Chapter 2

A Brief Overview of the History of CAD

Author's Note: The purpose of this chapter is to provide an overview of how the Computer-Aided Design (CAD) industry evolved without repeating any more than necessary the material that appears in subsequent chapters.

Introduction

I have always been fascinated by old structures and machinery. Buildings such as the Coliseum in Rome are all the more amazing when one realizes that two thousand years ago builders had none of the construction equipment we take for granted today nor did they have any of the tools for creating designs that we now use. It was more of an art form than traditional engineering with the master builder directing the work of thousands.

Today, the Coliseum exhibits only part of its past glory. On the other hand, many of the magnificent cathedrals and castles built in Europe during the Middle Ages still stand and many have been in continuous use every since they were first constructed.[1] While we have many examples of early construction, few machines from that era still exist. Most were war machines built to assault the enemy's castles and were probably destroyed in the process.

For centuries, engineering was focused on war, either building defensive fortifications or the machines to attack these fortifications. In fact the first non-military engineering discipline is called "civil" engineering to distinguish it from its military counterpart. Here also, few documents exist today describing how these early military war machines were built. Those that do exist were done on parchment or scratched into clay tablets.

That is not to say that these early builders did not use sketches and drawings. As an example, the Greek Parthenon could not have been constructed unless someone carefully calculated the size and shape of each stone that went into the building. Most likely, some method was used to document that information since many people were involved in the work. It was only during the early part of the 15^{th} century that the concept of graphic projections was well understood by early Italian architects. This was about the same time that paper began to replace parchment as a drawing medium.

Existing engineering drawings describing machines and buildings date back to the fourteenth and fifteenth centuries. Most of these are in bound volumes stored in European museums and libraries, particularly in southern Europe, and viewing them is restricted primarily to academic researchers. Today, we would describe them more as sketches than as technical drawings. They were not to scale nor did they have dimensions. Many of these documents contain extensive textual descriptions that help one understand the intent of the drawings.

Early engineering drawings served two purposes. On one hand, they were a reference experienced craftsmen used to build or construct what was portrayed. While the drawings were more symbolic than what we are familiar with today, these craftsmen

[1] Wilkinson, Philip, *Amazing Buildings*, Dorling Kindersley, New York, 1993

understood the intent of their iconic descriptions and were not concerned by the lack of dimensions since every machine or building they worked on was unique. The other function of these drawings, particularly those collected in portfolios, was for presentation to the designer's patron, either a prince or wealthy merchant.[2]

Some of the best known early engineering drawings is the work of Leonardo da Vinci. While he is well known for his Mona Lisa, he was also a designer of military machines and forerunners of today's industrial machines. Leonardo's design work was artistic in nature - more illustration than engineering drawings. No multi-view drawings of any of his designs are known to exist today. Yet during the past century, skilled craftsmen were able to construct models of many of his designs working strictly from his sketches.

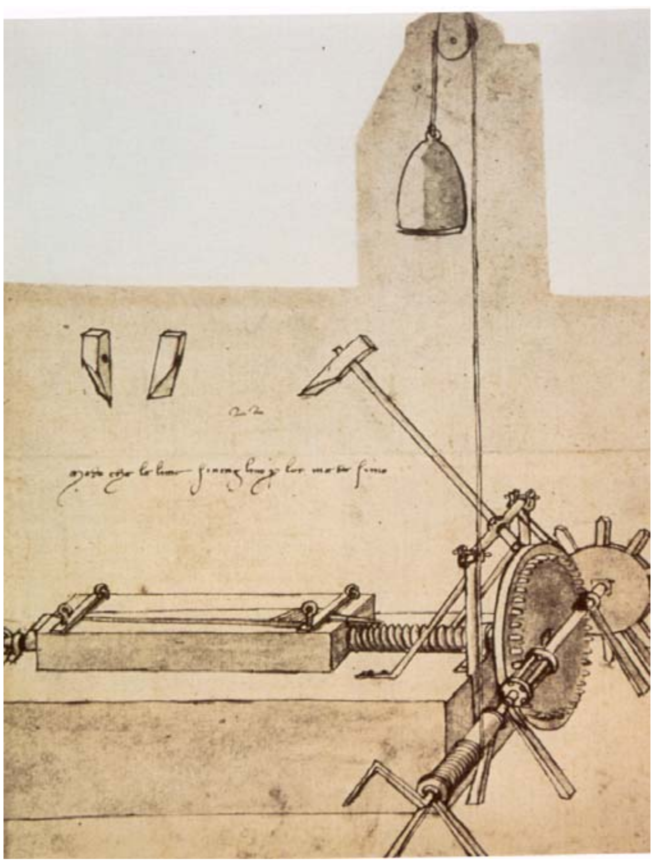

Figure 2.1
Leonardo da Vinci Machine for Cutting Files

> "Both the drawing's beauty and the ingeniousness of the mechanics make this file cutting machine very interesting. The operation is completely automatic: the weight falls unwinding the rope and activating both the rise and fall of the hammer and the progress of the piece to be cut, by using gears and levers. The complete automation not only helps Man but also gives more homogeneous results, foreshadowing modern production processes."[3]

[2] Lefèvre, Wolfgang, *Picturing Machines 1400-1700*, MIT Press, 2004
[3] Cianchi, Marco, *Leonardo's Machines*, Edizioni Becocci – Largo Liverani, Florence, Italy

Early Drafting Practice

Most early practitioners of engineering drawings – such as Leonardo were also artists. Gradually, a realization developed that drawings had to stand on their own merits and that greater precision was needed. One early proponent of this belief was Leon Battista Alberti who, in 1435 and 1436, wrote two works that explored the need to incorporate more Euclidian geometry in contemporary drawings.[4] He also proposed drawings with multiple views rather than the single view then common.

Modern engineering design and drafting practice can probably be traced back to the development of descriptive geometry, especially the work of René Descartes (1596–1650) and Gaspard Monge (1746–1818). Engineering drawing began to evolve more rapidly in the late 18th century and picked up speed with the Industrial Revolution of the 19th century.

Peter Booker, in *A History of Engineering Drawing*, does a good job distinguishing the more technical practices of the European continent from the craft practices of England. He also describes in depth how early drafters (many of whom actually had degrees in engineering) used water color paints to highlight their drawings. This practice lasted until the early part of the 20th century. What is somewhat surprising is the fact that drafting standards, as we know them today, were not taken seriously until after World War I. The first American standard in this area was not approved until 1935, just two years before I was born.[5]

It is my impression that a major catalyst in the development of technical drawing was the growth of the patent process. In order to receive a patent for a new device, one had to submit drawings in specific formats. This was complicated by the fact that until the development of blueprints, no means existed to economically copy drawings and if multiple versions or copies of a drawing were needed they had to be copied or traced by hand. Sir John Herschel discovered the blueprinting process in 1840 and introduced it in the United States in 1876 but it was much later before it was widely used.

