market Entry</td>
<td>55</td>
</tr>
<tr>
<td>5.5.3</td>
<td>Attack from Below</td>
<td>56</td>
</tr>
<tr>
<td>5.5.4</td>
<td>Moving Up-Market</td>
<td>57</td>
</tr>
<tr>
<td>5.5.5</td>
<td>Segmentation</td>
<td>58</td>
</tr>
<tr>
<td>5.6</td>
<td>Concept Modeling and Value Networks</td>
<td>59</td>
</tr>
<tr>
<td>5.6.1</td>
<td>Value Network Acrophobia</td>
<td>59</td>
</tr>
<tr>
<td>5.6.2</td>
<td>Value Network Myopia</td>
<td>61</td>
</tr>
</tbody>
</table>

**CONCLUSION**

**BIBLIOGRAPHY**

**APPENDICES**

1) Industry Overview
2) Organizations Researching RP
3) Patents Granted to 3D Systems Inc.
4) Rapid Prototyping Citations

**LIST OF FIGURES**

1.1 Learning Curve
1.2 Dynamics of Innovation
1.3 Explosive Growth from Dominant Design
1.4 Industry population (firm entry and exit)
1.5 Henderson & Clark Innovation Framework
1.6 Abernathey & Clark Innovation Framework
1.7 Foster Innovation "S" Curve
1.8 Christensen & Rosenbloom Technology Trajectories
1.9 Technology Trajectory Frontier
1.10 General Layout of Stereolithographic process
1.11 Stereolithographic Apparatus #1 (SLA-1)
1.12 SLA-190
1.13 SLA-250
1.14 SLA-350
1.15 SLA-500
1.16 RP Industry Population
1.17 RP Industry Citings
1.18 RP Industry Sales
1.19 Multi-Jet Modeler
1.20 Technological Trajectories
INTRODUCTION

There has been much written about the importance and or meaning of innovation as a force in competitive business strategy. But what is innovation? Where does it come from, what motivates firm to attempt it? Is there a fundamental difference between what industry and market the firm serves and what approach it will follow in innovating? Is innovation really important to the long term survival of the firm? Let us first consider a definition.

Innovations is composed of two parts: the generations of an idea or invention and then the conversion of that invention into a business or other useful application:

Innovation = invention + exploitation.

The notion of an invention is well recognized: to find or discover, to come across the novel idea, product or process which did not exist before. To innovate, a firm must exploit inventions. Exploitation involves reducing to practice and bringing to market an invention. Reduction to practice is often highly technical and isolated from the market. It involves getting the invention to work. Brining a new product to market however is quite the opposite. It tends to be void of technical content and involves sociological and logistical concerns.

The two activities may actually be one. Inventions which do not work for the benefit of a market will not succeed while markets for technologically novel products require familiarization before the market can value the innovation accurately. An iterative learning dynamic is naturally formed between the innovating firm and the market. Trial innovations result in market learning which feeds back into further innovation refinements. Christensen et al. call this dynamic the firms “value network.” The ability of firms to develop and practice this innovation learning dynamic is critical to its long term success.

When firms are entering a market for the first time, they often learn well to connect the technological inventiveness of the firm with the needs of the market. It is when the firm has experience in a given value network that it may fail to recognize new connections between its technologic competencies and novel markets. It is this failure to search out and learn new connections which threatens the long term viability of firms.
A lesson in strategy from 1934...
Professor G.F. Gause known as the father of mathematical biology published the results of a set of experiments in which he put two small animals (protozoan) of the same genus in a bottle with an adequate supply of food. If the animals were of different species, they could survive and persist together. If they were of the same species, they could not. This observation led to Gause’s Principal of Competitive Exclusion: No two species can coexist that make their living in the identical way. (Henderson, B. 1989)

1.0 Differentiation

Firms compete for economic gain. The basis of this competition may take many forms, but broadly speaking, all firms compete through differentiation. That is, one firm will attempt to make its products or services appear different (more desirable, more valuable) from other firms offering similar products and or services in the hopes that the difference will induce a purchase preference. There exists an infinite variety of ways to achieve differentiation. However, most would fit into one of two broad categories: price or performance.

1.1 Price

A differentiation strategy based on price leadership will induce a firm to devise means of becoming the lowest cost supplier in the market. Inherent in this strategy for differentiation is the assumption that price is an important differentiator in the market or at least a significant segment thereof. If this assumption is false, attempting to differentiate on low price leadership will fail.

Allowing that low price is important, success is usually achieved through providing the most efficient means of production and delivery, by employing standard designs, specialized (often expensive) production equipment, volume purchases,
and high production volumes (economies of scale). This approach is sometimes referred to as "a race down the learning curve" in that the firm attempts to learn more quickly than its competitors how to reduce costs, and increase availability of value to the market.

A learning curve model relates learning acquired by the firm through increased production volume to the costs associated with producing that volume. As more units are produced, the firm learns how to do the job more efficiently, and as it learns, its costs should drop as that learning is incorporated into the firm's operations. The firm successfully employing this strategy will learn how to lower its costs of production and distribution faster than its competition. Thus, it will be able to offer a lower price to the market, gain an increase in market share, increase volumes still further, and develop and deploy even greater cost-savings techniques. The greatest gains go to the firm able to descend the learning curve ahead of its competitors.

![Learning Curve Graph](image)

Figure 1.1 The Learning Curve

1.2 Externalities

A variant of the price leadership approach can be found in the software industry (and others) where sufficient market share leads to a different sort of differentiation, through externalities. In the software industry it has becoming increasingly important
for a design to become broadly accepted and supported. To such a design is afforded the greatest support of external value addition. An example of this is found in Microsoft, and the operating systems software used in another familiar design; the IBM-compatible personal computer. MS-DOS gained a slight lead over competitors owing probably to its association with its companion product (the IBM PC). Once MS-DOS gained a lead share of the PC operating systems (OS) software market, more application programs were written for use with it, simply due to an aligned motivation on the part of applications developers to write software for the largest and fastest growing OS market. The availability of a fast-growing number of applications for MS-DOS increased the attractiveness of MS-DOS itself. Once this dynamic was initiated, with its strong positive feedback structure, the MS-DOS design quickly became the most prevalent. It became difficult for an alternate product to compete in the same market. MS-DOS did not gain economies of scale which afforded lower cost of production in the traditional sense; it gained economies of scale from the associated products (externalities) built upon it.

1.3 Performance

Yet another approach available to firms is to adopt a strategy of differentiation through performance. The firm may seek to deliver product and service attributes which have greater value to customers and enable it to receive a premium price. Presumably these product and service attributes which command a premium price also provide value to the consumer above and beyond that available from the "standard" offerings. Such performance differentiation must be sufficiently unique to the firm for the strategy to succeed. If the performance is easily imitated by competitors, the differentiation is transitory and the innovation will quickly diffuse throughout the industry. If the performance is unique to the firm, the firm has more flexibility in its pricing of that premium value. Presumably the firm will attempt to price at a level maximizing its economic gains. Consumers wishing to obtain said performance value will have few options but to pay the premium price or abstain.

The question becomes: to sustain competitive advantage, either through cost or performance differentiation, what must a firm do? The means by which firms develop and deploy performance and price differentiation is through innovation and most often through technological innovation.
"...innovation is a central determinant of longer-run success and failure for manufacturing firms." (Utterback, 1994:xxvii)

2.0 Competition Through Innovation

Firms develop and deploy performance and price differentiation through innovation. Innovation leads to totally new products and/or services with unique performance attributes. It can lead as well to improvements in process and manufacturing technique which lower the cost of production and aid the firm employing a price differentiation strategy. Firms which master innovation and learn to bring innovative products and services to market will gain a competitive advantage over others. The central question is: How do firms understand and manage innovation?

2.1 The Study of Innovation

The effects of technological change and innovation on the firm has been the objective of much study. Schumpeter recognized that modern industrial competition employed innovation as a competitive weapon (Schumpeter, 1937). Studies have treated technological innovation as something that happened to the economic system but was not determined within it (Solow, 1957). These studies have split into two broad categories focused on the understanding of innovation from an economics or an organizational point of view. The economics school examines differences in the patterns of innovation between industries, nations and over time (Dosi, 1988). The organizational school focuses on structures and processes involved in innovating new products and services (Clark & Fujimoto, 1990; Brown & Eisenhardt, 1995). This thesis focuses on the organizational school and specifically look into an area known as technological discontinuities (Anderson & Tushman, 1990). These are innovations that dramatically advance an industry's price and or performance frontier and often result in major dislocations in the make up of firms, industries and economies. We first examine below various frameworks developed in the literature.
2.2 Innovation Life Cycle

One school of investigation into the innovation process follows a descriptive thread through the temporal changes in the technology of products and process themselves. Here, innovations fall into two broad categories: those innovations which are introduced prior to the establishment of a standard product type or “dominant design” as it is called (Abernathy & Utterback, 1978), and those innovations occurring after the emergence of a dominant design. A dominant design has been defined as “a single architecture that establishes dominance in a product class” (Abernathy, 1978).

![Graph showing Product Innovation and Process Innovation over Fluid phase, Transitional phase, and Specific phase]

Figure 2.1 The Dynamics of Innovation

The emergence of a new technological paradigm is characterized by an early or fluid phase of technological development where many approaches are tried. A transitional phase follows in which design consolidation occurs and a dominant design or standard emerges. Finally, in the specific phase, innovation is directed toward incremental improvements in cost and performance.

The pre-dominant design, or fluid phase of innovation is initiated by the introduction of a novel or disruptive innovation. Fluid phase innovation is characterized by wide ranging technological experimentation and subsequent testing for latent market needs. This fluid phase is also characterized by firms entering the market to compete while sales volume growth remains small. This explorative, fluid phase is delightfully presented in a work by James Utterback titled Mastering
the Dynamics of Innovation (1994). In this he describes the invention and subsequent variations in typewriter machine designs in the late 19th century. This wide ranging exploration he describes may be typical of first-of-type innovations where it may not be clear to either the market or the innovating firm what value their innovation provides to the market. Familiar examples of first-of-type innovations include digital computers, xerography, and instant photography (Polaroid). In innovations where the value of a product or service is less novel, and more easily evaluated however, the exploration phase may be brief, or more bounded around a preexisting consensus within the market of what is important. Compact Disc digital recording is a good example of this later type of innovation. Despite their incompatibility and expense, CD’s quickly overturned the existing paradigm of LP’s and to some extent tapes.

![Graph showing explosive growth from a dominant design](image.png)

**Figure 2.2** Explosive Growth from Dominant Design

At some point, one or more firms offer a design to the market which taps a substantial, latent need. The design which best satisfies this latent market need experiences rapid, sometimes explosive growth in demand. This design may and often does become the standard or dominant design. Henry Ford’s Model T automobile is an often quoted example of just such a dominant design, where prior to its introduction, there existed a plethora of variations on horse-less carriages (automobiles). Innovators, including Ford, experimented in product features through variations in power plants, drive systems, brakes, and user interfaces. Very few of these designs were sold. But with the introduction of the T, automobile
sales skyrocketed and millions of Ford’s “T” design were sold ushering in the modern age of mass production.

As the dominant design captures the dominant need of the market at a point in time, competition among related product firms will move from market-product fit experimentation to the efficient delivery of the dominant design. Post-dominant design innovations are more closely focused, usually around efficient delivery and broader acceptance of the dominant design. Abernathy and Utterback call this the “transitional phase” of innovation in that the process is moving from fluid and confused, to more structured and specific.

Innovation in the transition and post-transitional (specific) phases is characterized by improvements in the processes of production and market penetration. Firms explore innovations which lower cost, increase reliability, and compatibility with other needs. Exploration and development of market segments fits into this category as firms may explore the correlation between market demand and variation of product attributes around the dominant design paradigm. Firms may innovate within the post-dominant design domain (transition phase and specific phase) to exploit untapped market opportunities, niche markets (Abernathy, 1978) or in what Utterback calls “Sales Maximization.” These innovations help the firm conserve and strengthen its established competencies, designs and dominance (Hamel, Prahalad, 1989). (See section 2.3)

Process innovation is a critical ingredient in industries where the basis of competition may be around cost. Approximately half of the improvement in performance stemming from a radical innovation originates in the post-dominant design phases. This incremental innovation also accounts for more than half of the economic gains derived from a given innovation (Utterback).

