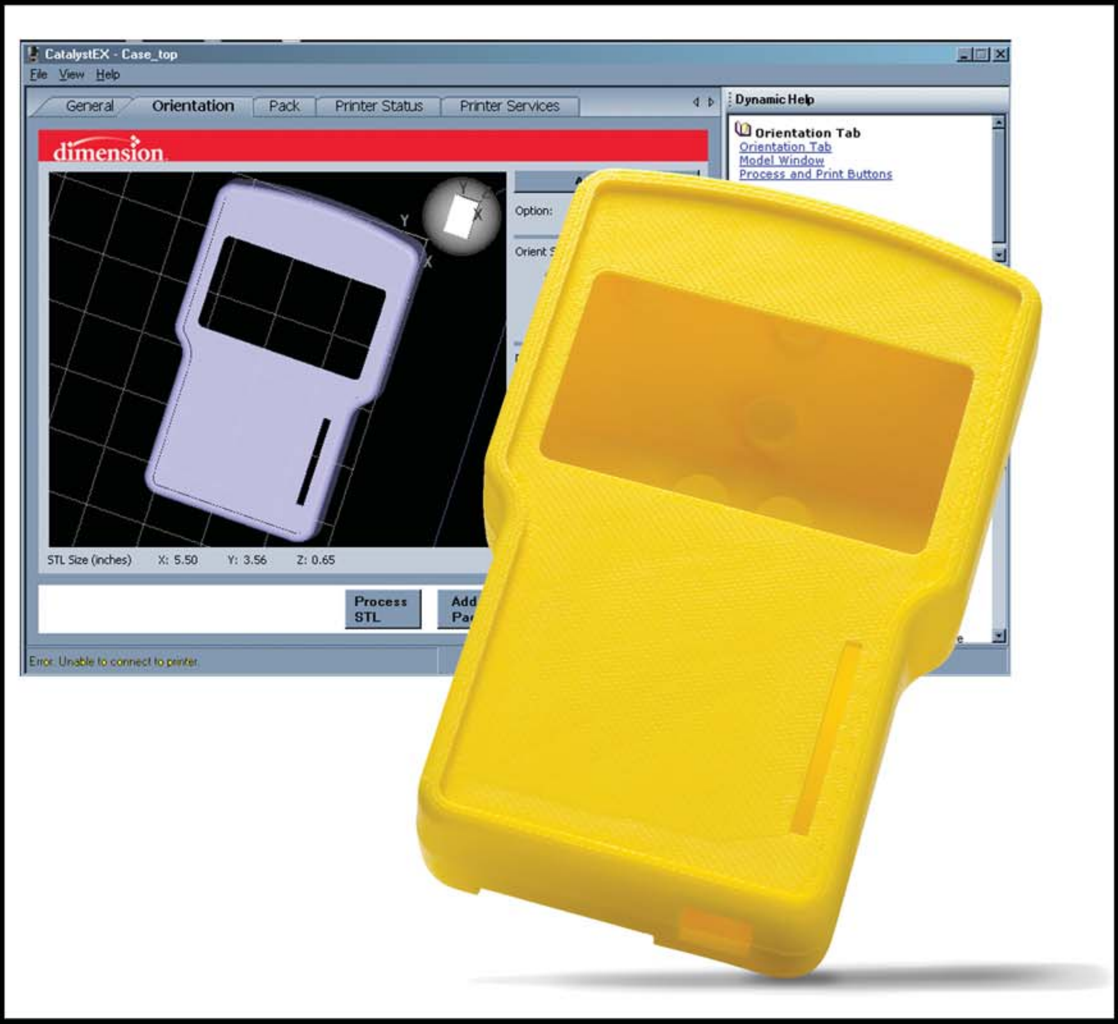
3D Printing Learning Modules



Instructor's Guide

P/N 400-30000

dimension

Acknowledgements

We appreciate the individuals and organizations that contributed to the 3D Printing Learning Modules.

A special thanks goes to Terry Wohlers, who provided content for "Module 1: Introduction to Additive Fabrication."