Early engineering drawings were often works of art. Like contemporary penmanship, this is a skill that few retain. Permanent drawings were often made with ink. An initial drawing was done using a pencil, T-square, triangles, scales, irregular (French) curves and drawing instruments such as compasses and dividers. Early drafting text books spent pages describing how to sharpen pencils and how to hold them to obtain an even line.

Once the pencil drawing was done, a sheet of tracing cloth would be tacked or taped over the original drawing. Each line would then be copied using pen and ink. Particular attention was always paid to lettering on the drawing. Over the years, various templates and other devices were introduced that enabled drafters to produce consistent quality lettering. Perhaps the most commonly used device was the Leroy Lettering Set manufactured by Keuffel & Esser. The set consisted of several templates of various sizes and a pen device that followed the shape of the

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[4] Lefèvre, Wolfgang, *Picturing Machines 1400-1700*, MIT Press, 2004, pg. 176

[5] Booker, Peter Jeffrey – *A History of Engineering Drawing* – Chatto & Windus 1963

letter in the template and reproduced that character in ink on the drawing. The company sold a variety of templates with different fonts.

Another major advance was a device called a Universal Drafting Machine as shown in Figure 2.2. This device basically combined the T-square, triangles, scales and protractor. It enabled the drafter to create perpendicular lines at any orientation. Among the manufacturers were Universal Drafting Machine Company, Frederick Post, Bruning, and Keuffel & Esser. The latter two are of particular interest in that they subsequently attempted to develop CAD system businesses selling mid-priced systems. Both lettering templates and drafting machines are still sold today although it may be hard to find a local dealer.

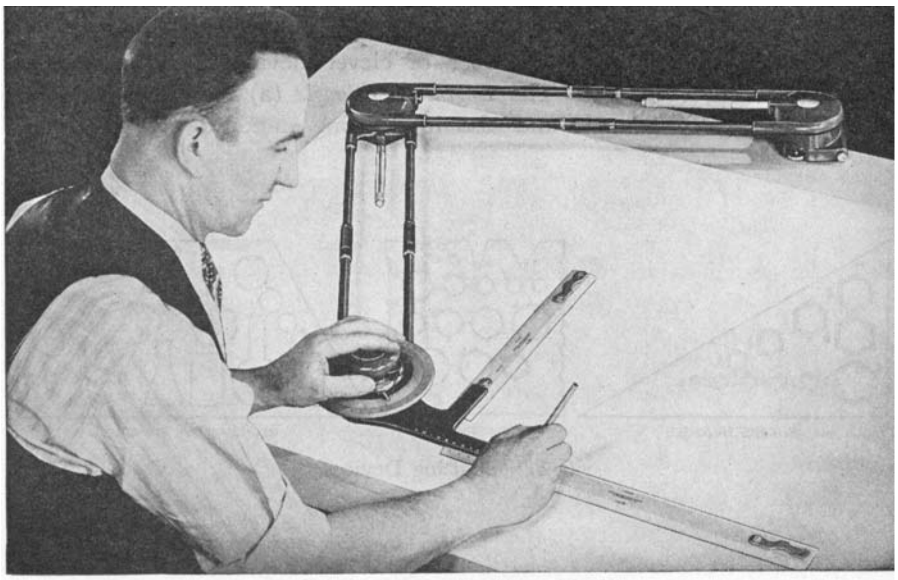

Figure 2.2
Universal Drafting Machine

Eventually, different engineering disciplines developed their own methods and approaches to engineering design and drafting. Architects had a style that was applicable to their work but was much different than what aeronautical engineers used. A major problem in the latter case was the need to produce accurate drawings at 1:1 scale for large components of an airplane since it was not possible to convert smaller drawings into the templates needed to produce these parts. Figure 2.3 shows several engineers and technicians creating a aircraft master layout.

During the decades following the Second World War, drafting equipment suppliers introduced a variety of materials to improve the productivity of the drafting process. Instead of drawing every detail on a drawing, stickers representing these items could be applied to the drawing. Together with a new generation of reproduction machines, the time to create routine drawings was reduced substantially.

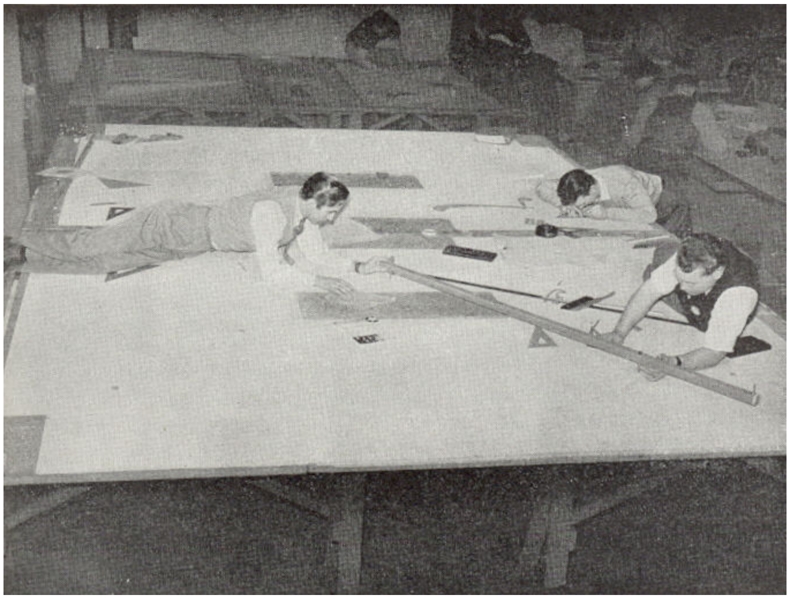

Figure 2.3
Creating an Aircraft Master Layout

In addition to the difficulty of producing engineering drawings, the design process itself was complicated, particularly by the lack of computational machines. I clearly remember one homework assignment in structural engineering in the late 1950s. The problem was a fairly straightforward two-story building - perhaps three by four bays. Working with simply a pad of paper and a slide rule, the assignment took most of a weekend. I didn't learn much about structural design but it did sharpen my arithmetic skills. Today, a student with a notebook computer can work on a building ten times as large and learn much more about what makes for a good design by trying different size structural members and different arrangements of these components.

Calculations were typically done with slide rules, electromechanical desk calculators and handbooks of mathematical tables and engineering data. Many technical calculations were done using logarithms which enabled multiplication and division calculations to be done using addition and subtraction. The most popular handbook for doing these calculations was first published in 1933 by Dr. Richard Burington. Unfortunately, these handbooks often contained minor errors. Burington's handbook was reprinted numerous times, each with corrections from prior editions.[6]

The engineering design process, including the preparation of drawings, was fraught with opportunities for error. One result was that every calculation and drawing was checked multiple times, especially when the consequences of an error could be disastrous. While computers have taken much of the drudgery out of engineering design, we know they are not perfect and it is still possible to make horrendous mistakes if one does not exercise the appropriate levels of care.