The industry as a whole may also undergo a transformation following the introduction of a new dominant design. Firms who entered to compete in the fluid phase may exit in the transition and/or specific phases in an industry “shake-out” as they find they are ill equipped either in competencies or capital to produce the now popular design in economical volumes.
Another class of firms is vulnerable to a shake-out during the transition phase: firms whose product or service is being rendered obsolete by the new dominant design. Buggy whip firms are the classic case in point. Buggy whip makers saw their market disappear overnight because of an innovation in a related field: the horse-less carriage industry. With the introduction of the Ford Model T, demand for horse drawn carriages disappeared and buggy whips with it. Innovation can cause significant “collateral damage” in closely related industries such as is described in the computer Winchester disk drive industry (Christensen & Rosenbloom, 1995) where the emergence of new computer architectures obsoleted the previous dominant design and related components along with it. Bower and Christensen (1995), introduce a framework (described below in more detail) which provides some insight into this phenomena of collateral damage. They hypothesize that the damaged firm does not recognize the innovation as an attack on its business; such disruptive or “radical innovation is seen as lying outside a firms value network...”. Where value network describes a firm’s recognized, normal business activities and most importantly, its normal customers.

The Abernathy and Utterback model of technological innovation, describes the whole of pre and post-dominant design innovation as a “Life Cycle” where significant innovations are born in the “fluid phase”, attain maturity and displace
others in the "transitional phase" and competition lacking, live a long, profitable life in the "specific phase." Of course, competition is never lacking for long, especially if there are "economic rents" to be earned.

2.3 Linking Innovation and Core Competencies

Subsequent work in technological innovation has introduced additional dimensions of investigation. In particular, work has centered around what effect innovation within firms and industries has on firm competence and linkages between the firm and its markets, (Henderson & Clark, 1990). In general it has been widely recognized that some innovations disrupt, destroy and make obsolete established competence within the firm, while other innovations may refine and improve firm competence (Abernathy & Clark, 1985). From the Abernathy & Utterback model perspective, competency disruptive innovations are those which attack a post-dominant design firm from the fluid phase. Conversely, those innovations which enhance firm competence originate from same-phase competition (both fluid phase for example).

Henderson and Clark describe an innovation framework in which the firm’s organizational learning limits its ability to address competitive innovation which originates in the same phase. They introduce a finer division of innovation and describe a four quadrant structure consisting of incremental, architectural, modular, and radical innovations, each occupying a quadrant of a grid. The grid maps variation of concepts along the X axis, and variation in linkages between concepts and components along the Y axis.

This framework is reminiscent to one proposed earlier (Abernathy and Clark, 1985) where variation in firm competence is along the X axis, and variation in linkage between the firm and markets is along the Y axis. Both these frameworks are useful in practice as each quadrant not only categorizes a different innovation domain, but also different managerial environments.
Henderson & Clark focus on the role of communication channels, information filters, and problem solving strategies in managing innovation. They posit that innovations which alter the architecture of a product without changing its components may destroy the usefulness of the architectural knowledge of established firms. Architectural innovation is defined in this context as changes in the way components in a product are integrated together into a system with its target market remaining largely unchanged. Thus, in the Henderson and Clark
framework, a novel architectural configuration of existing components addressing existing customers represents a new and potentially disruptive innovation.

It is not clear how architectural innovation fits with Abernathy and Utterback's fluid / transitional / specific phases of innovation. If one assumes the architectural innovation addresses new market needs, the two models are consistent, however it appears that a strict adherence to Henderson and Clark's contention that the architectural innovations address unchanged market needs results in a contradiction. This author suspects that if the market were truly unchanged as Henderson and Clark posit, the basis of selection between the innovation and the existing product would be indeterminate, and the architectural innovation would not result in reversal of firm dominance. It may be that the architectural innovation is behaving much like a fluid phase innovation (radical/disruptive) in that it is addressing a significant, latent need in the market.

2.4 Linking Innovation and Markets

One particularly interesting stream of research into technological innovation looks for explanation of the failure of existing, strong and often leading firms when confronted with all but the mildest of innovations. Christensen et. al. have collected a rich data set covering the evolution of the Winchester disk drive industry over the past 30 years. They build on the concept of a value network and describe the effect that the network has on a firm's view of innovation.

The value network is defined as the context within which the firm competes and solves customer problems. Incumbent firms led in the innovation of new technologies of all sorts "...as long as technology addressed customer needs within the value network in which the incumbents competed," but failed in adopting technologies which addressed user’s need in different or emerging value networks, (Christensen & Rosenbloom, 1985). They argue that "...the firm’s competitive strategy, and particularly its past choices of markets to serve, determines its perceptions of economic value in new technology that in turn shape the reward it will expect to obtain through innovation."
Failing to adopt innovations which address user needs outside one value network would not necessarily foretell of incumbent firm distress. However, within a framework describing the attackers advantage (Foster, 1988), technologies do not follow parallel development trajectories in performance space. Foster posits that the rate of improvement in performance of a given technology would follow an S trajectory in linear, performance space (effort as independent variable, performance as dependent). First improving slowly with initial investment, building to a peak rate of improvement, then falling back off with continued investment in a maturing technology.

![Graph showing Technology A and Technology B trajectories](image)

**Figure 2.6 Foster's S Curve**

Development of other technologies would follow similarly shaped curves, but would be offset in performance space. Further and perhaps the most interesting for our study is the potential for curves to intersect. The offsets reflect fundamental performance differences in technology, while the intersection of curves represents a reversal of rank ordering of return on investment (ROI). The curves drawn by Christensen and Rosenbloom are similar to the Foster S curve but plot performance vs. time in semi-log performance space, which has the effect of smoothing the lower portion of the S into a straight line.
Figure 2.7 Christensen & Rosenbloom Technology Trajectories

Key to practical application of the Christensen value network framework is the notion of a rank ordering of performance attributes within a given network. Different value networks will prize different performance attributes. In the disk drive industry the rank order of performance attributes for the mainframe computer value network placed speed and storage capacity very high. Within the notebook computer value network, power consumption, ruggedness and price are among the most important.

The path innovation will trace out in performance space: the “technology trajectory” will lie between two limits defined by the performance demanded over time within a given value network and the performance technologists are able to deliver. If the performance technologists are able to deliver exceeds the demands within their traditional value network, the option to address superior value networks is available. Since the superior value network may offer superior margins, it is an attractive proposition for the innovating firm to “attack from below,” thus becoming disruptive.
This attack from below in performance space has been the dominant mode of competition within the disk drive industry over the past 5 technology generations. Examples are also available from the automobile industry (Honda and Toyota attack Mercedes and BMW), and the reprographic industry (Canon attacks Xerox), and in the case presented in section 3: computer-aided rapid prototyping attacks traditional model making. In all these examples the competitive and market environment faced by innovating firms required them to aggressively innovate to improve product performance and sustain firm profitability. Having achieved greater performance in lower margin markets enabled them in turn to migrate their innovations up the value space to reap greater rewards in higher margin markets.
"...at rare and irregular intervals in every industry, innovations appear that command a decisive cost or quality advantage and that strike not at the margins of the profits and the outputs of the existing firms, but at their foundations and their very lives." (Schumpeter, 1942: 84),

3.0 The Established Technology: Model Making

The established technology which was the object of disruption in this case was craft-based model making and fabrication of engineering prototypes. Traditional approaches to model making and prototyping are generally subtractive, that is they are descendants from carving and sculpting. Traditionally, a desired shape is captured in a drawing (a two-dimensional, engineering drawing) which defines the shape and size of the object to be built. A skilled craftsman interprets the symbols on the drawing, and transforms his interpretation into material form. This is often performed via a metal working machine-tool in which a block of metal is carved via special techniques to arrive at the desired shape. Originally, designers would draw or “draft” their ideas into engineering drawings which were then given to model makers. Computers were later introduced to aid in the generation of drawings: Computer Aided Design or CAD. Use of CAD offered more rapid iterations of design evolution and less repetition of mundane tasks as well as broad data/design sharing across and between entities. The physical model or prototype fabrication step remained more or less unchanged.

3.1 A Disruptive Innovation: Stereolithography

In 1986, a radical innovation was introduced to the Computer Aided Design world: it was called Rapid Prototyping (RP). Briefly, RP is a technique for transforming digital CAD data, directly into physical, three dimensional form. The technology is distinguished from traditional prototype fabrication techniques in that it accepts the digital design data directly, transforms it into machine instructions and builds the object all without human intervention.
3D Systems Inc. was the pioneering firm in RP field with its introduction of the Stereolithicography (SL) process in 1987. Other innovators followed shortly behind 3D Systems. A new industry grew out of the technology, complete with its own trade groups, specialized language, and academic research groups. Perhaps because of its early entry, and the lead it established in technology development, 3D Systems’ SL technology is the most widely used today. 3D Systems has approximately 40% market share and 60% of all RP equipment is based on SL. An industry paradigm was also emerging. Initially, RP was a tool for aiding in the visualization of designs. Subsequent process development has improved the accuracy, robustness, and applicability of the models. Today, it is often employed in design validation (functional testing), and in producing the end product, either directly, or in producing intermediate tools which in turn produce the product. RP equipment has become larger, faster, more complex, more capable, and more expensive.

Not more than 8 years after its invention, RP itself was faced with an attack by a disruptive innovation: Convenience Modeling. These new RP machines were simple, safe, easy to use, and could operate in an office environment (until that time, RP equipment was found in laboratory settings only.) Most importantly, because of their simplicity, convenience modelers cost substantially less than that of the established RP machines. At first, these early, low cost machines were not considered serious threats by the industry leader: 3D Systems. Not until another industry leader: IBM, offered its version of a convenience modeler did 3D Systems recognize the innovation as real and significant. Convenience modelers became disruptive innovations to those firms producing RP equipment at the time.

The following is a history of the original RP innovation by 3D Systems, a description of the industry that grew up around it, the attack it underwent by a new, disruptive innovation and 3D Systems’ response.

### 3.1.1 Stereolithicography and 3D Systems

3D Systems Inc., founded in 1986, pioneered the development and commercialization of the first Rapid Prototyping (RP) technology called
StereoLithography. StereoLithography can be described as three-dimensional laser printing. The process produces solid, tangible, three dimensional copy (plastic models) direct from digital data. StereoLithography is an extension of the photolithography process found in the semiconductor device industries. Interestingly, the inventor of StereoLithography was developing ovens for photo-curable printing inks when he experienced his “ah ha!”

As in photolithography, a uniform layer of photopolymer material is selectively exposed to a directed source of energy (in this case ultra violet light). Wherever the polymer is struck with sufficient light, it solidifies, while the unexposed polymer remains fluid. The layer in process is very thin, perhaps one tenth of a millimeter. Following exposure, the surface of the solidified polymer is re-flooded with a fresh, fluid layer (again one tenth of a millimeter thick). Another exposure of UV light is applied, selectively solidifying a new layer of polymer and also bonding it to the previous, solidified layer. The process is repeated, until the entire “object” is built up from solidified layers. The additional term “stereo” added to lithography is meant to highlight the additional dimension added to the traditional, photolithographic technique.

As mentioned above, the invention of StereoLithography occurred during the development of an “oven” for photo-curable inks in the early ‘80s. The inventor, Charles Hull, noticed that the inks upon exposure to the UV light, would solidify into a raised form (out of the plane of the printing surface). He speculated that sequential layers of the UV ink, printed, exposed, printed again, one on top of the other, could be built up, creating an object in three dimensions. StereoLithography is invented.

What followed was a number of years of experimentation around techniques to implement the basic concept of sequential printing and exposure of UV curable polymers. Various configurations of printing, and UV light exposure techniques were attempted. First, the intent was to reduce the invention to practice for the purposes of filing for patent protection. This accomplished (in 1986) and backing secured for building a commercial prototype, attention focused on developing a robust product architecture around commercially available modules and components.
The first, proof-of-concept prototype employed an arc-lamp UV source, a fiber-optic cable conveying the light up to a \textit{X-Y} pen plotter positioned focusing optic suspended over a vat of photopolymer. The solidified layers were carried and positioned relative to the free liquid surface via a motion system working orthogonal to the \textit{X-Y} plane: the \textit{Z} axis. These were all modules "borrowed" from other laboratory appliances, and not specifically invented for StereoLithography.

Subsequent prototypes employed a largely new architecture. A laser replaced the arc lamp. Instead of a fiber-optic bundle feeding an \textit{X-Y} positioned optic, the laser beam was "pointed" at the polymer surface via two, orthogonally arranged, galvanometer driven mirrors. Optics located between the laser and the "galvos" focused the laser light to a small diameter. Focusing the laser to a small spot enabled "drawing" small features and sharp corners of the object. The \textit{Z} axis was as before. With the addition of an enclosure, computer controller, and power...
supplies, this machine became the first product offered for sale by 3D Systems. It was called simply: “SLA-1” for StereoLithography Apparatus #1.