Also, thanks to Steve Bailes for his input in developing this educational guide.

About Terry Wohlers

Industry consultant, analyst, author, and speaker Terry Wohlers is president of Wohlers Associates, Inc., an independent consulting firm he founded nearly 19 years ago. For the majority of this time, he has served as a voice in the additive fabrication industry. He has been quoted in countless domestic and foreign publications including the *Chicago Tribune, The Economist, FORTUNE, Forbes,* and *Los Angeles Times.*

In May 2004, Terry received an Honorary Doctoral Degree of Mechanical Engineering from Central University of Technology, Free State (Bloemfontein, South Africa). Nelson Mandela, former president of South Africa and Nobel Peace Prize winner, received this honorary degree in 2002.

Terry has authored 290 books, articles, reports, and technical papers on engineering and manufacturing automation. In the past five years, he has given 20 keynote presentations on four continents in cities ranging from Frankfurt and Cape Town to Beijing and Tokyo. His appetite for adventure has driven him to climb the Great Wall of China, hike the rain forests of New Zealand, dive among sharks in Belize, bathe in the Dead Sea, ride elephants in Thailand, and encounter lions and rhinos in Africa.

In 1992, Terry led a group of 14 individuals from industry and academia to form the first association dedicated to additive fabrication. In 1993, the association joined the Society of Manufacturing Engineers (SME) to become the Global Alliance of Rapid Prototyping Associations (GARPA) involving 18 member nations around the world.

About Steve Bailes

Steven R. Bailes
Associate Professor
Computer Aided Drafting - Mechanical & Architectural &Division Chair - Manufacturing
Owensboro Community and Technical College

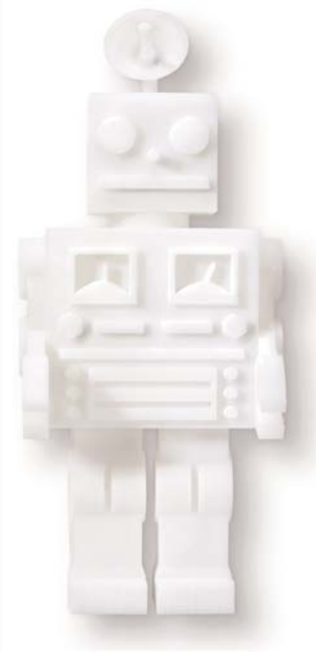
Worked in the occupational education and industrial training profession for the past twenty-seven years; has worked as a mechanical/electrical drafter, training coordinator, vocational drafting instructor, training director, technical education sales consultant, robotics instructor, industry trainer, and has been employed for eight years at Owensboro Community and Technical College where he is an associate professor, division chair for manufacturing, and directs the rapid manufacturing center at the college Downtown Campus.

Steve, who resides in Owensboro, Kentucky, has been married to the same lovely lady for over twenty-five years and has four sons.

In addition, we would like to thank McGraw-Hill, for their contribution to this educational guide:
Specifically, for the use of the following text and images:

- Module 3: Figures 1 - 13.
- Module 4: Assignment 1, Figure 1
- Module 6: Assignment 1, Figure 1
- Module 7: Assignment 1, Figure 1

Engineering, Drawing, and Design 6th Edition
Cecil Jensen, Jay D. Helsel, Dennis R. Short
Copyright 2002
Glencoe/McGraw-Hill



Contents

I. Introduction to Additive Fabrication....pg. 4

II. 3D Printing....pg. 19

III. Basic Design - Theory of Shapes....pg. 29

IV. Basic Design - Dimensioning and Tolerancing....pg. 35

V. Mechanics and Materials - Fasteners ....pg. 37

VI. Mechanics and Materials - Casting....pg. 38

VII. Mechanics and Materials - Ratchet Assemblies....pg. 39

Module 1

Introduction to Additive Fabrication

With the exception of the real world application vignettes highlighted throughout, this entire section was taken from Wohlers Report 2005 with permission from Wohlers Associates. Some content was edited for style.