[6] Burington, Richard S., *Handbook of Mathematical Tables and Formulas*, Handbook Publishers, Sandusky, Ohio, 1955

Understanding the technology food chain

There is a phenomenon that takes place in the computer industry that is the reverse of the biological food chain. Except in this case, rather than the larger animals eating successively smaller animals the lower levels of the technology food chain absorb the capabilities of the higher levels. This phenomenon explains both the vast improvements we see in performance coupled with steadily reduced costs, particularly in regards to hardware.

So how does all this relate to design automation technology? One can look at the components of a computer system as being similar to a food chain. A system used for CAD applications might be organized somewhat as shown here:

Training and system usage
Customized applications
Information services
Standard applications
Application development tools
Database technology
Modeling and drawing production
Graphics systems
Operating systems
Computer systems
Specialized expansion boards
Function specific circuits
Computer microprocessor(s)

What is taking place in the computer industry is that specific capabilities are relentlessly moving down the food chain. Functions that once had to be done as part of an application package are now done in the operating system, and functions that once were done in the operating system are now part of the basic computer processor. Typically this results in faster performance as these functions move closer to the core of the computer. It also has the benefit of reducing costs.

One easy example to follow is what happened over time to floating point processors. Thirty to 35 years ago most minicomputer systems handled floating point operations with software routines embedded in the operating system. The need for greater performance encouraged the computer manufacturers to fabricate hardware floating point accelerators. These were typically the size of a small refrigerator and cost $20,000 or more. Early engineering workstations typically came with board-size floating point options that sold for several thousand dollars. During the mid-1980s, a number of semiconductor manufacturers developed individual chips or a small set of chips that performed the same floating point operations as did the add-in boards. These chips were simply added to the computer’s motherboard. In the PC world, they were called math coprocessors. The manufacturing cost came down dramatically, the computer systems vendors easily incorporated these chips into their products and performance improved. The next step involved adding floating point functions to the basic microprocessor chip.

Performance improved since data did not have to flow between multiple circuit boards or even between individual circuits. Floating point operations are virtually transparent to today's computer systems and operating systems. In fact, most non-technical users are not even aware that this capability exists it has become so ubiquitous.

There are many other places in the technology food chain where functions have moved from one level to a lower level. Graphic services software is a good example. Graphic services are those functions that handle user interactions in a graphic system and display requested images on the display screen. In the past, every CAD system vendor invested a significant portion of its development resources producing software to handle these functions. There were two reasons for doing this. First, standard software was not readily available from the hardware vendors and second, this was how software vendors attempted to discriminate their products from competitive products.

Over time, industry standards such as X-Windows, MOTIF, and Open GL became accepted in the market and workstation and PC vendors began offering this software as part of their standard operating system. As a result, the vendors of application software revised their development strategies. They began to use standard operating system functions instead of proprietary software code for these tasks. Typically, 80 percent or more of the earlier proprietary software was replaced through the use of standard techniques incorporated in the operating system.

There are many other examples that could be used to explain this concept including graphic cards, networking, file management software and printer support. In the early days of the CAD industry, system vendors had to spend considerable effort designing basic hardware components and programming foundation-level software functions. Today's PC comes with all these capabilities built in and as a consequence CAD software vendors are able to concentrate their development resources on providing enhanced and more reliable applications.

For many year, programmers spent considerable effort compensation for limited main memory, small data storage devices and slow performance. The changes since the first commercial system were introduced have been astounding. In 1972 vendors such as Calma agonized over the cost of increasing their systems main memory from 16KB to 24KB. Disk drives were typically 5 to 20MB. And this had to be shared by typically four users. Today, you can buy a PC with 2GB of memory and a 250 GB disk drive for about $1,000. Companies that were successful were the ones that understood the pace the technology was changing and focused their R&D on what would be rather than what had been.

As we will see in following chapters, many companies never did understand these concept or were simply incapable of adapting to the fast pace the underlying technology was changing.

The computer begins to change engineering practice.

Chapters 3 and 4 provide a detailed description of some of the early developments involving computer graphics and research in applying computers to design and manufacturing. It is not my intent to duplicate that information here. Rather, lets just try to put this pioneering work in perspective.

Early computer development in the mid-1940s was mostly funded by military agencies and these machines were used to calculate information such as ballistic trajectory tables. In fact the term "computer" was originally used to describe the people who did these calculations manually. A decade later, IBM, Sperry-Rand and a few other companies began delivering computers to large engineering organizations, especially in the defense and automotive industries. Gradually, a number of programs for solving engineering problems were developed. In some disciplines, such as highway design, programs were readily shared between users while in other areas they were treated as highly proprietary.

The typical process for solving a technical problem involved the engineer filling out a coding form with applicable data. These forms would then be given to a keypunch operator who would produce a deck of punch cards and perhaps a listing of the data. The engineer would then review the numerical listing for errors and have the keypunch operator make corrections if necessary. The card deck would then be submitted to a computer operations scheduler who would submit the job to be executed.

These computers ran one job after another in what was referred to as a batch operation. The results of the computer run would then be provided to the engineer in the form of a numerical listing. Frequently, this meant that someone had to carefully plot the results in a way that enabled them to be visually interpreted. The overall process was referred to as a "closed shop" and it could take anywhere from a day for a minor problem to several weeks for a complex problem.

Lower cost computers that could be operated directly by engineering departments began to appear in the mid 1950s. Machines such as the Librascope LGP-30 (Librascope General Purpose) were vacuum tube machines that were slower than today's hand-held calculators but still provided a substantial advance over manual calculations. Output was mostly in the form of numerical listings although digital plotters from CalComp Computer Products began appearing around 1960.

IBM introduced the very popular 1620, an all-solid-state computer, in 1960. This machine leased for about $3,000 per month (most IBM computer were leased rather than sold outright at the time) and had performance of less than 0.01 MIPS (Millions of Instructions Per Second). While this is incredibly slow by today's standards, it was more than adequate for solving many engineering problems.

Large mainframes such as the IBM System 360 Model 60 leased for $40,000 per month and had performance of about 0.36 MIPS. These computers supported double precision floating point arithmetic and therefore were used for more complex engineering analysis applications.

Development of in-house CAD systems

In the mid-1960 time frame there were no commercial graphics systems on the market except for the Control Data Digigraphics system described in Chapter 6 and only a few of these were sold. The need for computer-based graphic systems to improve the productivity of engineers and drafters was slowly being recognized by large manufacturing companies, especially those in the automotive and defense and aerospace industries. Some of the work undertaken by these companies is described in Chapters 3 and 4.