![Image of SLA-1](image)

Figure 3.2 SLA-1 From 3D Systems “The Edge”

As with many “inventions” much of the components and modules of the SLA-1 were borrowed from existing products and equipment. The way they were combined, the architecture of the SLA-1, however was truly novel and represented a first-of-type expression. Innovation did not stop with a physical prototype. Making an SLA function required much more than assembling physical components. Determining the exact order of process steps and coordination required of each component and module within the SLA-1 had yet to be accomplished. The study, understanding and controlling of the interplay between these newly introduced modules making up the SLA would become arguably the greatest strategic advantage 3D Systems would develop. The firm’s expertise in the process of StereoLithography has allowed it in subsequent years to effectively compete with new, and strong entrants and maintain a large market share. A few of these competitors (Sony, Mitsubishi, Du Pont) are well known for their abilities. Many of these and other competitors have entered the market offering superior module, and/or component performance, but 3D Systems has held its lead in the market with superior system (architectural) performance.
The basic architecture of the SLA survives to this day, as does SLA-1 Serial #1, which can be seen on display at the Ford Museum in Dearborn Mi.). A great deal of incremental, component and modular innovation has taken place to arrive at the current generation of SLA’s. Some of the innovations have been a direct result of 3D Systems’ efforts, others have come from outside in the form of component and module supplier initiated innovations. Together, these innovations have transformed the quality of the models and their value in the market. The models from early SLA’s were at best, rough approximations of the digital data. Incompatibility of the different modules and process steps resulted in distortions and anomalies in the model. All too often there was outright failure of the SLA to produce a model at all. Build failures were referred to as “rats nests” due to their visual appearance.

Today, the accuracy and usefulness of an SLA model rivals that of traditionally produced prototypes such as CNC machining of aluminum. SLA models, for example, are preferred over traditional methods for use as patterns in short run, complex investment castings. SLA’s come in three basic sizes or platforms, and within each platform, offer a different mix of system performance.
Figure 3.3a   SLA-190

Figure 3.3b   SLA-250

(From WWW.3D.Com)
3.1.2 Lead Users

When StereoLithography was first introduced, there was considerable excitement about it. It was featured on TV and in magazines (Commercial TV: Good Morning America; on PBS shows: Robert Reich's "Can America Compete?"). Demand for the SLA-1 was quite strong. A small batch of machines was built and shipped to hand picked customers. Most, if not all the lead users were large, rich, progressive organizations. The SLAs found their way into laboratories and departments of these organizations responsible for testing the frontiers of commercial technology. Generally, a respected technical person within each organization was assigned full
time responsibility to bring SL in to the organization, own it, and evaluate it. These individuals tended to be self-selected, and highly motivated to succeed.

At the time, the US industrial base was undergoing somewhat of a self-esteem crisis. Many were convinced that US industry had lost its one-time lead to Japanese and German competitors in the technological innovation race. Offering its innovation at this time, with the accompanying national sense of urgency about “catching up” in technology, may have aided 3D Systems in gaining such broad support within large, established, and traditionally conservative organizations.

The Beta customers (as these early users were officially called) were either officially tasked by their organizations to explore and try out new design and manufacturing tools, or were entrepreneurs within these firms and managed to sell their management on the value of exploring the new technology. Computer Aided Design was a hot area (much like the Internet is today) that was beginning to really take hold in the most progressive manufacturing businesses in the US. StereoLithography represented another, exciting new development in the area. Most of the new computer aided design and manufacturing technologies had steep learning curves for both customer and supplier. There may have been a feeling that if one wanted to stay on top of the wave of technical innovation, each new promising approach had to be evaluated.

The emphasis for all concerned, 3D Systems and the Beta customers, was on exploring the space, to see what it could do, find its weaknesses, and fix them. Universally, all wanted to see it succeed and become a valuable tool. Among the basic questions yet to be answered were:

- How to import the digital data from all the differing sources and formats in use
- What interaction was necessary between the SLA and the user?
- What were the performance limits of the process?
  - Accuracy
  - speed
  - reliability
- How toxic was the photopolymer?
- What could the models be used for? (the search for value)
An informal technical partnership formed between lead users of the technology and 3D Systems personnel. The developers were eager to learn from the users what they thought of the technology. In the opposite direction, the user community was eager to find value in the new technology and were encouraged by the rapid pace that 3D Systems responded to their input. The Beta customers were exploring rapid prototyping, providing feedback to the technical staff at 3D Systems about problems encountered. The technical staff in turn would incrementally modify the SLA to address these problems, and on it went. Through this close interaction, users and developers formed personal relationships. A officially sanctioned users group was formed by 3D Systems and held regular meetings to facilitate the sharing of learning and to provide a communications channel to its customers.

3.1.3 Commercialization

A major revision in the SLA-1 was undertaken as a result of beta customer feedback. The revised product was labeled the SLA-250. The number was officially said to represent the millimeter dimensions of the largest object which could be built within the machine. Unofficially, it was to remove the connotation of how many products had been produced by the young firm (SLA-2, SLA-3, etc.).

3D Systems proceeded to develop a commercial product based on the SLA-1 incorporating many of the attributes suggested by the beta customers. In general the requested features provided for ease of experimentation. Greater access was provided for changing operational parameters in the software. The product was tailored for the technological explorer: great variability and flexibility in operation, very complex, un-automated. Beta customers had become experts, specialists in the new technology. They even called themselves “StereoLithographers.”

A product launch was organized, a sales force assembled, and StereoLithography was offered for sale to the general public. Following an initial flurry of sales upon introducing the SLA-250, volume dropped off precipitously. It was not possible that the entire market had been saturated at fewer than 25 units. A survey was commissioned to find out what was inhibiting sales. The consultants reported back with a long list of deficiencies which the new SLA-250 owners/operators had
reported were limiting the value of their new SLA’s and thus inhibiting their ability to recommend the product. The survey reported that StereoLithography was an interesting technology, but had little application in the customer’s commercial operations. The machine was too complex, too difficult to operate, too many parameters to juggle. The models produced were not accurate enough for the applications required. Interestingly, many of the same product attributes the beta customers had found so useful, were not appreciated by the new customers.

New development programs were launched by 3D to address each problem raised by the survey. Engineering projects to fix each deficiency were organized, staffed, and tracked. Two years later, the last project addressing the list was completed. Sales of SLA’s rose steadily. It is not known how strong the correlation was between the change in sales and fixing the deficiencies, but 3D management felt it was high.

The beta customers for the SLA-1 wanted a different product than the commercial customers for the SLA-250 wanted. Eventually, 3D Systems leaned more of what the commercial market wanted and evolved their products to meet its interpretation of those needs. Over the ten years since the SLA-1 was first tested, 10 further iterations on the basic design have been produced. By 1996, over 600 SLA’s had been sold to customers throughout the world.

3.2 An Emerging Industry

The industry has formed into segments where different RP products hold different advantages and disadvantages. Briefly, use falls into these broad categories:

Functional prototypes: Used for physical testing and data collection in market tests etc.

Tooling forms: Used as input to other processes to arrive at a production tool

Form & fit prototypes: Used to check dimensional validity of design

Concept models Used to validate design concepts

Communication aid models. Used to communicate the design intent, idea, visual aids
The number of firms competing in the industry has been growing since 1987 with only two firms leaving. Both of these quit the industry under court order from patent infringement suits filed by 3D Systems.

Figure 3.4 RP Industry Population
The number of articles written with RP as their major focus has also been increasing over the years as the figure shows.
Unit sales in the industry have also been growing, but not uniformly. Sales dropped over 50% during a recession in 1991. The industry has fully recovered and total unit output has more than doubled each year since 1992.

As a further sign of the technology and industry maturity, groups have formed within academic institutions around the study and teaching of the technologies concepts.
(See appendix 2)

3.2.1 Du Pont

Du Pont had been experimenting in creating three dimensional objects from UV photopolymers since the 1950’s. Its efforts were concentrated on a single exposure through a variable density mask to form the solid, rather than the sequential, layered exposures that 3D Systems employed. Following 3D Systems' commercialization
of its process, Du Pont rapidly developed and began showing perspective "customers" a machine based on a Du Pont process called SOMOS for Solid Object MOdeling System. It was very nearly a direct copy of the now patented 3D Systems process; StereoLithography. Other copies of StereoLithography appeared from companies with familiar names like Sony, Mitsubishi, and from start ups: Quadrax, EOS, Qubital. 3D Systems exercised its intellectual property protection and successfully limited entry into the commercial market within the US, by any firm infringing its patents. (see appendix for a list of 3D Systems' currently issued patents).

A number of approaches emerged based on novel technologies which 3D Systems was unable to inhibit thought legal means and was forced to address serious new entrants to market.

3.2.2 Stratasys

A process called "Fused Deposition Modeling (FDM) was commercialized by Stratasys, inc. The process uses thermoplastic wire filaments which are melted in a robot manipulated delivery head and then extruded and deposited on a layer by layer basis. The process is sometimes likened to cake decorating, in that the extruded, plastic filament is drawn out on the surface of the building part much like a baker might write "happy birthday" on a cake. One great advantage of the process is the range of materials usable in the building of models, and the ease at which the material can be changed. Models can be built from standard "engineering" plastics and thus the models can not only represent the physical shape and size, but the mechanical properties as well. This enables the models to function like designed object. The process is uncomplicated, fairly compact, and does not require expensive lasers and optics. The major disadvantage is the coarseness of the extruded plastic bead which builds up the model. It is generally about one quarter, to one half of a millimeter in diameter which results in fairly rough model surface.
3.2.3 DTM

DTM (meaning of acronym unknown) uses a process called Selective Laser Sintering in which a layer of powder is fused (sintered) together with a high-powered laser. A fresh layer of powder is spread over the previous layer and the next model cross-section is fused by the imaging of the models cross section by the laser spot. This process has many similarities to StereoLithography except that the powder replaces the liquid, and the phase change is thermally driven. Powders employed are typical engineering plastics (ABS, Polycarbonate, etc.) such that the resulting models may inherit familiar physical properties and are often used as operational prototypes where physical robustness is important. Surface finish is not a strong point, and models from DTM machines are not commonly used in generating patterns for casting final product. DTM’s machines are large, expensive (lasers, optics, vector imaging system, environmental controls, etc) and complicated to operate. In many respects DTM’s process is the most similar of the new RP technologies to StereoLithography’s in the accommodations it requires of the user.

DTM has sold equipment into service centers, which typically have multiple RP machines, shared among users. Some of these service centers are captive within large firms while others are small entrepreneurial firms selling their services broadly.

3.2.4 MIT/Soligen

Another RP process is currently under development by the Massachusetts Institute of Technology called Three Dimensional Printing (3DP). In 3DP, a bed of fine powder is selectively bound together with a substance (binder) delivered via a ink-jet print head. In much the same layering process as StereoLithography, thin layers of powder are spread, an image of the models cross section is delivered in binder via the ink jet which “sticks” the powder together. Layers are added one upon the other until the full model has been imaged and is now encased in a bed of unstuck powder. The stuck-together powder (model) is removed, and the remaining powder falls away. The model, now in a green state is more permanently bonded
together using sintering or infusion processes. 3DP is currently being commercialized under license to Soligen Inc. and others.

Soligen is developing a machine which generates ceramic molds and mold inserts directly from CAD data. The initial market they are addressing is in “investment” casting so called because of the investment required in generating a mold pattern that is then sacrificed in generating a mold. Traditionally a positive pattern of the desired object is formed from wax. The wax form is dipped repeatedly into a ceramic slurry in order to build up a thick ceramic shell around it. Once a shell of sufficient thickness is deposited, the wax is removed by melting leaving a hollow shell which is an exact negative of the original wax pattern. A material of choice (usually metal) is then poured into the ceramic shell, cooled, and the shell broken away to reveal a metal copy of the wax pattern which started the process off. The process does not require expensive tooling and can generate very complex, and highly accurate parts. Many jet engine components including turbine blades are fabricated this way.

Investment Casting is a relatively expensive, labor intensive process and tends to be cost effective only in complex shaped objects of limited production quantity. Soligen proposes to short cut the production of the ceramic mold, making it directly from the CAD data, thus removing many of the slow, labor intensive steps but retaining the advantages of replicating complex geometry’s accurately in the material of choice.

Few Soligen machines have been sold to date. However, this author recently examined molds created using this process and was very impressed with their quality, physical properties, and surface finish. Soligen can offer a significant value proposition to the investment casing market.