OBJECTIVE:
Provide an understanding of the history, mechanics and applications of additive fabrication

Introduction to additive fabrication

Additive fabrication refers to a group of technologies used for building physical models, prototypes, tooling components, and even finished series production parts-all from 3D computer-aided design (CAD) data, CT or MRI scans, or data from 3D digitizing systems. Unlike CNC machines, which are subtractive in nature, additive systems join together liquid, powder, or sheet materials to form parts that may be impossible to fabricate by any other method. Based on thin horizontal cross sections taken from a 3D computer model, they produce plastic, metal, ceramic, or composite parts, layer upon layer.

Design and manufacturing organizations use additive fabrication to produce models, patterns, and production parts for products in the consumer, industrial, medical, and military markets, to name just a few. Digital cameras, electronic games, mobile phones, automobile engines and interior trim, airplane subassemblies, power tools, and medical devices are just the beginning of a long list of products that have benefited from additive processes.

Additive fabrication is a tool that streamlines and expedites the product development process. In an effort to reduce time to market, improve quality, and reduce cost, companies of all sizes have come to rely on it day in and day out. As a visualization tool, Additive fabrication helps companies reduce the likelihood of delivering the wrong product, or a poor quality product, to the marketplace.

Methods, processes, and systems for tooling are also developing. While early efforts were focused on faster delivery of tooling, new developments are underway that improve the performance of short-run and production tooling. Many of these new concepts involve an additive process to achieve results that are unthinkable in machined tooling.

Additive processes are having a profound impact on the way companies produce models and prototype parts. Companies are successfully applying the technology to the production of finished products. It is believed that this practice, termed rapid manufacturing, will grow and significantly overshadow the use of additive fabrication for prototyping and tooling applications.

After more than 15 years of research, development, and use, the industry continues to grow with the addition of new technologies, methods, and applications. Additive fabrication has had a tremendous impact on design and manufacturing, and it will continue to expand over the coming years.

How it works

Most CAD solid modeling software products can output an STL file, the input format used by RP systems. An STL file approximates the shape of a solid model using small triangles called facets. The smaller the facet size, the better the surface approximation, but at the expense of file size and processing speed. If you were to open and view the contents of an STL file, you would see a list of x, y, and z coordinate triplets that describe a surface mesh of triangular facets.

The job of the CAD solid modeler is complete once it has exported a valid STL file. At that point, the RP system software takes over. Using special slicing software, RP systems cut thin horizontal cross sections through the STL file. If you want to build a part using 0.2 mm (0.008 inch) thick layers, you would set the software to slice the model at this increment. The RP system control software uses the stack of digital cross sections to produce each layer of material, one on top of the next.

RP machines function similarly, although the specific technologies they use differ widely. StereoLithography (SL) from 3D Systems creates plastic parts from thin layers by directing laser light onto the surface of photosensitive liquid polymer. Laminated Object Manufacturing (LOM) from Helisys produces solid parts from sheet material, such as paper. After a heated roller presses and bonds the sheet to the previous layer, a computer-guided laser cuts the material. Selective Laser Sintering (SLS) from DTM uses powder material to produce solid objects. Similar to SL and LOM, SLS directs laser light onto the surface of the new layer. The heat from the laser causes the powder material to fuse together.

Solid Ground curing (SGC) from Cubital is a photopolymer system that solidifies an entire layer at once. The system directs a flood of UV light through a glass plate mask created from electrostatic toner. Sanders Model Maker (MM) uses ink jet technology to build wax parts. One jet deposits the model material while a second deposits a material used to support overhanging geometry. Fused Deposition Modeling (FDM) from Stratasys produces parts by depositing multiple filament materials through two heated extrusion tips. One tip deposits the model material while a second deposits support material.

Several manufacturers of RP systems are located in Germany and Japan.

In Germany, EOS and Fockle & Schwarze offer machines based on stereolithography technology. EOS also offers machines that sinter powder materials using a laser. In Japan, Denken, D-MEC, CMET, Meiko, Mitsui Zosen, Teijin Seiki, and Ushio offer machines that use a variation of stereolithography technology. An eighth Japanese company, Kira Corp., manufactures and sells an RP machine that laminates plain sheets to form objects.