This early work fell into two categories. On one hand, automotive companies such as Renault and Ford focused on the mathematical definition of complex surfaces while other companies, such as Lockheed California focused on improving drafting productivity. The Renault work eventually evolved into Dassault Systèmes's CATIA while Ford's PDGS software is probably still used on occasion today. Lockheed's work, of course, resulted in the CADAM product described in Chapter 13.

What was common to this in-house activity was that these companies used large mainframe computers, primarily those produced by IBM, and they mostly used vector refresh graphics terminals. A key hardware development was the introduction of the IBM System 360 product line in April 1964 which included the Model 2250 refresh graphics terminal. In subsequent years a number of companies including Adage and Spectragraphics produced terminals that were "plug compatible" with IBM's equipment, but typically less expensive. Other than CADAM and CATIA, little of this in-house work led directly to successful commercial systems.

Introduction of commercial systems

The CAD industry, as it subsequently evolved, started in 1969 with the formation of Applicon and Computervision. They were joined within a few years by Auto-trol Technology, Calma and M&S Computing (Intergraph). These companies and other early industry pioneers are described in later chapters.

While the in-house systems mentioned above used mostly mainframe computers and vector refresh graphics terminals, the early commercial systems used minicomputers such as the Digital Equipment PDP-11 and the Data General Nova-1200 and Tektronix storage tube displays. The typical system consisted of a 16-bit minicomputer with an 8KB or 16KB main memory, a 10MB or 20MB disk drive and one to four terminals. Most systems included large digitizer tables, keyboards for command entry, a tablet for coordinate entry and a digital plotter. The primary manufacturers of plotters at the time were CalComp, Gerber and Xynetics.

The typical system included a considerable amount of proprietary hardware. For the most part, these companies were equipment manufacturers who developed software to help sell their hardware. Fifteen years later most were struggling to make the transition to a software business model where industry-standard computer hardware was being used. Early systems were predominately two-dimensional drafting oriented with a particular focus on integrated circuit and printed circuit board layout. In the latter case, artwork was often generated on photoplotters produced by Gerber Systems.

A typical single station system sold for about $150,000 in 1972 with additional stations costing perhaps $50,000 each. This is equivalent to about $700,000 and $230,000 respectively 25 years later. Domestically, all these companies sold their systems through a direct sales organization. With just a few exceptions, the sales people were all men. Internationally, country distributors were utilized.

These systems were marketed predominately on the basis that they could reduce current operating costs. If you had a drafting department with 20 drafters, buy one of these systems, run it around the clock and you could get the same amount of work done with perhaps 10 or 12 people. In some cases, productivity improvements were truly spectacular, especially within organizations that did a lot of repetitive work. Most of these early systems had user-centric programming languages that facilitated the development of automated processes for generating standardized drawing working off minimal input data.

Performance was often an issue and early manufacturers put significant effort into building graphic interfaces that would speed up the process of generating display images. When a graphical element was moved or deleted from a storage tube display, the entire image had to be regenerated. Adequate performance required imaginative software and specialized hardware.

Throughout the 1970s, the CAD industry grew from virtually zero to a billion dollar hardware and software business. New companies constantly joined the fray but the market was dominated by the five turnkey vendors mention earlier.

Evolution of geometrics modeling

One area where university research played a significant role in the evolution of the CAD industry was in geometric modeling, both in regards to surface geometry and solids modeling. The earliest CAD systems simply handled two-dimensional data, emulating traditional drafting practices. The initial transition to three dimensions was done using wireframe geometry – points in space and the lines connecting these points.

Solid objects and surfaces were defined simply by lines that represented the edges of the geometry. Without additional information, it was not possible to generate shaded images of wireframe objects nor could hidden lines be removed without manual intervention. Obviously, better methods were needed.

Surface modeling technology was driven by the automotive and aircraft industries since manually defining and manufacturing sheet metal parts for these vehicles was becoming increasingly time-consuming and costly. One just needs to compare the boxy Ford Model A of 1930 to the 1975 Chevrolet Nova to see how the automotive industry was changing. Likewise, new jet aircraft required smooth contours to reduce drag.

Sheet metal parts were manually designed using cross-section drawings from which templates were made. These were then used by patternmakers to produce a wood pattern that subsequently was used to machine stamping dies with a milling machine that copied the pattern. Many different people were involved in the process which was susceptible to error at each step. By the early 1960s, NC machine tools were becoming more commonplace and a way was needed to economically generate the digital information to drive these devices.

One of the first techniques for mathematically describing surfaces, known as Coons patches, was developed by Steven Coons at MIT in the mid-1960s.[7] Another major center of surface definition research activity was in France. As early as 1958, Paul de Casteljau, working at Citroën, developed a mathematical approach for defining surfaces. Due to a perceived competitive advantage, Citroën did not

[7] Coons, Steven, *Project MAC-TR-41*, MIT 1967

disclose his work until 1974. By then, a number of academic and industrial researchers had moved on to implement other techniques.[8]

Around 1960, Pierre Bézier proposed to Renault's management that the company develop a method for mathematically defining automobile surfaces. By 1965 this work was well underway and by 1972, Renault was creating digital models and using the data to drive milling machines. The company called the system UNISURF and it eventually became an important component of Dassault Systèmes CATIA software (See Chapter 13). A key aspect of the work was the development of the well known Bézier curves and surfaces which are still used in many graphics applications. Bézier based his work, in part, on the earlier development of the Bernstein polynomials, introduced in 1911 by Sergi Bernstein.

The work of Rich Riesenfeld, Elaine Cohen, Robin Forest, Charles Lang, Ken Versprille and others led to the introduction of a number of other ways for defining curves and surfaces. The sequence of events went somewhat as follows. Coons was working with Ivan Sutherland (See Chapter 3) who had gathered together a group of very good mathematicians and programmers including Bob Sproul, Danny Cohen, Larry Roberts, and Ted Lee. At times it is somewhat confusing as to what went on at MIT and what work was done at Harvard University but suffice it to say that this group was instrumental in developing some of the early theory in the area of geometric modeling.

They were soon joined by Robin Forrest who was a graduate student in the Mathematical Laboratory at Cambridge University. During the summer of 1967, Coons and Forrest developed a technique for defining rational cubic forms. This was followed in 1969 by Forrest's Ph.D. thesis in which he defined methods for describing different graphic entities using the rational cubic form methodology.

A year later, Lee's Ph.D. work at Harvard extended Forrest's research to describe bicubic surface patches. Coons moved to Syracuse University in 1969 where he became Rich Risenfeld's Ph.D. thesis advisor. Risenfeld's described a new approach called B-splines in 1973.[9] (The term B-spline is derived from the term Basis Spline of which the Bernstein Basis is a special case.) During the 1970s, there was a constant flow of individuals between Syracuse, New York and Cambridge, Massachusetts. Eventually, the University of Utah became a player in this story when some of the Harvard and Syracuse people joined David Evans and Ivan Sutherland to focus on graphics applications.