3.2.5 Helisys

Helisys has developed an RP process called Laminated Object Modeling (LOM) in which the cross-section of the model under construction is cut from a thin film and the cut-out stacked one layer upon another. The typical film is paper, and bonding of films is usually accomplished with a pressure sensitive adhesive. The process is
very fast, and models are quite robust. Typically uses are for tooling patterns, especially for sand castings as the resulting model is very similar in look and feel to a wood form which is traditionally used in sand casting. The models are also easily modified after construction, allowing cutting off or grafting on of pieces. LOM equipment is relatively expensive again due to the requirement for a high powered laser, optics, imaging system along with the material handling and environmental control systems. Accuracy of LOM models has not kept pace with SLA and DTM processes and small, or delicate featured models are not easily formed.

In general, the RP paradigm has centered around bigger, faster, more capable machines used increasingly in production shops to speed the production of end-use products. This is often done through the use of RP equipment to produce patterns for tools, which in turn produce the end-use product. The machines are tended by experts, housed in special facilities, with limited access and often shared among many groups to amortize the high fixed cost over a larger user community. The technology is so expensive, the equipment has to be keep nearly 100% utilized to be cost effective.

3.3 Second Iteration of Disruptive Innovation: Convenience Modelers

Contrary to this trend, a number of small, modest machines began appearing either for sale, or in beta test programs around the early 90’s. These machines produced models which were of poorer fidelity (accuracy, finish, strength) but the equipment was easy to use, inexpensive, and suitable for placement in an office setting. Demand was weak initially, but the offerings in this product area improved very quickly. These new machines appealed to a completely new customer type. New names were used to differentiate between the two products. The traditional RP equipment became know as “Precision Modelers” reflecting their ability to produce very accurate, precise three dimensional representations of CAD data. The new, low fidelity modelers became known as “Office Modelers” or “Convenience Modelers” highlighting their different operational characteristics. The industry leader: 3D Systems paid little attention to these “novelties” at first as they were no threat to its traditional business. However, some within the company were reminded of the lesson learned by Xerox in the late 70’s and early 80’s. Xerox discovered that a small and seemingly insignificant competitor, entering the market
with a low-end product could turn into a real threat someday as Canon had done to Xerox in the copier business.

3.3.1 Sanders

Sanders Inc. introduced a convenience modeler in 1993. The machine was small, about the size of a desk-top laser printer. It produces models from a wax like material delivered from a two axis, robot positioned ink-jet. The physical configuration is very reminiscent of the first proof-of-concept prototypes built by 3D Systems when it was exploring the earliest incarnations of StereoLithography. A small, X-Y “pen plotter like” system positions the ink jet nozzle over the build area. A simple elevator or Z-stage maintains the building model the correct distance from the jet nozzle. The nozzle is vector scanned in the pattern of the model cross section under construction. The one novelty required for this ink-jet based modeling machine is the maintenance of an “image plane”. This is best explained using an example. Suppose a model of a coffee cup with a handle is building. The cross sections of the cylindrical “body” of the cup are imaged one upon the other in a building cylinder. After each layer is formed, the z-stage lowers the part one image thickness such that the next layer may be imaged with the Image Plane the same distance from the jet. Now comes time to image the handle. There is nothing underneath the handle but space. The jet can shoot droplets (image) the first cross section of the handle, but there is nothing there to stop the droplets: no image plane. They fall uselessly below forming a fine dust.

The solution invented by Sanders is to build an image plane along with the model. This is accomplished using a second jet, and a different material. The support material as it is called is automatically placed under any feature of the model which will later require support (an image plane). The support material is removed via a solvent which dissolved the support material but not the model material. This works quite well. The disadvantage however, is one the need for a secondary, solvent based process to extract ones model. And second, the need to image a second material adds more equipment (cost) to the machine, and slows down the model building process since not only must the model be drawn, but so must the support structure, and using a vector based imaging system, the time to image
grows linearly with number of vectors which grows exponentially with model cross section.

Sanders has positioned the machine as a low-cost, easy to use, office environment modeler well suited to low volume, small model shops. Their initial target market has been jewelers who use a scaled down version of the investment casting process to make custom jewelry. Since the models are formed from a wax similar to that used in the casting process, a piece of jewelry can be designed in CAD, built in a Sanders machine, and that model used as a from to cast the final metal item. Quick and hopefully easy.

3.3.2 Ballistic Particle Manufacturing (BPM)

Ballistic Particle Manufacturing (BPM) is an RP process again employing ink-jet printing techniques, but in this incarnation to deliver droplets of molten material from a 5 axis positioned single orifice print head. The model is built directly from these droplets. Very simple, small and potentially inexpensive. The process is still in fundamental development with only a hand full of machines in use at test sites. The models produced are of high quality, good surface finish, but very slow in formation. Given that the process employs one ink jet nozzle, delivering approximately 100 pico-liter drops at no more than 30 kHz fire rate works out to be no more than 10 milli-liters per hour of material delivered to the model building process. Not very rapid. But, this technology may find a home in low volume, price sensitive modeling markets where model geometry fidelity is critical. This technology has a unique approach to the support/image plane issue Sanders solved via a second support material. BPM positions the ink jet to fire over one \(\pi\)-steradian angles (half sphere). Thus in the case of the coffee cup, the jet is rotated horizontally and the overhang is formed directly. Solves the image plane issue in most cases, but is somewhat slow. This process possesses many if not all of the advantages that the Sanders process offers.

Despite the entry from these novel products, it appeared that the bulk of the RP industry was settling down to the business of incremental refinement, and evolution, around the supposed industry standard set by 3D Systems. The focus in product development was in higher accuracy, greater speed, and tailored model
functionality. DTM was testing a process which could produce metal models, either directly or through a simple secondary process step. Soligen was offering a process to create RP molds for metal casting. And 3D Systems was rolling out an improved process to create RP patterns for investment casting.

3.4 Traditional Technology Response:

3.4.1 Incremental Improvements

The traditional machining methods of prototyping should not be underestimated. Some advances have been made in this area, such as the introduction of the three-axis tabletop CNC milling machine by companies like Light Machines Corporation and Roland Digital Group. These systems will machine a block of material secured to an x-y table. The vertical spindle controls the z-axis. It machines materials such as ABS, Polycarbonate, composite, wax, wood, aluminum, and brass. Like the rapid prototyping systems, the three-axis tabletop CNC milling machines can accommodate 3-D CAD data in producing a prototype part. Tabletop CNC lathes are also available.

5.7.2 Hybrid Improvements

Other prototyping technologies which are fighting for market include spray metal tooling which is a process that lends itself to plastic molding. It is not a new concept, but recent improvements are noteworthy. The process begins with a model of the part to be molded. The model is secured on a parting surface and is sprayed with a sealer and release agent; this allows the metal-sprayed coating to stick better and provides easier release upon completion. Then electric arc spraying equipment, resembling a paint spray gun, coats the model with a kirksite- or zinc-type alloy. The spraying process is complete when a shell of desired thickness is achieved. The shell is then fitted into a mold form, and the back is filled. The type of backing depends on the type of molding process to be used. An aluminum-filled epoxy backing would be used for light pressure applications such as vacuum forming or reaction injection molding (RIM). A low-melt castable alloy backing can be used for injection molding
applications. The other half of the model is then put through the process. The use of RP systems in creating the model or pattern for this molding process has resulted in an even quicker turnaround time.
4.0 IBM and Rapid Prototyping

The rapid prototyping industry was stabilizing around the development of higher accuracy, greater speed, and tailored model functionality. More RP firms were focusing their development efforts on automating a greater number of steps between the designer (working in CAD) and the production of the end product. There were of course the activities of Sanders, BPM and others around small, simple, low-cost modelers, but in general they were looked upon as toys by the "established" RP firms. That is until one day.

A new, powerful, competitor was preparing to enter the RP fray, and their machine was not a high-end, "precision modeler" but a low-end, "convenience modeler." The new entrant was IBM. Word of an RP machine from IBM reached 3D Systems in early '93. This new entrant was a serious company. IBM already had significant product presence in the CAD industry (CATIA software). This new venture by IBM could signal the RP industries first forward integration.

The IBM RP process was nearly identical to that of Stratasys Inc. (see section 3.2.2) save a more professional execution and greater focus on computer integrated control and data processing. The technology was an outgrowth of an effort at IBM to build robots for pick-and-place of components onto printed circuit cards. The robot placed a controlled amount of "glue" on a controlled spot on the PC-card where the electronic component was to be positioned and held in place by the glue during soldering. The IBM researches observed that by repeating the same glue operation, the robot would build-up a 3D shape with the glue. Ah ha! A computer controlled robot extruding glue could make 3D objects.

4.1 3D Systems Responds

When 3D discovered IBM's effort, it was not just getting started. IBM had already placed evaluation prototypes with a number of 3D Systems' leading customers. 3D
Systems would not ignore the convenience modeler threat any longer. It recognized an attack of some kind. It was not clear how 3D should respond. What was the nature of the IBM threat? Clearly a large component was that it emanated from such a powerful company. IBM was already or could quickly bring greater resources to their effort than all the other RP firms combined. IBM had greater sales, distribution, manufacturing resources to bring to their project as well. 3D Systems was very small and ill equipped to confront such a competitor along one, let alone multiple dimensions.

3D Systems chose to focus its efforts and respond along what it felt was its most advantageous dimension and what it suspected was most important in the market: model quality. 3D Systems suspected that IBM’s technology would be slow to improve along this critical market dimension. It was further determined that the IBM technology was most superior to 3D’s as to its cost. IBM’s was fundamentally such a simple approach, no laser nor optics or environmental control. The IBM machine could be produced and sold for much less than 3D Systems’ products. However, 3D knew what the market demanded: high quality, application specific models. Thus, management determined that the cost of producing a high quality, high functionality model would be the basis of competition between themselves and IBM.

Interestingly, 3D Systems did not view the IBM product as offering a fundamentally new value proposition to the market. It did not seriously consider whether the combination of low cost, ease to use, small, unobtrusive, quick, limited application models represented a new and potentially lucrative market which 3D Systems had ignored? 3D Systems however that IBM’s technology would improve and potentially become a direct threat to markets 3D currently served.

4.1.1 Component Innovation

A rush study was conducted under the direct guidance of 3D Systems’ president Chuck Hull. The purpose of this study was to determine how inexpensively an SLA could be produced given complete freedom to redesign any and all components making up the then, least expensive SLA. The best designers from
each functional area were assigned to the study and were relieved of all other commitments.

Included in the study were detailed and lengthy discussions with key component and subsystem suppliers to investigate clever combinations and team efforts which could lower the cost of supplied components and subsystems. The result was an accurate estimate of the lowest cost design for producing an SLA given known technology, expected volumes and realizable development efforts. The cost was still twice the target cost. The low cost SLA effort was abandoned.

4.1.2  Modular Innovation

With no success at meeting its cost goals employing component redesign, the scope of the effort was escalated to include consideration of wholly new subsystems combined in new ways to arrive at the same end-product: The objective of the innovation effort remained unchanged: a low cost, RP technology capable of producing SL quality models.

A substitution of the most expensive subsystems within the current architecture SLA was attempted. The imaging subsystem represented the greatest cost component in the SLA (the UV laser and the galvanometer driven mirrors). It was replaced with a lower cost an ink-jet print system. The laser and “galvos” were responsible for “imaging” a cross section of the digital data on the surface of the liquid photopolymer. The image defined where the liquid polymer would solidify. Ink-jet was chosen because of it was relatively inexpensive, less than laser based imaging by a factor of about 10.

The replacement of the laser based imaging system by an ink-jet system however presented a formidable challenge to the group. Ink jets deliver fluid not photons. Replacement of the laser with an ink jet required a redesign of the chemistry for converting the liquid polymer into solid plastic. A new chemistry was found, based on a catalyzed, two part reaction where a fluid vat of polymer is solidified when a catalyst is delivered from the ink jet. Thus, the ink jet could “image” the model cross section in catalyst.
The president of 3D headed this team as well. He reassembled those individuals working at 3D Systems, or willing to return, who helped originally develop StereoLithography in the mid 1980’s. The team members were relieved of all other responsibilities and physically isolated to concentrate on developing the next version of StereoLithography. The project was kept secret from most of 3D’s employees, and all outsiders. It was felt that the new technology could result in significant proprietary knowledge and patents.

Work continued for over a year, and made little progress. The models produced via the catalyzed, ink-jet imaging process were terrible. The model shapes were nearly unrecognizable. The project failed to develop a commercially viable technology which could address the threat from IBM. Activity in the group decreased, and team members began to work on other projects. 3D began to shop for an outside RP technology to purchase. There were a number of firms marketing low-cost modelers which could be absorbed by 3D Systems and developed into a low-cost product.