Applications

Designers and manufacturers are constantly being pushed to reduce product development time. However, meeting time-to-market goals at the expense of cost and quality is of no benefit to any company. Additive fabrication is a powerful tool to address and manage the pressures of delivering new products in less time, with greater quality, and lower expense.

The diversity of applications of technologies for additive fabrication is limited only by the imagination. The more obvious, conventional applications are easy to understand and appreciate. However, when additive fabrication is applied to more than one aspect of product development, or applied in a manner that creates new ways of thinking and alternative approaches, the power can be nearly inconceivable.

Although there are many applications, it is possible to trace nearly all of the benefits to two closely related features. First, additive fabrication improves communication to ensure that all interested parties have a complete understanding of the design. This then fuels the second benefit, which is the ability to manage, control, and detect changes and required modifications.

The application of additive fabrication has moved well beyond that of a prototyping application. Increasingly, companies and individuals are applying these processes to the needs of disciplines outside of design engineering. Colleges and universities are using it in unique ways to do research better and less expensively than ever before. Artisans and sculptors are finding that these technologies free them from the constraints of the production process and allow them to think more broadly. Additive fabrication is also applied to the creation of tooling and the manufacture of sellable, production-quality units.

Communication

In new product development, communication is critically important to success. Engineering drawings provide necessary information such as dimensions, section views, and details. Shaded renderings offer a view of parts and assemblies that most people appreciate, especially when the design is complex. However, when the design is described through prints and renderings, people can misinterpret the design and often do not fully understand how the product will look, feel, and function. While developers of CAD systems have created impressive design aids, these tools are no substitute for the tactile and visual feedback provided by touching and studying a physical model of a design.

People tend to learn more, in a shorter period of time, from a physical model than from printed drawings and renderings. This does not suggest that a physical model is a replacement for engineering drawings and renderings. Instead, it indicates that the combination of engineering drawings and a physical model becomes a powerful communication tool.

Design, development, and manufacturing of a product are not executed in a vacuum. Delivering the right product requires review and input from many sources. Beyond the technical disciplines, it is not safe to assume that others will fully appreciate a design when presented on paper or on a computer monitor. Even those who are technically oriented benefit from the ease and clarity of a design communicated by a physical model.

In fact, the failure to properly communicate is often the root cause of problems in new product development. Additive fabrication offers a quick, clear, and concise description of a new design that improves comprehension of a design and communication between interested parties. Better communication leads to the development of better products.

Real World Application: Artic Spas

Dimension has helped improve communications between Arctic Spa and its manufacturers, as well as provide the company additional peace of mind before molds are made for final part production. "When you give someone a part to hold in their hands, there's no confusion. Molds can cost up to $25,000, and with Dimension, we know we have an accurate model before beginning that stage of the development process," notes Arctic Spas' CAD department manager Pete Van't Hoff.

Engineering Changes

Design changes are a fact of life in the world of product design and development. Whenever there is a need to revise a design, an engineering change order (ECO) is required. The cost of an ECO increases by roughly one order of magnitude as the design progresses from one significant development phase to the next. An ECO that costs $100 at the detail design phase might cost $1,000 at the prototype and testing phase, and could easily cost $10,000 in the tooling phase. After the product is in production, an engineering change might cost $100,000, and when the product is in the field, the cost of a change could escalate to $1,000,000. This is why it is critical to model and prototype early in the design cycle, when changes are least expensive.

Successful product development teams consider manufacturing processes as they shape their plans for new or revised designs. Those responsible for materials, tooling, assembly, and finishing use the physical model to evaluate the difficulty and cost of producing the intended design. Early involvement from these groups shortens the time it takes to manufacture products and reduces production costs.

Michael Jones, electro-mechanical technician for Bell & Howell Company (Lincolnwood, Illinois) stated, "Once the design is frozen, the manufacturing costs are fairly fixed. Any changes you make in assembly technique or construction material won't affect manufacturing costs much."