Another Syracuse Ph.D. candidate at the time was Ken Versprille who was working on the definition of rational B-splines. He completed his Ph.D. thesis on the subject in 1975 prior to joining Computervision.[10] Versprille is credited by many people as being the developer of NURBS (Non-Uniform Rational B-Splines).

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[8] Bézier, Pierre – A *View of the CAD/CAM Development Period* – Annals of the History of Computing Volume 20, Number 2, 1998

[9] Risenfeld, Rich *Applications of B-Spline Approximation to Geometric Problems of CAD*, Ph.D. thesis, Syracuse University, February 1973

[10] Versprille, Kenneth J., *Computer-Aided Design Applications of the Rational B-Spline Approximation Form*, Ph.D. thesis, Syracuse University, February 1975

The next step at Syracuse was the work done by Lewis Knapp whose 1979 Ph.D. thesis was also a key building block in the evolution of NURBS.[11]

An additional step was the development of what became known as the Oslo Algorithms. In early 1979, Riesenfeld and his wife, Elaine Cohen, took a sabbatical from Utah to work with the CAD Group at the Central Institute, a research activity associated with the University of Oslo. Together with Tom Lyche, they defined a set of mathematical techniques that substantially enhanced the functionality of B-splines.

Significant work on surface definition techniques was also being done at a number of aircraft and automotive companies. Boeing was particularly active in the late 1970s and early 1980s working on surface geometry techniques based on this earlier academic research. One of the key developments at Boeing was the work James Ferguson did with cubic curves and bicubic surface patches.[12] Boeing was also one of the early proponents of IGES (Initial Graphics Exchange Specification) based on CAD system interoperability efforts it had underway at the time. In 1981, Boeing proposed that NURBS be added to IGES. This subsequently occurred in 1983.[13]

The development of NURBS technology has proven to be one of the key building blocks for advanced geometric modeling. As David Rogers, a professor at the United States Naval Academy, so eloquently puts it:

> "…with NURBS a modeling system can use a *single* internal representation of a wide range of curves and surfaces, from straight lines and flat planes to precise circles and spheres as well as intricate piecewise sculptured surfaces. Furthermore, NURBS allow these elements to easily be buried within a more general sculptured surface. This single characteristic of NURBS is key to developing a robust modeling system, be it for computer aided design of automobiles, aircraft, ships, shoes, shower shampoo bottles, etc. or for an animated character in the latest Hollywood production ……."[14]

A key observation needs to be made at this point. Much of the work going on in developing better surface definition techniques was being done at academic research centers and was typically published in widely available journals. Each researcher was, therefore, able to build on the work of those who had tackled earlier aspects of the problem. As seen by what occurred at Citroën, this would probably not have occurred if the work had primarily been done by industrial companies.

In regards to this latter issue, most automotive manufacturers were also working on internal surface geometry applications. Their major focus was in taking

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[11] Knapp, Lewis, *A Design Scheme Using Coons Surfaces With Nonuniform Basis B-Spline Curves*, Ph.D. thesis, Syracuse University, February 1979

[12] Ferguson, James C. *Multi-variable curve interpolation*, Journal of the ACM, Vol. 11, No. 2, 1964, Pg. 221-228

[13] Rogers, David F., *An Introduction to NURBS*, Academic Press, San Diego, 2001, Pg. 130

[14] Ibid, Preface

data points from full scale clay models and converting that information into digital surfaces that could be used to machine stamping dies.

Moving from wireframe and surface geometry to solids modeling

This subject could easily be a book in its own right and, in fact, a number of books on solids modeling have been written in recent years. Unfortunately most are filled with complex equations and diagrams that only a mathematician would appreciate. My intent is to try to put the evolution of solids modeling into more readable terms. It is interesting to note that there was little overlap between the individuals working on surface definition technology and the early proponents of solids modeling

There were a number of different research threads that eventually led to today's solid modeling technology.[15] One of the most important of these revolves around the activities of The CAD Group in Cambridge, England. Starting in the late 1960's, the efforts of this organization resulted in what is probably one of the more influential series of innovations and developments in the CAD industry. Basically, The CAD Group created the foundation for the three-dimensional solids modeling software that has been used as a technical building block by hundreds of CAD software companies and is used by millions of users worldwide today.

Determining where three-dimensional solid modeling started has proved almost impossible. Solid modeling research started in at least eight geographic locations independently of each other, almost all at the same time in the late 1960s and early 1970s. Even with activity and research being conducted around the world, no real usable product was available until the late 1970s and it really wasn't until the late 1980s that solids modeling became a commercial reality. However, many consider the first commercial product to be MAGI's SynthaVision which used primitive solids with high resolution rendering. Launched in 1972, SynthaVision is famous for its use in Walt Disney Productions' 1982 movie *TRON*, the first full-length animated feature film.

It was at the PROLAMAT Conference, held in Prague in 1973, that many of geographically disparate groups initially met – and started talking about this technology. At this conference, Ian Braid, from Cambridge's CAD Center, presented BUILD – using what is now called B-Rep or Boundary Representation technology. At the same event, Professor N. Okino from Hokkaido University, introduced TIPS-1, a CSG-based solid model program.[16] Also in attendance were Herbert Voelcker from the University of Rochester who was managing the PADL research activity, Professor Spur who was conducting research into solids modeling at the University of West Berlin, Dr. J. M Brun from University of Grenoble who masterminded Euclid (See Matra Datavision in Chapter 21) and others who helped drive the proliferation of solids modeling in following years.

The CAD Group at Cambridge was involved in this work far longer than any other organization. They developed technologies in the 1970s that are still being used (albeit using newer state-of-the-art programming techniques) today. ACIS (See Spatial Technology in Chapter 21), subsequently developed by this team, is currently used in

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[15] Particular thanks go to Rachael Taggart for help with this section as well as input from Charles Lang.

[16] CSG or Constructive Solid Geometry builds a solid model using primitive shapes such as cones and spheres and Boolean combinations of these basic elements. Boundary Representation of B-Rep models use surface definitions to describe the enclosed solid.

several million CAD seats. The same group also pioneered what became Parasolid, which supports another million or so CAD seats worldwide. None of the other solids modeling pioneers can boast of this type of track record.

Charles Lang graduated from Cambridge University in 1960 with a degree in engineering. After several years at Mullard Research in England, Lang enrolled as a graduate student at MIT in 1963 and worked at Project MAC for more than 18 months with Doug Ross and Steven Coons. Lang was then recruited back to Cambridge University's Computer laboratory by Professor Maurice Wilkes.