4.1.3 Architectural Innovation

Having exhausted their creative resources, the project team began to disclose their work to others within the technical departments. A self selected “gorilla” group formed and began experimenting after hours with an alternate approach. This self-formed team pushed out the rule boundaries of the problem space, they were allowing more of the StereoLithography paradigm to be called into question. Rather than attempt to adapt StereoLithography to an ink-jet, the gorilla team began looking for an approach, incorporating the cost advantages of ink-jet imaging, but consistent with its limitations. The gorilla team decided to try building models from ink, not polymers.

This approach obtained promising results very quickly. In a few weeks a new project effort was formed. The new team incorporated the gorilla team and was placed under the control of the line manager responsible for executing evolutionary innovation within the SLA product class.
The project was organized to accomplish two simultaneous goals:

1) Invent the technology and develop process understanding in ink-jet printing based RP.
2) Design a product based on the as yet undefined technology

This ambitious, twin charter for the team was largely a result of lost time from previous failed efforts. Other competitors in the convenience modeler market had been progressing with commercial efforts while 3D had been experimenting. IBM of course had been progressing on their product development and commercialization efforts. Their beta program was winding down and they were preparing their product's commercial release. Sanders was now selling their product and Stratasys was showing a "desk-top" version of their product targeted at the convenience modeler segment. News was coming from Japan that there too were efforts to commercialize a convenience product.

3D had given up on one of the major dimensions it planned to compete with IBM along: it would not be building convenience models with the same attributes as StereoLithography models. The models from the new process had few of the physical characteristics found in SL models. They were soft (the jetted material was chemically similar to paraffin), and fragile. A model would be destroyed simply passing it between a few people. Conventional wisdom at 3D held that models had to be accurate, durable, stable, etc. to be accepted in the market. (see section 3.1.3). People began to ask: what would these new "convenience" models be good for? What value would the market find in them? From this debate, a picture emerged about how significant a change the new technology represented and perhaps, for the first time, the threat from IBM could be seen along more value dimensions than price alone. These new machines were not only less expensive, and easier to use, they were not going to be useful in the same way that SLAs were. A new market understanding would likely be required to accompany the new technology.
4.1.4 Marketing

The fundamental product innovation that was emerging from 3D Systems’ cost cutting effort was beginning to look as if it would require a new value proposition to the market. The mode of use for this product could be quite different from any currently sold by 3D Systems. Fundamental concerns about the nature of the change were considered. What value might the new machine offer traditional customers or what new customers would find the new product valuable? Since the machine was still in the early stages of development, marketing could have an impact on its development, if it acted quickly.

Marketing staff were dispatched accompanied by members of the development team to explore the value space with existing 3D Systems customers. Marketing’s operational perspective was to find the optimum product benefit mix to position the new offering to both effectively compete with IBM’s expected offering, and to compliment the existing SLA product line. A set of product expectations were developed. The expectations were very ambitious.

- Product to be delivered within 12 months
- Sale price of $50K
- Larger model size than mid-sized SLA-250
- Twice the building speed than SLA-250
- Small enough to fit on a desk-top
- Initial production volumes in the 100’s/year

The convenience modeler was envisioned by marketing as fitting into existing SLA customer operations. It would provide the same service as SLA’s had in their earliest days: that of checking the validity of CAD designs. To be cost effective in this role, they had to be fast, inexpensive and easily accommodated in a design office setting. Marketing did not investigate non-traditional or new types of users for the convenience modeler.
4.1.5 Results

The basic approach that emerged for 3D's new convenience modeler is quite similar to that used by Sanders, with some important differences. The Sanders machine is simple but slow due to its single ink jet and it's minimal material delivery rate. 3D devised an architecture that allowed for simple scaling: the addition of more jets, many more jets.

An array (initially linear later 2 dimensional) jets down. The array is scaleable as needed in multiples of 100 jets. The model cross section is generated via a scanning of the ink jet array in a raster pattern. Imaging time decreases with the number of jets in the array, and increases with the model cross section (area to scan). Thus, as larger model building sizes are desired, the product architecture can be easily scaled by adding more jets to the array to render imaging time unchanged. Similarly, more jets may be added to the array for a faster, more expensive product, and conversely, jets may be removed for a slower, less expensive product.

Figure 4.1 Actua 2100, A Convenience Modeler from 3D Systems
The resulting convenience modeler, now called the Actua 2100 built upon the new Multi-Jet Modeling (MJM) technology went into beta test in late '95 and expanded over the next 6 months to include 6 test sites. The product met or exceeded many of its original performance objectives. It is extremely easy to use, fast, and totally compatible with an office environment. The surprise, is that the models are extremely accurate but extremely delicate. The ink used to build models is not the best structural material. Models tend to disintegrate during handing. Small details and features have a very short life. The biggest disappointment of the program came when the cost of the new machine was calculated: it was still too expensive.

Still driven by a strong commitment to price competition with IBM, a second iteration of the product design was initiated before the beta machines were finished. The "commercial" units as they were known were re-specified to greatly reduce the cost of manufacture. As of this writing, the commercial units are under construction, with the estimated cost approximately half that of the Beta units. Their performance is estimated to be similar to the Betas, and to date, these estimates look correct.

IBM's never offered their RP technology to the general market. The technology was sold to Stratasys Inc in 1995. Stratasys has since brought it to market under the name: The Genisys 3-D printer.
5.0 Customer Context

Although managers like to think they are in control, customers have considerable input into a company's technological innovation activities. Managers naturally look first to their customers, their familiar markets, to ask: what would you like? How many would you like? When would you like it? These questions are appropriate for a development effort focused on existing markets, but is this the only line of questions a manager should be asking. Are there other markets she can compete in using her firm's knowledge base (core competencies)? Are there emerging or developing technologies which will attack her markets that she should be watching out for? Are there technologically unrelated developments which will radically effect her markets? The answers to these questions are difficult to find, but one thing is almost indisputable, the answer is never no! There is always a threat, some emerging technology or trend which will alter a firm's competitive landscape.

Christensen et al (1992, 1995) looked at the computer hard disk drive industry spanning 30 years, and found that the top firms serving current markets always failed to recognize the emergence of a new market for disk drives incorporating novel architectures and performance features. Dominant firms were displaced by new firms investing in new technology addressing emerging markets. This is a disturbing result especially considering that these same, dominant firms were not slow in recognizing and using new technologies. In some cases the dominant firms actually led in the development of these new technologies but failed to utilize them in new ways. The leading firms failed to recognize the new technology served a new market which had different needs. These emerging markets often appear unappealing: they offer lower margins, lower volumes, and serve unfamiliar (risky) market segments. Worse yet, they may be markets into which the firm's current products sell, but perhaps not effectively.
5.1 Emerging Markets

The firms which choose to go after these new, unappealing or emerging markets are often small and less able to compete in the dominant markets. They are firms willing to take a fresh look at the needs of the market and try a new approach. The threat to the dominant firm comes when the new entrant gains experience and competence in satisfying the demanding needs of the emerging market. The new firm may soon learn how to satisfy the needs of the dominant market as well, usually at a lower cost. If this happens, the new firm quickly displaced the old. A paradigm shifts.

Christensen found that “...processes and incentives that companies use to keep focused on their main customers work so well that they blind those companies to important new technologies in emerging markets.” (Christensen & Rosenbloom, 1995).

It would be one thing for the dominant firm to give up a potentially profitable, emerging market in favor of a its more familiar, stable market but often it not only forsakes the emerging market, it looses the current market as well. To understand how this happens, Bower & Christensen, (1995) use the concept of technology trajectories, which describe the rate at which the performance of a product improves, and is expected to improve over time.

5.3 Technology Trajectory

Technological innovations affect performance trajectories in different ways. Incremental innovations tend to sustain a current trajectory (maintain constant growth). Radical or architectural innovations introduce a different mix, a different relationship between performance and investment resulting in a change in the trajectory slope. The new technology may initially start below the sustaining technology trajectory but rise steeply.
The lower starting point (lower performance) of the innovation make it ill suited to address the market being served by the dominant technology undergoing incremental innovational improvements. The developer of the "new" technology is compelled to find a new market, one which values the particular attributes of the new technology. However, once established in an emerging market the new entrant has every incentive to improve his technology since a greater market is calling, that which is now served by the older, dominant technology. If the performance potential of the new technology is greater than the old, its performance trajectory will not only meet, but exceed the old. The new firm having started with a more demanding market with perhaps lower margins has not only developed a new technology, it has also learned more cost effective ways to bring it to market. This double performance gap facing the established firm is too much and they are often forced to exit the market. Innovations which behave in this fashion are termed "Disruptive" for obvious reasons.

Perhaps the most disquieting result of Christensen's work is that even those firms which were champions of a disruptive technology in one generation became the defenders in the next as they fail to "look below." Instead, defenders focus their efforts at current and "up-market" opportunities. Innovators had not learned the
lesser themselves had taught and the next generation of technological innovators were soon displacing them as well. Why do firms behave in this way? Christensen uses the framework of the firms value network to help explain (Christensen & Rosenbloom, 1995).

5.4 The Value Network

In general, the value network is the firm’s context of operations and in particular the context of its relationship with its customers and most specifically it is the context in which the firm addresses its customer’s needs. The definition of value in the eyes of both customer and firm is derived from the technological paradigm in use. Put another way, what can be imagined is limited by what is known. It is only during times of tumult and uncertainty, that the definition of value comes under scrutiny.

Value in these networks is relative in that value is rank-ordered. In particular the metrics for assessing value will differ between networks as will the assessment of performance attributes. Each technological paradigm serving a value network will be organized to best serve the rank ordering of performance value within that network. Further, “The scope and boundaries of a value network are set by the dominant technological paradigm and the corresponding technological trajectory employed at the higher levels of the network.” (Dosi, 1982)

What does the value network concept contribute to our understanding of the emergence of innovative technologies and their effect on markets? First, the position an established firm holds within a given value network influences and may even define the innovation opportunities perceived by the firms management. Christensen argues that both the perceived attractiveness of a technological opportunity and the degree of difficulty a producer will encounter in exploiting it are determined by the firms position in the relevant value network (Christensen, 1992). As firms gain experience, they are likely to develop their capabilities and cultures to best fit that position and meet that networks distinctive requirements.
5.5 Rapid Prototyping and Value Networks

I will examine the RP industry, and 3D Systems behavior in particular in the framework of value networks described above in the hope that such an analysis can provide insight into the action of both the defender in a mature market and the attacker in an emerging market.

5.5.1 Context

The overall value chain applicable to RP is that which connects the designer of a product with the consumer of that product. The network encompasses the designer, his tools, methods, etc. It involves the entities that realize a design which include model makers, machine shops, and various fabrication and manufacturing concerns. An expended network might involve the advertisers, the transporters, the retailer and post sales support organizations. For the purpose of this thesis we will restrict our consideration of that part of the value network responsible for generating the consumable, purchasable object.

The design process itself has and continues to evolve multiple intermediate steps leading from idea to product. A designer must first synthesis the product and manufacturing requirements and constraints into a design concept. The design concept is reduced to some transportable representation and shared among interested parties. After the concept of the design has been determined, a detailed design is fashioned. The detailed design will contain all the information and specification to realize the design concept at least in prototype form. A detailed design always integrates with other designs and often the effective interface with other designs requires testing and verification. This is often done with physical prototypes or models. Design performance is also tested against specified performance using physical prototypes which realize the salient properties of the design under test. Testing may include obtaining preliminary user feedback in the form of market tests. Once the detailed design has been verified as acceptable, a means of production must be devised. Tools to produce the design are themselves designed, tested, and verified following a similar process steam from concept, prototype, through to final articles.
5.5.2 RP Initial Market Entry

We begin the analysis of RP's attack of the above described value network by recalling that the disruptive technology does not competitively address traditional markets and therefore first finds a foothold in an emerging market.

For StereoLithography, the first RP technology, the traditional market was human interpreted 2D drawings that were transformed via craft techniques into physical models and prototypes using carving, sculpting, machining, casting and others. The emerging market was in design operations employing Computer Aided Design or CAD. The early adopters of CAD were motivated by the promise of greater designer productivity. Use of CAD offered more rapid iterations of design evolution and less repetition of mundane tasks as well as broad data base and design component sharing across and between groups.

One problem with CAD was that designers were unfamiliar with it. There were many ways which mistakes could creep into designs and remain undetected. A second problem was that once a CAD design was generated, the next step in the design process often required a model or prototype to be built. The CAD representation was then translated into a two dimensional paper version (a drawing). This 2D representation was then re-interpreted by a craftsman back into a three dimensional representation in the form of a physical model or prototype. The multiple translations required time, organizational coordination, and introduced more errors.