Additive fabrication is also the tool for improving design for manufacturability, since it facilitates good communication between the design and manufacturing functions. Better ideas, better designs, and early detection of errors are all possible with the technology. The result is quicker delivery of a new product with better quality and lower cost.

Injection molders use additive fabrication to refine designs and communicate alternate solutions to their clients. This helps add value to their service while reducing starts and stops on projects once projects enter the production phase. Smoother production schedules improve throughput and help provide a more competitive bid against overseas vendors.

Sometimes, the benefit of additive fabrication is to discover that further investment in a design concept is a poor idea. Kvaerner Eureka's Oil & Gas Division (Lysaker, Norway) found that a new pump design would not increase efficiency and scrapped the project before investing in any tooling or manufacturing. Although computational fluid dynamic calculations showed that a new design would be more efficient, functional laser-sintered prototypes proved otherwise. With the assistance of the Institute of Industrial Design at the Oslo School of Architecture, Kvaerner produced a prototype rotor and diffuser ring. Once loaded in the test stand, the prototypes were subjected to intense conditions: a 20 kW motor driving the prototypes at 1,500 RPM for three hours with fluid temperatures reaching 60°C (140°F). Contrary to the computational data, the functional tests revealed no improvements over the current design. These results saved Kvaerner from investing additional time and resources in a design that would yield no benefit.

The necessity to decrease time to market, coupled with the increase in new product development, is driving the demand for additive fabrication. Playing a positive role in nearly every aspect of the design and development process, the technology delivers remarkable gains and advantages. These benefits are broad-based, affecting and influencing nearly all disciplines within an organization, not just the engineering department. The variety of additive fabrication applications illustrates the scope of the impact.

Powerful ideas and proposals

Visual aids help sell ideas. Those that can be touched and held in the hands are the most compelling. When a physical model is part of a presentation, the proposal has an advantage that can make it the winning solution. Better decisions are made when the audience learns more about the proposed idea and can better gauge its value.

An astonishingly high number of new product initiatives fail. In their report, "3000 Raw Ideas = 1 Commercial Success," Greg Stevens and James

Burley present an analysis of new product development, showing that 60% of new product launches have some degree of commercial success. That is the good news. As the title of the paper indicates, the bad news is that it takes nearly 3,000 raw ideas, 125 small projects, four major developments, and 1.7 product launches to deliver a single successful product.

In a business climate where many companies are asking employees to do more with less, investing a design team's time in a poor product is a waste of valuable resources. With CAD solid modeling and additive fabrication, companies can experiment with new ideas-before turning them into products-to help them determine whether they will succeed and if they are worthy of additional resource investment.

At E-Z Painter (St. Francis, Wisconsin), all new designs are prototyped and hand finished to look like production parts, then presented to stakeholders- managers, the client, and manufacturers-in the project. Many of these products need to meet ergonomic and styling requirements, so it is necessary to have physical models to prove the design.

Real World Application: Wood Group Pressure Control

"Pictures and sales collateral don't always communicate the intricacies of the product. A tangible object, like the models created from the Dimension 3D Printer, makes all the difference in the world," said Mat Trumbull, project engineer for Wood Group Pressure Control, a market leader in the manufacture of surface wellhead equipment and gate valves for the oil and gas industry. "Helping customers understand the product is important, and Dimension helps us do that. It has helped to break down language barriers and convey our solutions in a much better way. The Dimension BST is truly having a positive impact on our sales process."

Concept Models

3D printers are less costly variations of additive fabrication technology that are positioned as a tool to create quick and inexpensive models early in the design cycle. The ability to make such quick and affordable physical models allows designers to model multiple concepts. The best analogy is to the world of design on paper-if a physical model is the full-blown engineering drawing, the concept model is the quick sketch on the back of a napkin.