The British Government arranged funds and resources that underwrote the activities of the Cambridge CAD Group in 1965 – the group founded by Wilkes and headed by Lang until 1975. In 1969, the group started developing solid modeling software on a Digital PDP-7 system using assembly language programming. "Unfortunately no one told us it was impossible," says Lang. "But then Ian Braid turned up."[17]

In 1970, Ian Braid joined the group and focused on writing solid modeling code with particular attention to data structures. The result of his first thesis was BUILD1 – a solid modeling system presented at PROLOMAT – that used Boolean logic and simple solid geometry, grey-scale images and hidden line drawings. "BUILD1 had only planar and cylindrical surfaces implemented incompletely," according to Braid. "But it showed how one might interact with a solid model held in a computer and what could be done with it in changing or recording models, generating pictures, finding mass properties or in generating cutter paths."

Alan Grayer joined the team in the early 1970s, and by 1975 was generating NC tapes for 2½ axis milling machines. "This was the first time anybody automatically generated NC from a 3D model," says Lang. The Cambridge team regularly worked with Pierre Bézier at Renault as well as maintaining close relationships with MIT, Utah and Syracuse researchers.

According to Lang, funding for the Cambridge CAD Group started looking uncertain in 1974, and the team formed a company called Shape Data. Founders were Ian Braid, Alan Grayer, Peter Veenman and Charles Lang. "The company started without money and indeed, we never really formed it to make money," says Lang. "We started it to make the technology work." Shape Data was the first spin-off from the Cambridge CAD Group and according to Lang there have been nearly 90 spin-offs from the computer labs since. Peter Veenman started with the company full-time although the rest of the team remained with the CAD Group until 1980.

"Our original vision for Shape Data was based on a great relationship with Dave Evans – he knew modeling was much more fundamental than graphics and he had a vision of Evans & Sutherland being a one stop shop for people to get components to build 3D systems," Says Lang.

In 1978, Shape Data completed the industry's first commercial release of a solid modeling kernel – called Romulus. In 1980, Lang, Braid and Grayer joined Shape Data full-time. Then, in 1981 the company and its technology was acquired by Evans & Sutherland. In 1985, Lang, Braid and Grayer left the company and formed Three-Space

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[17] Quotes from Lang and Braid are based on telephone conversations and emails in mid-2004 with the author and Rachel Taggart.

Limited without a particularly clear idea of what they would do. Within several years, the team was hard at work on a new solids modeler – ACIS.

Simultaneously, Shape Data began work on creating Parasolid – a solid modeling kernel that was derived from the original Romulus work but used newer techniques and technologies.

As described in Chapter 21, Spatial Technology funded the early development of ACIS which was initially released in 1988. That same year Shape Data released Parasolid, and the company was acquired by McDonnell Douglas. In 1989, Parasolid was first used in a release of McDonnell Douglas' Unigraphics software.

Another significant center of solids modeling development was the Production Automation Project (PAP) at the University of Rochester. PAP was founded in 1972 by Herbert Voelcker who was a professor of electrical engineering at the time.[18] The intent was to develop automatic programming systems for NC machine tools. Voelcker was joined by Ari Requicha in 1973. The group soon redirected its activity to solids modeling and its first system, PADL-1 (Part & Assembly Description Language) was demonstrated at a CAM-I meeting in 1976 and made publicly available 15 months later. This was followed in 1981 by PADL-2. In addition to the normal contingent of graduate and undergraduate students, PAP also benefited from the assignment of engineers on loan from industrial companies that were interested in understanding this new technology.

The initial PADL-1 software used a combination of CSG and B-Rep techniques. The software was written in a derivative of FORTRAN and therefore was able to be ported between computer system fairly easily. The University of Rochester licensed the software in source code format for $1,200 to universities and $2,400 to commercial users. Licensees had virtually unlimited rights to the software. Between 1978 and 1985, the university issued 80 licenses. Fifteen years later, PADL-1 was still being used in academic institutions as a teaching tool. The PADL-2 project was launched in early 1979 with Chris Brown as the project director. Approximately $800,000 in funding was provided by ten industrial sponsors and the National Science Foundation. The intent was to be able to model 90 to 95 percent of unsculptured industrial parts. PADL-2 was also written in FORTRAN for portability reasons although this restricted the development team's ability to fully utilize newly evolving object-oriented programming techniques.

PADL-2 was initially distributed to the project sponsors in mid-1981. While organizations such as Sandia National Laboratory and Kodak used the software extensively for internal applications, most of the industrial sponsors did little with the software. An exception was McDonnell Douglas Automation which began the development of UNISOLIDS based on PADL-2 in 1981 and demonstrated the software at AUTOFACT in late 1982. Public distribution of PADL-2 began in mid-1982. License fees without the rights to redistribute the software varied from $600 for educational institutions to $20,000 for commercial concerns. Companies that wanted to build commercial solutions around PADL-2 were charged $50,000, the same amount paid by the initial sponsors. Between 1982 and 1987, Rochester issued 143 license agreements.

In 1987, the PAP was disbanded and the PADL technology and Voelcker moved to Cornell University which continued to distribute the software for a period of time. One

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[18] Voelcher, Herbert B. and Requicha, Aristides A. G., *Research in Solid Modeling at the University of Rochester: 1972-87*, chapter in *Fundamental Developments of Computer-Aided Geometric Modeling*, Edited by Les Piegel, Academic Press, San Diego, 1993

interesting development involved Cadetron which recoded PADL-2 in C for use on PCs. Cadetron was subsequently acquired by Autodesk where the software was marketed as AutoSolid.

The basic structure of the CAD industry changes

The decade of the 1980s was perhaps the most significant period regarding the evolution of the CAD industry. At the start of the decade, the industry was dominated by five companies – Applicon, Auto-trol Technology, Calma, Computervision and M&S Computing (Intergraph). Other companies starting to make themselves felt included McDonnell Douglas Automation, SDRC and IBM which was marketing Lockheed’s CADAM software. Only Computervision and IBM manufactured their own computers but the other companies, except for SDRC, designed and built relatively expensive graphics terminals and other system components. For the most part, these turnkey systems vendors were manufacturing companies that happened to sell software. The industry’s early profitability clearly revolved around manufacturing margins.

Two significant changes took place in the early 1980s. One was the transition from 16-bit minicomputers such as the Digital PDP-11 and Data General Nova 1200 to 32-bit super-minicomputers such as the Digital VAX 11/780. At the time, Digital clearly dominated this segment of the computer market. The other change taking place was the shift from Tektronix storage tube graphics terminals to color raster technology. In the latter case, this actually enabled the companies to manufacture a greater portion of their systems. All of the companies were engaged in major revisions to their software – in some cases a total rewrite of these systems.

In general, CAD systems circa 1980 sold for about $125,000 per seat or the equivalent to over $300,000 today. That was a lot of money when you realize that you can purchase Autodesk’s Inventor Professional software and a moderately high performance PC for less than $10,000 today. Early systems often required an air-conditioned computer room. Even basic operator training took several weeks and, for most systems, it could easily be six months before they were back to a 1:1 productivity ratio.