StereoLithography was attractive because it offered to translate the CAD data directly into models. It allowed for quick verification of design intent. It gave CAD designers much needed feedback about the quality of their design representation. It also allowed group managers to retain control of the design iteration process, keeping the loop time short and tight.

In the mid '80s, CAD systems typically cost many 100's of thousands of dollars so a verification tool costing $200,000 could be justified. Pratt and Whitney which adopted RP technology in 1988 found a significant benefit in the identification of design errors prior to manufacturing involvement.
There was no competitive approach to SL. It provided for a direct test of the design intent, with no human translation. It was not uncommon for designers to use the first SL step, generating an SL “build” file as a quick and dirty verification of their design quality. If there were problems in the digital model, 3D’s software would find them. Use of SL removed the problematic and error prone steps of translating CAD designs into 2D paper “drawings” and then re-translating them by human craftsman back into 3D. RP technology could also realize designs that were very difficult to build using traditional techniques. For example, Pratt and Whitney uses rapid prototyping to aid in manufacturing production studies. An RP model of the “real” part can help the manufacturing shop prove out tooling and fixturing. P&W made an RP prototype of a turbine fan of interest to high performance jet engine design. The “shop” studied to RP model, and assessed that to it would not be possible realize the design in metal using traditional techniques.

In the emerging market for CAD based design support StereoLithography was just the technology to meet the needs of this new value network.

5.5.3 Attack from Below

Christensen points out in his value network framework that once an innovative technology gains a foothold in an emerging market, it may move up-market, attacking the traditional market (see Figure 5.1) and be transformed into a disruptive innovation. This will happen if the performance potential of the attacking technology can expand to address needs within the higher value network traditionally served by a mature technology.

As described in section 5.5.1, following the design concept phase, the detailed design must be verified. SL users became proficient with building concept design models, but could see the potential benefits of building models to test and verify detailed designs. for this purpose models needed to be of higher fidelity. The design interfaces with other elements and components needed to be tested and verified with higher fidelity than the errors being tested for. These tests required greater dimensional accuracy and greater model robustness. Users began experimenting, finding problems with SL technology, and pushing 3D to solve them. The emphasis at 3D and other RP firms became “test applications” and
delivering “functional” models and prototypes. Soon RP technologies appeared capable of delivering functional test models.

An example: two engineers on an engine upgrade program at Chrysler Corporation were given the task of designing the mating of a distributor cap and body. The parts were built using SL, and when they were put together, they did not fit. The distributor cap engineer made a design change and built another part in 24 hours. The new part fit. If conventional methods had been used, the problem would not have been seen until the prototypes came back weeks later.

5.5.4 Moving Up-Market

SL and other RP technologies could deliver functional prototypes, but none could deliver the actual end-product to the market. Traditional fabrication techniques were required to transform the detailed design into tools used in building the product. Production tools took into account the constraints imposed by processes, costs, and materials. Tools had to be able to withstand high temperatures, and pressures, along with thousands of cycles of use. It was a demanding job.

CAD vendors were expanding their product offerings into production tooling. They began offering CAD tools to transform product designs into production tool designs. Tool designers were beginning to use CAD as well. RP firms began experimenting in using their processes to generate production tools. Some of the first tools generated were patterns for metal and plastic casting applications. The RP models could be used as patterns around which a tool was formed. That tool would then be used to build the production part. Here, as in the previous evolutionary steps, RP first attacked market areas which had particular needs and were not well served by traditional techniques.

Casting of rocket and jet engine parts were among the first applications developed. These applications had very short production runs (sometimes only one piece), and cycle time was a pre-eminent performance measure. Traditional techniques were expensive and very time consuming, and the first value seen in the RP approach was in its speed.
Examples:

A division of TI builds advanced rockets for the Department of Defense. They found that using RP techniques to produce specialty cast components reduced product design cycle time on average by 50% (Jacobs, P. 1992).

Chrysler has used RP models to quickly create precise master patterns for secondary tooling applications such as room-temperature vulcanizing (RTV) molding, sand casting, resin transfer molding, vacuum forming, and squeeze molding. Parts produced include center consoles, interior trim panels, and instrument panel components. (Jacobs, P. 1992).

5.5.5 Segmentation

Firms within the RP industry have begun specializing within value networks by stressing different applications, performance and cost. Stratasys stresses design verification, DTM has competed along functional prototype applications but recently has entered the direct design-to-tool market. Cubital stresses high volume, sanders low cost, and Helsisys versatility across applications for a reasonable price.

Others RP firms are attempting to go the seemingly final step and build metal parts directly without intermediate processes. DTM, MIT, and perhaps others are attempting to fabricate designs direct in metal without using intermediate steps or materials. They are attempting the ultimate evolutionary step in this stream of design to product integration.

The RP industry has begun to show signs of maturity and has come to address more established markets. RP is now “traditional” in some settings. 3D Systems’ SL technology has become a benchmark technology in concept, design verification, functional prototyping, and RP tool applications. New entrants however, are attacking this position with new architectures offering different price/performance mixes. These entering firms are looking for and finding new, emerging and challenging markets out of sight of the traditional RP players.
5.6 Concept Modeling and Value Networks

3D Systems’ first served an emerging market: producing concept models from CAD data. This value network is where it first met its customers and began its growth. Perhaps because it started here, it might feel it understands this market and its development trajectory. It was not an easy lesson for it either. It’s first customers were experimenters. They trained 3D in how to build a piece of laboratory equipment but little about how to build a CAD peripheral. 3D was forced to relearn what mainstream CAD users wanted in the way of a concept verification tool. It was a hard won lesson too. 3D had acquired a deep understanding of this particular value network, or so it thought.

The appearance of low-cost, easy to use, office environment compatible RP machines was not a matter of great concern. These machines could not generate the type of models 3D knew its value network expected.

Henderson and Clark describe a behavior pattern in firms competing in the photolithography industry. Specifically, they found that dominant firms when evaluating competitor’s innovations within the dominant firms context of value (their value network) failed to observe any threat. The dominant firm’s criteria for assigning value did not allow them to perceive differential value in the innovating firms product. The dominant firms were however displaced by the innovating firms demonstrating that the market saw differential value. Perhaps it was fortuitous for 3D that IBM did venture briefly into the “convenience” modeler market space and provided the motivation for management to focus on this architectural innovation.

3D might have ignored the convenience modeler innovation altogether if a respected competitor had not entered the market and captured management’s attention.

5.6.1 Value Network Acrophobia: (Don’t look down market)

The first response of 3D to the IBM’s machine was to evaluate it within 3D’s current value network. The first assessment was that IBM would have trouble making decent models and therefor was not a serious, immediate threat, except...
IBM had brand recognition and 3D worried that just by entering the market, IBM might dominate it, regardless of how good their models were. Other than brand name, one advantage of the IBM machine 3D could perceive within its value network was its low cost. 3D did not see an emerging market developing where less accurate, poor fidelity models would be of interest. There was some worry that IBM might develop their technology to a point where it could compete in 3D’s value network. Initially, 3D behaved much as the photolithography firms had in the Henderson and Clark study; they could only see the IBM machine within their own value context.

3D’s strategic response to IBM’s convenience modeler can be characterized as an attempt at incremental, component innovation. 3D attempted to find a set of new components, costing less, which would fit into their traditional product architecture. In that way they could address the perceived value of the IBM machine, low cost, while maintaining the value important in traditional markets: quality models. They presumed that customers were the same, needs were the same, markets were the same. The IBM threat was about cost and reliability (brand name) which 3D had learning about from its current customers. These were issues which 3D could understand within its history and value network. It failed to perceive the IBM modeler as what it conceivable was: an architectural innovation addressing an emerging market within a different value network which could be disruptive to 3D’s traditional markets.

3D’s second attempt at answering the IBM innovation was an escalation in component innovation. 3D escalated its innovation effort and attempted a modular innovation. Still focusing on supplying the same model value to the same market at a lower price, it attempted to find low cost replacements for the expensive components in the existing architecture. The modular approach attempted to maintain the same model qualities found in 3D’s traditional products. Such a strategy allowed it to remain within the same value network. Models from 3D’s convenience modeler would serve similar applications as traditional SL models, only at a lower cost.

Perhaps it is lucky again for 3D that it did not work. For had the modular innovation succeeded at producing a low-cost product it would still not have addressed the emerging convenience modeler market. The technology still relied on
smelly chemicals which were messy and dangerous to handle. Models emerged from the machine dripping and in need of “post processed” before they could be used. This was not an office environment product.

Having failed at modular innovation, 3D was forced to address the basic product architecture and think anew. The resulting innovation (MJM) did not address the same value network. MultiJet Modeler applications were limited within the traditional RP value network. This innovation was not moving up market, but down, clear down to where 3D had begun: at concept models. This limitation forced 3D to reassess where the product fit. Its performance attributes were that it was fast, easy to use, quite, unobtrusive, small, and could easily fit into an office setting. It was so fast that 3D soon realized that selling the material from which models were built could become a sizable revenue stream (similar to Xerox and paper sales). It also became clear that the machine was so easy to use (about like a laser printer) that any designer could use it without training. The cost of using it was also small, both making it easier to get an MJM model. Perhaps the MJM model would not have to provide the same application value as an SL model to be accepted in the market. If the cost/value trade was set appropriately, demand might be substantial.

A first indication of the market acceptance of the product was obtained from another established market: the stock market. 3D shares rose from $14 to $21/share on the public announcement of the MJM machine. Investors seemed to like the innovation.

5.6.2 Value Network Myopia (Don’t see what’s down market)

A debate surfaced at 3D regarding what impact the MJM technology would have on the core SL. Some believed the new technology to be inferior and of no threat to the established market served by SLA modelers. Others however speculated that with development, the MJM process would rival traditional SL at generating wide ranging, application specific models. Especially vulnerable was patterns for use in investment casting. Models from the MJM process were inherently better suited to this application, one which now accounted for a large demand segment for SLA’s. 3D began to actively position the MJM product to not attack its “core” products.
We have seen that technologically based firms compete through innovation. The type of innovation a firm will attempt is strongly influenced by the market context in which it operates. Firms competing in mature “specific phase” markets will concentrate their innovative efforts at minor, incremental innovations improving the profitability and producability of their products. Firms competing in more dynamic “fluid phase” markets will be more prone to experimentation both in their technical and market approaches.

The firms operating now in mature markets have helped in the maturation of those markets through participation in the market’s fluid phase of development. They have invested in learning what the market wants, needs and is willing to pay for. The learning process is unpleasant, costly, and risky. Having arrived at the relatively stable specific phase, where a dominant design is known and accepted, the firm has more control, confronts less uncertainty and is not eager to return to participate in the marketing learning dynamic again. It is only when confronted by some marshaling event that the typical firm will re-enter the uncertainty and unpleasantness of a fluid phase market.

3D Systems tried repeatedly to avoid re-entry into an emerging market. The market entry of a greatly respected competitor, IBM finally forced it to re-enter. 3D’s success at re-entry appears to be a rare occurrence as the studies of Christensen et. al. have shown. But as is clear from this case and theirs, firms which fail to re-enter emerging markets will likely fail to survive.


INDUSTRY OVERVIEW

3D Systems - Stereolithography

Stereolithography is the process developed in 1984 by Charles Hull. A patent was issued for the Stereolithography system in 1986. Mr. Hull then joined Ray Freed in forming 3D Systems, Inc. (Valencia, CA). The Stereolithography Apparatus (SLA) was introduced at the AutoFact trade show in November 1987. It was the only rapid prototyping system offered commercially at that time.

In Stereolithography, a laser generates an ultraviolet beam that solidifies focused surface areas of a photopolymer in a vat. This process continues, slice by slice, until the system completes the part. Figure 1 illustrates the concept. 3D Systems offers three models of the SLA.

SLA-190:
- work volume of 7.5 x 7.5 x 9 in.
- costs $105,000

SLA-250:
- work volume of 10 x 10 x 10 in.
- costs $210,000

SLA-500:
- work volume of 20 x 20 x 23.75 in.
- fastest system
- interchangeable vats
- costs $420,000.

The SLA-250 features a recoater system which spreads higher viscosity resin quickly. It has a faster processing time than the SLA-190. "And it has a dual computer system. You can get an optional workstation to use as your slice processor, or you can put a separate CAD system on it."

This review will concentrate on the most commonly used machine, the SLA-250. An integral part of the process is the "slice" software that takes the CAD drawing and slices it into layers. These become the program steps that direct the laser beam in building the part layer by layer. The machine has a helium-cadmium laser that generates an ultraviolet beam.
The SLA-190 has the same laser; the SLA-500 features a more powerful argon-ion laser. The SLA-250 has a 7.8 gallon vat equipped with an elevator table. The vat is filled with the photopolymerizable liquid resin. Servomotors, controlled by the machine control unit, drive a set of mirrors that reflect the laser beam to the surface of the polymer material. The lasers' focused spot diameters are 0.008 to 0.012 in. A second system unit is the Post Curing Apparatus (PCA-250) that generates a long-wavelength ultraviolet light that provides the final cure of the parts built in the vat.