During the design phase of its V70 cell phone, Motorola (Schaumburg, Illinois) used additive fabrication to cut development time and cost. Early in the design phase, when various concepts were under consideration, the company produced concept models for review by the design, engineering, and marketing departments. Motorola found that the physical

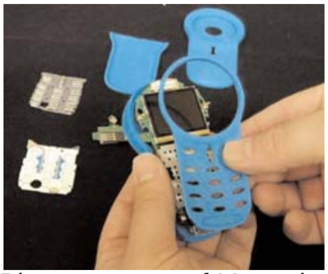


Photo courtesy of Motorola, Inc.

models allowed everyone involved in the review to better understand the designs. In turn, the company got better feedback that resulted in a better product. When compared to previous projects that did not use the technology, Motorola found that the development time was reduced by 50%. Working with team members around the globe, additive fabrication technology allowed the company to achieve real-time, global collaboration around the clock.

Verifying CAD databases

The design of complex parts and assemblies can be difficult and time-consuming. As complexity increases, the difficulty in confirming the accuracy of the geometric data also increases. Problems occur with misaligned holes, interferences, structural ribs in the wrong place, and improper mating of parts. Interferences occur with cables, wire harnesses, hoses, and tubing, as well as with other mechanical and electrical components and subassemblies.

Additive fabrication technologies allow the designer to verify the correctness of the CAD database. This is especially important prior to creating tool paths for CNC machining of expensive metal for molds. In many cases, identifying and eliminating a single interference has the potential to pay for an entire additive fabrication machine.

FreeForm, a design research studio in New York City, uses additive fabrication to verify the architecture, CAD, structure, and layout constraints of its products. This ensures the final cast foundry components will assemble on the construction site. The physical model of the final design also serves as the presentation model for the prospective client.

By combining additive fabrication with the power of SolidWorks, a CAD solid modeling system, Spring Brook Manufacturing (Grand Junction, Colorado) designed an innovative snowshoe and began its production in just nine months. According to Jim Watson, president of Spring Brook, "Standing at the injection-molding press to witness the first article was anticlimactic. Through analysis and verification of the Saguache snowshoe with the CAD solid models and prototypes, I was confident that there would be no problems." Watson continued, "I was right. The first shot from the mold produced a part that was perfect in every way."

Real World Application: Culligan, Inc.

Culligan, a leading manufacturer of high-quality water treatment products, realized tremendous cost savings with its Dimension 3D printer. In one instance, the engineering team was able to quickly identify potential interference issues with several product parts, and efficiently rework them before they committed to the manufacturing process, saving the company not only potential time spent fixing the design flaws later on, but also expensive tooling modifications.

Styling and ergonomics

Industrial designers use additive fabrication to produce early physical models to try new ideas. This approach is especially helpful with products that have many curved surfaces that are difficult or impossible to communicate using 2D drawings and renderings. People prefer to see a model of a proposed design in some form before it becomes too expensive to make dramatic changes.

An unprecedented number of plastic injection-molded parts that contain smooth-flowing shapes are created to satisfy modern-day styling requirements. Many of them must fit in some way to the human body. Examples include protective helmets, breathing apparatus in the medical industry, gear for the military, airplane cockpit controls, snorkel and dive masks and fins, handheld electronic devices, and hand and power tools that must fit and feel comfortable. Ergonomic design considerations include ease of use, noise, vibration, balance, size, and weight. With additive fabrication, designers can more easily test new shapes and sizes early in the design cycle.

Real World Application: Harman Becker Automotive Systems

Harman Becker Automotive Systems is dedicated to developing speaker systems that both are aesthetically pleasing and also produce exactly the right sound quality and integrity that audio system providers specify. With its Dimension 3D printer, the Harman Becker design team found a quick, effective and high-quality solution for developing functional 3D models that captured the quality of their designs and, most importantly, a robust output material that would not fracture, distort or require too much refining and cleaning up prior to fitting.

Fit and functional testing

Additive fabrication has progressed far beyond the brittle models produced in the early years. Advances in system technology and materials have opened the door to fit and functional testing of sophisticated designs.