Because these systems were relatively expensive they tended to be run on what is typically referred to as a “closed shop” basis. The systems were typically operated by individuals who spent full time working at the graphics consoles. Engineers and designers would bring work to the “CAD Department” and then come back hours or days later to received plotted output which they would carefully check. Marked up drawings would be returned to the CAD operators who would revise the drawings and return them once again to the requestor. It was a rare situation where an engineer was either allowed to use a system for interactive creative design work or sit with an operator and have that person directly respond to suggestions. The costly nature of these systems often resulted two, or even three shift, operation.

A snapshot look at the industry

In late 1982, Input, a market research firm then headquartered in Mountain View, California, prepared an in-depth analysis of the CAD industry for General Motors. This report was based on extensive interviews with both users and vendors. While I do not agree with all their findings, the report did highlight some key issues facing the industry and the user community at that time.

The lack of effective solids modeling was identified as a major constraint on industry growth. Enough research on the subject had been done by then to whet the appetite of users but workable solutions were still off in the future. The report also emphasized application integration or rather, the then current lack of solutions that integrated a variety of design and manufacturing applications. The need to tie database management tools into the application mix was also an urgent requirement. Users particularly wanted more reliable software. These three issues were felt by respondents to be more important than ease of use and adequate service and education.

Key trends then underway included the transition to intelligent workstations, networking and the shift to color graphics. The need for color was reported to be a much higher priority in late 1982 than it had been in a similar study the firm did just a year earlier. The report also identified a major shift in costs that was already underway – hardware was becoming less expensive and software was becoming more costly. Input's report did not spend much time discussing the stress this would put on current turnkey system vendors.

A portion of the report touched on the subject of user productivity. The authors pointed out that most companies were justifying the technology simply on drafting productivity and were not taking into consideration other elements of productivity including shorter product cycles and improved product quality. The inability of most vendors to expound on this issue was considered a drag on market acceptance of CAD technology.[19]

Engineering workstations replace minicomputers

One of the most significant hardware development in the 1980s was the introduction of the engineering workstation. Most CAD system vendors had been implementing more and more capability in their graphic terminals, offloading an increasing portion of graphic manipulation functions from the host computer. The engineering workstation took this one step farther and offloaded all application software execution as well. The minicomputer or mainframe host was now needed just for file management if at all and this was soon replaced by a specialized form the workstation called a server. The other key characteristic of these devices was that they could be networked together so that they could share data and even computer programs.

The first engineering workstation vendor was Apollo Computer, started by John (Bill) Puduska. The company's early machines were more oriented towards software development but shortly after signing OEM customers such as Auto-trol and Calma as well as Mentor Graphics, a leading EDA vendor, Apollo began producing systems with good graphics capabilities. These early machines used Motorola 68000 microprocessors and their floating-point accelerators were reduced in size to just a single circuit board.

There were a number of advantages to workstation based CAD systems over the older minicomputer based products. First of all, the entry cost and the per seat cost was much lower. Prices quickly dropped to about $75,000 per seat and within a few years to under $50,000. In addition, performance was more predicable. When a company had six

[19] *Overview of the Computer-Aided Design and Manufacturing Engineering Marketplace,* Input, Mountain View, California, November 1982

or eight terminals hung off a VAX 11/780 and one user initiated a complex analysis task, the performance of all the other terminals suffered. If the host computer failed, all the terminals were inoperative. With engineering workstations, performance depended upon what the specific user did, not other operators, and if one workstation failed, the others were still operable.

Apollo's workstations incorporated a significant amount of proprietary technology, particularly in regards to its operating system and networking. The AEGIS operating system was UNIX-like but it was not UNIX. The token-ring network was proven technology but it was not Ethernet which was rapidly emerging as a computer industry standard. Sun Microsystems was started just enough later than Apollo that it was able to use industry-standard UNIX software and Ethernet components. Sun was soon joined by Silicon Graphics or SGI as most people know it. SGI emphasized high-performance graphics but otherwise produced relatively standard workstations and servers.

Soon, the computer industry exploded with perhaps 20 or more manufacturers of engineering workstations. They were often referred to as JAWS (Just Another Workstation System). Most never really got off the ground and soon faded from sight. The major computer manufacturers were a different story. Companies such as IBM, Hewlett-Packard and Digital realized that these workstations were a competitive threat and they introduced similar products. IBM's RS/6000 was a respectable product but HP and Digital struggled to gain momentum in this area. Digital never really established significant market share. HP solved its problem by acquiring Apollo in 1989.

As described in later chapters, the early industry leaders struggled in making the transition to industry standard workstation hardware and becoming more of software and services businesses. The fundamental problem was that they each had made significant investments in manufacturing facilities and personnel and now were faced with the problem of unwinding that business. This was not easy. Some like Auto-trol tried to maintain a manufacturing focus by repackaging its Apollo workstations in the same terminal configurations it had used earlier. There was no easy way out and it led to the eventual downfall of all the early leaders except Intergraph.

Meanwhile a new group of vendors gained significant market share. Key among them was IBM teamed up initially with Lockheed's CADAM Inc. and later with Dassault Systèmes, McDonnell Douglas Automation which eventually morphed into UGS, SDRC and two newcomers, Autodesk and Parametric Technology, both of which are described below.

As the price of CAD systems came down, changes in how they were used also began to occur. While many organizations continued to operate CAD departments, other began to disperse systems into their design and manufacturing organizations. Instead of providing sketches to a professional CAD operator, design engineers were trained to do this work themselves. This became increasingly significant as new versions of the software enabled users to create drawings as a byproduct of the design process. The basic organizational structure of design teams began to change as companies adapted to the quickly evolving technology.

The personal computer becomes the new wild card

By 1987, vendors of traditional CAD systems had sold about 100,000 seats of software and the equipment to support these users. It had taken them 17 years to do so. In just five years, the new PC software vendors installed a like number of seats.[20] Today there are literally millions of CAD users, the vast majority working at PCs.

Personal computers actually predate the engineering workstation described above. The early machines were more collections of components for the computer hobbyist than serious technical tools. This began to change in August 1981 when IBM introduced its first PC, the Model 5150, which came with 16KB of memory, an alphanumeric display and no hard disk drive. But it only cost $1,995. The key decisions on the part of IBM were to use an Intel microprocessor, a 4.7 MHz 8088, and a new operating system from a small company in Seattle, Microsoft. As the familiar line goes – the rest is history.

It took some time before IBM PC-compatible machines had the performance and graphics capability to handle CAD software. Initially, the few companies such as T&W Systems (see Chapter 20) that were providing PC software worked with similarly priced computers such as the Apple II or more expensive machines such as Terak 8510. There were also a fair number of custom systems that people were experimenting with. Prior to starting Autodesk, John Walker and Dan Drake built PCs using Texas Instruments' 9900 microprocessor and Mike Riddle provided some of the software for these PCs using the CP/M operating system from Digital Research.