The process begins with the vat filled with the photopolymer liquid and the elevator table set just below the surface of the liquid. The operator loads a three-dimensional CAD solid model file into the system. If needed, supports are designed to stabilize the part during building and post-curing. The translator converts the drawing into the .STL file. The control unit slices the model and supports into a series of cross sections from 0.004 to 0.020 in. thick. The computer-controlled optical scanning system directs and focuses the laser beam so that it solidifies a two-dimensional cross section on the surface of the photopolymer. The elevator table then drops enough to cover the solid polymer with another layer of the liquid. A leveling wiper moves across the surface of the polymer. The laser then draws the next layer. This process continues, building the part from the bottom up, until the system completes the product. The part is then raised out of the vat and cleaned of excess polymer. It then proceeds to the Post Curing Apparatus for the final cure.

In the spring of 1991, 3D Systems introduced a new method of building called the "Weave." This method increased accuracy by as much as 20 times. It solidified 96% of the part in the vat before post-curing. The previous method left 40-60% of the part as liquid trapped within the walls of the cured resin. Previous distortion was primarily caused by stresses during post-curing. The Weave technique achieves very small crosshatch spacing in each layer by making two separate passes perpendicular to each other. Post-cure time, shrink, and swelling are reduced with this new technique. The Weave also improves long-term dimensional stability by producing considerably fewer locked-in stresses due to post-cure. It also improves surface finish, especially on horizontal surfaces. Later, the "Star-Weave" was introduced. This technique cures the resin to 99% during the laser drawing process. This system's accuracy is \( \bar{n}0.002 \) to \( \bar{n}0.005 \) in./in., depending on geometric complexity and operator skill.
The material used in building prototypes with StereoLithography is photocurable resins. The price of this polymer is $300 to $350 per gallon. The resin in the vat not cured by the laser beam can be used again. To make a part 6 cubic inches, it would take $25 worth of resin. 3D Systems and Ciba-Geigy Ltd. are in a joint research and development program constantly working on new resins. They have two latest developments:

* XB 5149, for SLA-250
* XB 5154, for SLA-500

These new resins exhibit better toughness and machinability. Previous materials had a problem with excessive brittleness. Allied Signal, Inc., has also introduced the Exactomer 2201 resin, which demonstrates excellent material properties. Du Pont also works in the area of liquid photopolymer development, and has come out with four new materials:

* 2100, for argon-ion laser
* 2110, for helium-cadmium laser
* Both feature high flexibility and bone-white color.
* 3100, for argon-ion laser
* 3110, for helium-cadmium laser

Both feature high toughness and transparency. Several modeling shops and service bureaus spread throughout the country use SLA systems.

**DuPont/Teijin-Seiki - SOMOS/Soliform**

The SOMOS Solid Imaging System was developed by DuPont Imaging Systems (New Castle, DE) and introduced in November 1989. This system is similar to SLA but differs in the photopolymer used and the laser system. The material is a white, low shrinkage, proprietary resin with properties similar to silicon rubber. This material is claimed to have "high photospeed, low shrinkage and warpage, wide exposure latitude, flexible and homogeneous photoformed parts, and good layer-to-layer adhesion." 6 The SOMOS system employs an argon-ion laser with high-precision scanning in a raster pattern and high-speed beam modulation. Accuracies for this system are "x and y axes, 0.002 inch/inch; z axis, 0.006 inch/inch; and layer thickness, 0.005 to 0.020 inch." 7 This system uses a Unix workstation to process CAD data. The one-cubic-foot vat has a high-speed
resin coating system. Post-curing is not necessary but recommended to improve the integrity of the material. This system can produce prototypes measuring 12 x 12 x 12 in.

DuPont no longer manufactures or sells the SOMOS system. Teijin-Seiki of Tokyo, Japan, has licensed the patents to this system, and now make it commercially available in Asia. The new name of the machine is Soliform. DuPont's plans are to concentrate on the development of resins for the photopolymer liquid based rapid prototyping systems.

Stratasys - Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a nonlaser-based process, developed in 1988 by Scott Crump, president of Stratasys, Inc. (Minneapolis, MN). The system is called the 3D Modeler. It takes CAD wireframe, surface, or solid models and builds the parts by depositing layers of molten thermoplastic materials.

The process begins with the input of the CAD data into the system. The UNIX-based workstation will accept data in IGES format, as NC code, or in the industry standard .STL format. The Strataslice software converts the part into its layers, and the data are downloaded to the 3D Modeler. A spool of 0.050 in. diameter thermoplastic filament, resembling wire, is fed to the heated extruding head. The liquid thermoplastic filament is maintained at a temperature 100°F above its solidification state prior to deposition. The material then solidifies in 0.1 second upon placement by the x-y controlled extruding head. The material is deposited onto a Styrofoam slab affixed on a computer-controlled platform that controls the z-axis.

This system requires no post-curing. Layer thickness ranges from 0.001 to 0.050 in., and wall thickness ranges from 0.009 to 0.250 in. Tolerance for a 12 x 12 x 12 in. part is 0.005 in. The materials used include machinable wax, a tough nylon-like material, and investment casting wax (all nontoxic). This system is capable of a one minute material changeover. The process does not require elaborate supports; any flat or near-flat overhangs should have a support structure.

The 3D Modeler is now commercially available at a cost of $162,000. The complete system (which includes the 3D Modeler, Strataslice software, and Silicon Graphics Personal Iris Workstation) costs $186,000. A mile-long spool of wax or nylon filament costs $350.
DTM - Selective Laser Sintering

Selective Laser Sintering (SLS) is a process that employs a powdered material approach to rapid prototyping. The process begins with the deposition of a thin layer of powder, which is heated to just below its melting point. A laser selectively traces the surface of the powder and sinters the material together. This process continues layer by layer until a final product is complete. Carl Deckard developed SLS at the University of Texas at Austin. In 1986, Dr. Paul F. McClure became aware of Deckard's work and founded DTM Corporation in Austin. DTM first introduced the SLS Model 125 in 1989. After software, hardware, and process improvements, DTM presented the Sinterstation 2000 in 1992. This new machine is currently being used in Beta Programs. It builds prototypes up to 12 in. diameter and 15 in. high. Figure 4 illustrates the Sinterstation 2000's basic components and process. Almost any material that softens and decreases in viscosity upon heating can theoretically be selectively sintered. Such materials include ABS plastic, PVC, nylon, investment casting wax, and polycarbonate. Future candidates for materials include powdered metals, ceramics, and advanced composite powders with suitable binders. DTM is cooperating with BF Goodrich Company, which owns a majority of DTM, in developing new materials for SLS.

The equipment is divided into three areas: computer/control, atmosphere control, and process chamber. The computer/control area contains a 486 UNIX-based computer system, which generates the .STL file and slices the part. This computer system also monitors and controls the entire building process. "The Atmosphere Control Unit houses the equipment to filter gas recirculated from the process chamber, maintains a set temperature on the air flowing into the process chamber, and regulates the nitrogen atmosphere used in the unit." 4 The process chamber houses the laser and powder handling system. Optics and scanning mirrors are used to focus a CO2 laser beam onto the part cylinder, sintering a layer of powder material. The part cylinder is 12 in. diameter x 15 in. deep. The powder material is supplied to the part cylinder by two powder cartridges on either side of the part cylinder. A powder leveling roller transfers the powder to the part cylinder.

The SLS process begins with the atmosphere preparation in the process chamber, which is heated to the operating temperature and filled with nitrogen. The 3-D CAD data in the .STL file format is input into the SLS system. The system slices the part into its cross-sectional data. Typical slice thickness is 0.005 to 0.006 in. One powder feed piston rises to
distribute a layer of material. At the same time, the part-building cylinder lowers to the desired layer thickness. The other powder feed piston also lowers to accommodate any surplus material, which the leveling roller transfers across the build area. The deposited powder is heated to a temperature just below its melting point. Using a raster scanning pattern, the laser draws one cross section of the desired part to sinter the powder particles. Unsintered powder remains to support the next layer, which is then distributed, leveled, and sintered. This process continues until the part is complete. The part-building cylinder then raises to allow the part to be removed for cooling. Excess powder is cleaned off the part by brushing or air-blowing. With the exception of the use of ceramic materials, no post-production curing is required with this system.

Building with powder materials results in rough surface finishes and porosity. "Amorphous powders more or less retain their shape during the process and therefore are more likely to produce rough surfaces. Crystalline powders are liquefied and smoothed by surface tension. ... While crystalline materials .. are melted during the process and can produce fully dense parts, sintered amorphous parts can be quite porous."

An advantage to this system is its ability to provide supported building. The unsintered powder surrounding the part in the build cylinder acts as a natural support for the next layer. No elaborate supports need to be built such as in some photopolymer systems. Also, the excess powder material can be returned to the powder feed cartridges for reuse.

This system has a part building speed of 0.4 to 2 in./hour for a part with 0.005 in. layer thickness. Accuracy is ±0.015 in., depending upon the material. The DTM Sinterstation 2000 is available at a cost of $397,000 to $427,000. This technology may also be accessed through DTM's service center in Austin, TX.

MIT - Three-Dimensional Printing

Three-Dimensional Printing (3DP) is a rapid prototyping process under development at the Massachusetts Institute of Technology. The process selectively binds powder material without the use of a laser, rather, this process utilizes a technology similar to ink-jet printing.
The process begins with the deposition of a thin layer of powder over the surface of a bin. This bin is fitted with a piston for incremental lowering as the part is built a layer at a time. A roller mechanism spreads the powder evenly over the bin. A CAD drawing of the part, again sliced into consecutive layers, is used to distinguish the cross section of the part to be built. Next, an ink-jet printhead containing a liquid binder material moves across the powder in a raster pattern. Small drops of binder material are sprayed across the powder surface only in the specific locations corresponding to the cross section of the part. The piston supporting the powder bed lowers so that the next layer of powder can be spread and selectively joined. The process continues until a solid part is complete. Depending on the powder material and binder used, this process may require post-processing. Due to the support of a powder bed, the part can be built with overhangs, undercuts, and internal volumes.

A problem area with this technology is its poor surface finish, which stems from three sources: "One, the powder is disturbed by the impact of the binder drops. Two, the current method of printing cross section geometry using raster lines produces horizontal stairsteps, or jagged surfaces. Three, inadequate flow control of the binder causes drop positioning errors." 13 MIT researchers are working on these problems.

The 3DP technology has been exclusively licensed to Soligen, Inc., for the Direct Shell Production Casting (DSPC) process. 3DP is the enabling technology that allows DSPC to cut a considerable amount of steps from the conventional method of investment (or "lost wax") casting. With investment casting materials such as silica or alumina powder and liquid colloidal silica binder, shells can be fabricated with integral cores directly from a CAD file. Molten metal can then be poured into these shells to form a part.

**Helisys - Laminated Object Manufacturing**

Laminated Object Manufacturing (LOM) is a system developed in 1985 by Michael Feygin, president of Hydronetics, Inc., which at that time was located in Chicago, IL. In 1989, the company changed its name to Helisys, Inc., and relocated to Torrance, CA. LOM differs from the systems previously reviewed in that, rather than building up a part by adding materials to a stack through a forming process, layers of sheet materials such as paper, plastics, or composites are attached to a stack, and the laser cuts away the unused portions.
The process begins with a computer slicing a 3-D solid model of the part into two-dimensional cross sections. Input data are in the .STL file format. The thickness of the computer-generated cross section corresponds to the thickness of the sheet material. The sheets can be 0.001-0.005 in. thick. A winding and an unwinding roll provide a ribbon of the material. A stepper motor positions the material onto the building platform. A heated roller moves across the surface of the material, bonding it to the stack. An x-y positioning table with mirrors and optics reflects and focuses the CO2 laser beam, which cuts a profile of the part. Cutting speed can be up to 15 ips. The area of material surrounding the part profile is cut in a crosshatch pattern to facilitate its removal later. The excess material left in the building block acts as a support structure for the next layer. Adjustments in the laser power and cutting speed enable it to cut through only one layer at a time. A vent removes the smoke generated by the laser cutting the material. The platform lowers to accommodate another layer of sheet material, which the rolls advance, and the thermal roller bonds to the stack. The laser cuts another cross-section. This process continues until the part is complete. Upon removal from the platform, the extra material surrounding the part must be removed. Since excess material is not removed until after the building process is complete, parts with hollow cores or internal cavities cannot be fabricated as a single part. Helisys is working on a vacuum system that would remove the excess material after each laser trace. This would solve the problem of excess material stuck inside the part, but it would also take away the advantage of using the excess material as a support structure.