Senco Products (Cincinnati, Ohio) manufactures a line of pneumatic nailers and staplers. Senco uses additive fabrication for more than one application, relying on it for product announcements, engineering reviews, and styling reviews. The company used the technology for its FinishPro 35 finish nailer. Laser-sintered models were constructed using the DuraForm GF material. After reviewing form and fit, a set of prototypes was painted and weighted to look and feel like the finished product. Once engineering and others in the corporation approved the design, additive fabrication was used to create patterns for a plaster mold process. From these molds, the finish nailer's main body was cast in aluminum. The castings were assembled into fully functional devices that were used to test fire nails and other fastening hardware.

To win a multi-million dollar contract for its high-end scanner, Bell & Howell Scanners (Wheeling, Illinois) used FDM. The Copiscan 8000 Plus rips through 125 sheets per minute, scanning both front and back. With these high-speed devices, the document feeder assembly is critical. Building functional prototypes on its FDM system, Bell & Howell tested multiple feeder designs, and each was sent to the customer for their own trials. With each test, Bell & Howell would get feedback for further design revisions. After five months of customizing the product, Bell & Howell was awarded the contract for 1,100 scanners.

Real World Application: Graco, Inc.

Graco, a manufacturer of paint spraying and texturing equipment for professional contractors and tradesmen, built functional ABS models from parts produced on the Dimension 3D Printer for lab and field testing. Their new spray texture gun was designed to deliver ceiling, wall, and floor coatings from a pressurized hopper or pump. During lab and field tests functional ABS models successfully operated at pressures up to 60 psi.

Prototyping

Prototyping was among the earliest applications of additive fabrication technologies and it remains as one of the most powerful tools for product development. Products ranging from medical instruments as small as the end of a pencil to pieces as large as the cab of a tractor-trailer have begun life in an additive fabrication machine. What do they all have in common? They allow engineers and designers to learn about a product design so that they can make sure that it meets the needs of the end user.

Metal castings

Case New Holland (New Holland, Pennsylvania) uses many metal parts for its agricultural and construction equipment. CNH typically needs 20 to 50 metal prototypes to complete functionality and durability testing. For its sand cast parts, CNH has replaced traditional pattern making with laser-sintered DuraForm (nylon) patterns to cut the time to produce castings by more than 50%. In some cases, what once took three to four weeks is now completed in only a few days. DuraForm parts are durable enough to withstand the pressure and abrasion of the sand to produce as many as 1,200 cast metal parts. CNH has also found that laser-sintered CastForm patterns (polystyrene and wax) have opened the door to investment casting of steel. In the past, the company relied on machined steel to simulate forged parts. Since CastForm patterns eliminate the need for tooling, CNH now investment casts the steel parts to better simulate the properties and characteristics of forgings.

Requests for quotes

When it is time to submit a request for a quotation, it may be advisable to include a physical model of the part. Providing a model helps clarify any ambiguities in the engineering drawings and design specifications, which, in turn, may result in lower quotes. Suppliers admit that they pad their quotes to cover misinterpretations of the design requirements. This can add one-third, or more, to the price.

Delphi Automotive Systems (Troy, Michigan) routinely sends additive fabricated models to its prototype suppliers and tool shops for quoting purposes. Ford Motor Company (Dearborn, Michigan) also practices this method of requesting quotes. Based on a study led by Peter Sferro of Ford, the company found that it could save 30-50% on vendor quotes when using physical parts. On a rocker arm project, enclosing a model with the request-for-quote package yielded a $.50 reduction in individual part production cost. After producing 10 million rocker arms, Ford had realized a savings of $5 million.

At Invensys Appliance Controls (Carol Stream, Illinois), all new projects have two sets of prototype parts made. One set is for internal evaluation and the other is for the client. One of the largest benefits of the prototypes is buy-in from the company's clients. The parts are also used in the vendor bidding process. With physical models in hand, bids are typically more refined, resulting in an estimated 10-15% reduction in tooling costs per project.