Over the next few years, Intel churned out a series of increasingly powerful microprocessors and math-coprocessors and third party vendors began offering graphics accelerator cards that could be plugged into a PC by a dealer or even tech savvy users. In 1983 Autodesk sold nearly 1,000 copies of AutoCAD worth about $1 million. There were a number of issues that separated the PC CAD market from that of the major vendors who were mostly in the midst of making the transition from being systems manufacturers to selling industry standard workstations and software.

- The concept was to sell 80 percent of the functionality of the larger systems for 20 percent of the cost. In reality, early versions of software such as AutoCAD and VersaCAD had much less than 80 percent of the capabilities in Computervision's CADDS 4, Intergraph's IGDS or Auto-trol's Series 5000.
- The PC software vendors did not try to do everything themselves. Third party software vendors who added application capabilities to the product were encouraged while the legacy vendors discouraged such activity by controlling access to the key programming tools used with their systems.
- This was a software only business.
- The software was sold through dealers who made most of their money selling hardware and by providing training services.
- Users called the dealer for technical support, not the software vendor.

Throughout the mid-1980s, the turnkey vendors treated the emerging PC market as something they wished would simply go away. Their sales people downplayed the capabilities of PCs and continued to push their own "big boy" solutions. By 1986

[20] Machover, Carl, *MicroCAD Trends – 1980/1990*, 4th Annual International Forum on Microbased CAD, September 23, 1987, North Carolina State University

Autodesk was doing over $50 million in annual revenue and these companies finally realized they had a fight on their hands.

The larger vendors took two approaches. Some ported a subset of their software to the PC, others created their own alternative to AutoCAD while several added UNIX co-processors to PCs and attempted to use the same software they ran on engineering workstations. In all cases, these were considered secondary products to the companies' mainstream systems.

A major inflection point occurred in mid-1993 when Microsoft introduced Windows NT. This made it much easier to support both UNIX and Windows versions of the same software and fairly soon all the vendors were offering Windows NT versions of their software. Although most charged the same whether the software ran on a UNIX workstation or a Windows NT PC, the hardware portion of a typical PC system was less than half that of an engineering workstation.

The PCs still were at a performance disadvantage, but the gap was closing rapidly, especially after Intel launched the Pentium microprocessor in mid-1995. Over the next decade, PCs became the primary platform for most CAD users with UNIX workstations relegated to specialty applications. PC performance is no longer an issue. In 12 years, Pentium clock speed has increased from 133 MHz to nearly 4.0 GHz, typical memory has gone from 256KB to over 1GB and graphic performance exceeds that of workstations costing over $100,000 in 1995. All this for just a few thousand dollars.

Substantially higher performance can be expected in the future. By late 2006, some PCs were equipped with microprocessors than contain dual or quad computing elements. Chips with eight, sixteen or more processing elements were expected over the next several years. CAD software, of course, has to be adapted to use this advanced processing capability.

Transition to feature-based parametric design

Parametric Technology Corporation (see Chapter 16) shook up the CAD industry in late 1987 when the company introduced a feature-based parametric modeling package called Pro/ENGINEER. While the software had some technical gaps, it demonstrated especially well and numerous companies began pilot installations in order to compare this new technology to the existing legacy systems most were using at the time. Other than Dassault Systèmes and SDRC, PTC's competitors were all going through the difficult transition away from manufacturing and/or marketing computer hardware. Unexpectedly, they were faced with making a major software change at the same time if they were to retain their existing customers.

While PTC did not necessarily invent all the concepts incorporated into Pro/ENGINEER, they did an excellent job of packaging and marketing the technology. Fairly quickly, the company began taking business away from the other vendors, especially Computervision. During the next five or six years, PTC's competitors added feature-based design and parametric capabilities to their mainstream packages with varying degrees of success. UGS, SDRC and Dassault did a good job making the transition while Applicon, Computervision and Auto-trol Technology soon faded from the scene. Eventually, even SDRC could not make it as an independent company and was acquired by UGS.

The emergence of mid-range systems

As the PC gained momentum as the CAD platform of choice, a new generation of CAD systems began to evolve. Usually referred to as mid-range systems to distinguish them from older legacy systems, they had several advantages over the older systems. This software was developed both by new start-up such as SolidWorks (see Chapter 18) and by established companies including Computervision and Intergraph. The mid-range systems differed both in the underlying technology and in how they were marketed.

- These systems were implemented strictly to execute on PCs running Windows.
- They used component software technology, especially for geometric modeling and constraint management.
- They focused on design and, to a lesser extent, drafting, and left other applications such as NC and analysis to third party partners.
- Like PC-based systems, the mid-range systems were predominately sold by dealers. The difference was that the vendors provided greater technical support.
- Typical software prices were between $3,000 and $6,000 per seat or about a quarter of the price being charged for full-function systems in the mid-1990s.

Over time, mid-range systems have somewhat merged with the full function systems although there are still some distinct differences. Dassault acquired SolidWorks and UGS acquired Intergraph's Solid Edge business unit. Autodesk entered the fray with Inventor and PTC repackaged Pro/ENGINEER in order to be more competitive in this space.

Where are we today

As explained in subsequent chapters, significant industry consolidation began to occur around the mid-1990s and continues as this is written. The major vendors now see themselves as offering more than just CAD and document management. The current term that describes the overall industry is Product Lifecycle Management or PLM. It is a $10 billion plus industry just for the software involved and there are literally millions of users of these tools. It has totally changed how engineering design is practiced and has been a major element in the increase in industrial productivity we have seen during the past decade.

In very simple terms, virtually no product, building, electronic component or system or factory is designed today in a developed country without the use of this technology. It has resulted in more reliable products that are less expensive to produce and are more attractive to potential customers. It has changed technical education and to a significant extent, the practice of numerous professions. Design engineers do analysis today that a few years ago was only done by highly specialized professionals. On the other side of the equations, drafting is rapidly going away as a profession as the new generation of design programs produce drawings as a byproduct of the design process and in many cases new designs are placed into production with few, if any, drawings.

In the past, there was a persistent battle between the desire to implement new software techniques and the performance of available computers. That has changed in recent years as the performance of low-cost computers has exploded. During the past 40 years, price/performance ratios of available systems have increased by a factor of a million and there is no indication that the pace is slowing. If anything it is accelerating. Software has become much more robust – there are few design problems that cannot be readily handled today.

The major problem remaining is applying the technology to increasingly complex projects. That means managing massive amounts of design data – a task some companies are doing well while others are struggling. Airbus S.A.S. has incurred a multi-year delay in launching the A380 super-jumbo aircraft due to data incompatibility problems between its German and French operations. Meanwhile, Boeing's launch of the 787 Dreamliner is staying on schedule even though its design and manufacturing is scattered around the world. The bottom line is that CAD is phenomenal technology that is revolutionizing engineering design and manufacturing, especially when used right.