This process can be considerably fast. Because the laser is cutting around the periphery of the object, building a thick-walled part takes no longer than a thin-walled one. A great advantage with this process, according to Helisys, is that it is not limited by the complexity of the part. Since there are virtually no internal stresses, the part has no deformation or shrinkage commonly associated with photopolymer systems. Precision is claimed to be below 0.005 in. Helisys offers two models of the LOM system.

LOM-1015:
- maximum part size of 14 x 15 x 10 in.
- cost of $95,000

LOM-2030:
- maximum part size of 30 x 20 x 20 in.
- cost of $180,000
Sony - Solid Creation System

The Solid Creation System (SCS) is a Japanese system co-developed by Sony Corporation and Japan Synthetic Rubber. This system uses similar technology used by 3D Systems' StereoLithography Apparatus, but has the ability to build larger parts. Three systems are available:

* JSC-1000
* JSC-2000
* JSC-3000.

The largest system has a build area of 40 x 32 x 20 in.

The SCS consists of three parts: the laser scanning device, the part building chamber, and the system controller. The controller obtains CAD data and computes the cross-sectional data used to build the model layer by layer. The 1000 model uses a helium-cadmium laser. The 3000 model uses an argon-ion laser, and the 2000 model can use either laser. All of the systems use a galvanometer-mirror scanning method. These systems are also capable of laser beam spot size adjustment. The machines build part-layers of 0.004 to 0.012 in.

This system is available through D-MEC Ltd., a subsidiary of Japan Synthetic Rubber. D-MEC markets the machine and resin, and they operate as a service bureau in Japan. Ten systems have been sold in Japan. No marketing attempts have been made in the United States.

Mitsubishi - Solid Object Ultra-Violet Laser Plotting

The Solid Object Ultra-Violet Laser Plotting (SOUP) system was developed by Mitsubishi Corporation in Japan and is marketed by CMET (Computer Modeling and Engineering Technology), Inc. This system also uses similar technology to the StereoLithography Apparatus. Laser lithography is used to build a model in a vat of photocurable resin.

"The SOUP system consists of a laser lithography unit and a workstation used for the SOUPware controller. The SOUPware, which generates curing work data based on three-dimensional data, is isolated from the hardware controller and run on the engineering workstation. This allows for selection of an engineering workstation suited to the size of
the three-dimensional data, thus simplifying the curing work data management and enhancing the transparency with the LAN environment."

Four types of hardware are available for different work sizes, and two types of laser scanning are used:

SOUP400:
- work envelope of 16 x 16 x 16 in.
- helium-cadmium or argon laser
- uses a galvanometer-mirror scanning method.

SOUP530:
- work envelope of 21 x 14 x 14 in.
- helium-cadmium laser
- uses an xy plotter method.

SOUP600:
- work envelope of 24 x 16 x 16 in.
- argon laser
- uses a gantry-type xy plotter method.

SOUP850:
- work envelope of 34 x 24 x 20 in.
- argon laser
- uses a gantry-type xy plotter method.

The SOUP400 has a high-speed raster scan with a fixed diameter laser beam (0.004 in.). The SOUP530 scanning method attains a positional precision of ±0.002 in. for all working areas; the laser accommodates both vector and raster scanning. The gantry-type x-y plotter (SOUP600 and SOUP850) provides a maximum scanning speed of 40 ips. The beam diameters for the 530, 600, and 850 systems can vary from 0.005 to 0.080 in.

The software used to interface the CAD data with the rapid prototyping system offers a simulation function, many CAD interfaces, many editing functions, selection of working conditions, and has the ability to automatically generate support structures.

The epoxy resin used with these systems is claimed to have a low shrink factor, excellent mechanical properties, and no need for post-curing processes.
Mitsui - Computer-Operated Laser Active Modeling

The Mitsui Ship Building Company in Japan has produced the Computer Operated Laser Active Modeling Machine (COLAMM). The COLAMM-300 machine also works similarly to StereoLithography, but builds parts from top to bottom. The photopolymer resin is exposed to light from below, through a transparent substrate. The helium-cadmium laser light is conducted by fiber optics and scanned by an xy plotter method. The beam spot diameter is adjustable from 0.004 to 0.020 in. The platform raises one layer thickness after each build cycle. The building surface does not need leveling since the transparent substrate is already flat.

Cubital - Solid Ground Curing

Solid Ground Curing (SGC) was developed by Cubital Ltd., which is jointly owned by Harwix GmbH, Clal Electronics Industries, Scitex Corporation, and private investors. Cubital is headquartered in Israel with subsidiaries in the United States and Germany. The Cubital machine is called the Solider 5600, and is illustrated in Figure 2. It consists of a workstation and production machine. The workstation uses a UNIX-based operating system, which runs the proprietary Solider software that generates the part slice data from 3-D CAD data. The production machine uses these data to cure an entire layer of photopolymer in a solid environment. An ultraviolet light completely cures the material through a photomask. No post-curing is required. This machine can build parts at a maximum size of 20 x 14 x 20 in.

The SGC process is illustrated in Figure 3. It begins with the input of the three-dimensional CAD data of the part and selection of layer thickness. The computer then generates the cross-sectional slice data of the model. An image representing the cross-sectional layer is sent to the mask plotter, where a glass plate is charged with ions, and electrostatic toner develops the negative image of the layer. At the same time, the workpiece carriage is at the resin application station. A 0.006-0.008 in. layer of liquid photopolymer is applied at this station. The carriage and mask meet at the exposure cell, where a shutter opens for 3 seconds exposing the resin to ultraviolet light through the transparent areas of the mask. All exposed areas are completely cured. The mask moves back to the plotting station where it is physically and electrostatically erased in preparation for the next layer. At the same time, the carriage moves to the aerodynamic wiper, which vacuums the uncured
liquid polymer. The part is again exposed to ultraviolet light without a mask. This solidifies the residual resin that the wiper could not pick up. The carriage then moves to the wax applicator station, which deposits a layer of wax 0.008 in. thick to fill in all voids and cavities. The wax is solidified by a cold plate at the cooling station. The workpiece then moves to the milling station where a fly cutter mills the layer down to the desired thickness. A vacuum collects any chips produced during this process. The workpiece carriage lowers to accommodate the spreading of resin for the next layer, and the process continues until the part is complete. The building time for each layer is 90 seconds. The entire building process concludes with the part embedded in a block of wax. The water-soluble wax is melted in a microwave oven, and the part is cleaned in warm water.

Cubital claims that this system has a dimensional accuracy of 0.02 in., without the dependence on a skilled operator. The x-y resolution is better than 0.004 in. Layer thickness can be 0.004-0.006 in. Building speed is 60-100 layers per hour.

This system fully cures each layer as it is built. This minimizes shrinkage and eliminates the need for post-curing. Also, the solid polymer and wax environment eliminates the need for elaborate support structures. This contributes to the ability to build parts of geometric complexity.

A problem area with this system is that it produces a lot of material waste. The resin picked up by the aerodynamic wiper and vacuum during the milling process cannot be used again. Uncured resin is hazardous material. One way to solve this problem would be to nest as many parts as possible in one building cycle. Cubital supplies their resin for approximately one-third the price of StereoLithography materials. Because the aerodynamic wiper does not remove all of the uncured photopolymer, residual resin remains, adding to surface roughness and layer inaccuracy.

The Solider 5600 is a very large machine that requires a shop environment. Its dimensions are 13 ft 6 in. x 5 ft 7 in. x 4 ft 10 in. costing $550,000, it is the most expensive rapid prototyping system available.
Nottingham University, England
Bremen Institute of Industrial Technology and Applied Work Science (BIBA)
Clemson University
Helsinki University of Technology, Finland
University of Dayton
Carnegie Mellon University
MIT
University of Delaware
University of Texas
The Manufacturing Technology Information Analysis Center (MTIAC)
IVF-KTH, Stockholm, Sweden
Sandia National Laboratories
Rutgers University
Alberta Research Council
University of Utah
IWB-GERMANY
General Electric Co.

Formigraphic Engine/Battelle - Photochemical Machining

Photochemical Machining, a process similar to SLA but still under development, uses two intersecting laser beams to form a three dimensional prototype out of a photopolymer block. Research on this process by Battelle (Columbus, OH) and Formigraphics Engine Corporation (Berkely, CA) dates back to the 1960s with related patents. However, in the 1980s Formigraphics, still holding the patents, shelved these developments to pursue other projects. "Battelle estimates that several years of intensive effort will be required to bring photochemical machining to market once third party support is found." 11

Because of the use of two lasers, this method could be the most versatile photopolymer-based rapid prototyping process. One beam moves in the x-y plane. The other beam moves in the y-z plane. Each beam has different wavelengths. The combination of the intersecting beams polymerizes the material, rather than a single laser beam solidifying an area on the
surface of the material. Forming a part in the z-axis no longer needs to be done in layers. Initializing the laser's movement in any set of x,y,z coordinates allows the ability to trace the part in three dimensions rather than two. This capability would reduce prototyping time even more.

Areas in need of research and development are in the lasers and in the photopolymer. The lasers need improvement in the selectivity of the laser sensitizers and in quality of the beam. Also, work needs to be done on the speed and efficiency of the beams; it currently takes almost a minute for the beam to cure the polymer. Work also remains to be done in developing a polymer that will not cure by the exposure of a single laser beam.

The term used in this particular technology, "photochemical machining," should not be confused with the process of removing material by chemical erosion, also called "photochemical machining."

Carnegie Mellon University - MD*

The Masking and Depositing (MD*) technology was developed by researchers at the Carnegie Mellon University Robotics Institute. Robotic controls are used to thermal spray metal onto a substrate through a mask. A stencil, or mask, of the cross section of the object is placed against a substrate. The disposable masks are cut from pressure-sensitive labeling paper using a carbon dioxide laser. A thermal spray gun deposits a thin layer of metal. A complementary mask is placed exposing the unsprayed areas. A low-melting-point alloy (the support material) is then sprayed to result in a layer of part and support metals. This process is repeated for all layers of the part until completion. The average layer is 0.004 in. thick, but layers as thin as 0.001 in. can be produced.

An area in need of further development is control of residual stresses. When metal cools, it shrinks and locks residual stresses in the part, causing distortion. The researchers at Carnegie Mellon University have found that incorporating shot peening into the building process helps relieve these stresses. Also, work needs to be done on keeping uniformity in layer thickness. Finally, attempts are underway to develop this system to operate in a vacuum or inert gas atmosphere. This would prevent the formation of embrittling oxides.

This technology can also utilize many different materials in one object.
Texas Instruments - Printed Computer Tomography

Texas Instruments in McKinney, TX, is also working on a system very similar to BPM's. TI's system is called Printed Computer Tomography (PCT). This system has a one-foot cube work envelope, and is purported to have a building speed of one layer per minute.

U.S. Navy - Electrosetting

Electroset technology, also called "programmable molding," is a new rapid prototyping technology. Electroset Synergistic Technologies Corporation holds the international patent rights, and the U.S. Navy's David Taylor Research Center holds the U.S. patent rights. Electroset rapid prototyping technology uses electric fields to shape objects. Figure 9 illustrates a typical Electroset system. This system consists of a personal computer, an electrode printer, and a high-voltage power supply. All of this equipment is readily available. The personal computer must have a graphics system. "The electrode printer may be a plotter that has specially adapted pens and ink for making the electrode design, or it may be a laser jet printer or even a copier machine. The high-voltage power supply preferably should be capable of delivering up to 5 kilovolts and 50 milliamps of DC power."9

This process takes several steps. First, a cross section of the object is generated on the computer. The computer then sends the image to the printer where the electrodes are formed into the shape of the image and attached to a frame (the frame is a sheet of conductive material such as aluminum foil). When all frames are complete, they are sandwiched into a mold, which is connected to a power supply. The mold is immersed into a bath of Electroset fluid and energized. Upon energizing, the fluid between the electrodes solidifies. The mold is withdrawn from the bath and excess fluid drains from the object. After trimming off the mold framing, the part is complete. The hardware required for a manually operated system of this type would have a price of about $5000. Any added automation would drastically raise the price.

A unique feature in this technology is the ability to electrically predetermine the material properties of the cured object. "Material properties that are programmable include density, compressibility, hardness, and adhesion." 10 The material properties can be programmed during Electrosetting by controlling the maximum applied current independently from the
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