Real World Application: Motorguide Marine

The ability to bring functional parts to a meeting with manufacturing partners was a bonus for Motorguide Marine, something that most manufacturers had never experienced. "Our manufacturing partners were used to seeing designs from us, but they had never had us come in with functional parts. It was very much appreciated, and really helped our discussions," said Mikel Janitz, research and development manager for MotorGuide.

Tooling

For many years, the additive fabrication industry has hoped to reduce the costly and time-consuming practice of machining metal molds and dies. A number of companies are now beginning their traditional processes with rapid tooling to produce parts in end-use materials for both functional prototype evaluation and low-volume production.

Manufacturing support

The ability to quickly develop quality products is a necessary ingredient for success in today's marketplace, but it is not sufficient to keep a company profitable. Organizations must also learn how to get new products into manufacturing quickly and cost-effectively. Toward that end, manufacturing engineers have come to embrace additive fabrication to help them design and build factories more quickly than ever.

Manufacturing of parts

Product development is just one contributing factor to the length of time needed to release a product to market. Of equal importance is the time to begin producing the product after the design has been frozen. Some forward-thinking companies have successfully applied additive fabrication to the production of finished manufactured parts to further decrease time to market and product expense. Others have chosen to apply additive fabrication to offer a product that is uniquely manufactured for the individual consumer.

Additive fabrication is in the early stages of becoming a manufacturing tool. With early successes by pioneering companies, more applications will surface in the coming years. Limitations in speed, materials, and accuracy create barriers to success. Yet, as organizations demonstrate successful applications, more effort will be placed on the development of additive fabrication technologies for the manufacture of parts, and many of these barriers will be overcome.

It may seem impossible for parts made on a 3D printer to be battle ready, but EOIR Technologies (Spotsylvania, Virginia) produced battle-ready parts for its M1 Abrams tank and Bradley fighting vehicle project. When a subcontractor's design for a camera mount failed testing, EOIR had little time to regroup. After a quick redesign of the mount, EOIR used its Dimension 3D printer to build ABS parts for functional testing. While the original mission did not include deployment of these models as production parts, EOIR found that the ABS camera mounts were tough enough for battle. Forty mounts were produced on the Dimension machine, saving the company nearly $100,000.

At an FDM user's manufacturing plant, a pulley on a production line belt sander cracked, taking the belt sander out of commission. The cracked pulley was made of aluminum, but to avoid any more downtime, the fabrication manager decided to try a polycarbonate part from the FDM Titan. After a month of operation, the pulley was still going, and the fabrication manager was in no hurry to replace it with its aluminum counterpart.

SL and FDM are being applied to the creation of parts for the manufacturing process at Northrop Grumman (El Segundo, California). The company has made more than 700 tools (hand tools, not molds or dies) to support the manufacturing, repair, and servicing of aircraft. In one case, the company produced an aircraft repair kit that included metal shaping tools, guides, and gauges. Built entirely from SL, this field kit allowed the reshaping of an inaccessible component without tearing down a section of the aircraft.

Research

As much as additive fabrication has been embraced in the field of product development, so too has it come to be recognized as very important for extending the reach of researchers. Groundbreaking research in diverse fields is being undertaken at government laboratories, private enterprises, and universities. Research aimed at furthering the development of additive fabrication itself has been ongoing since the technology was invented, but we now see it being employed as a means to entirely different ends. With the widespread adoption of the technology in technical organizations, its visibility has gained the attention of a wider audience, many of whom are asking how they can put it to use for their own work, often with very unique results.

Art and Sculpture

With the recent introduction of new systems to the marketplace, some artists, sculptors, and jewelers have come to recognize that the beauty of additive fabrication is more than just skin deep.

With system costs and piece part prices dropping, and higher resolution equipment now available, it has become feasible in many instances to make sculpture and jewelry directly with additive fabrication equipment. Many artisans are now "going digital" in a big way to extend the reach of their talents.

Real World Application: Karim Rashid

"Dimension allows us to narrow in on a design solution much more quickly, and as a result, better serve our clients. The precision of the models Dimension creates is so exact, we are able to present something very real to clients almost immediately - an invaluable communications capability," said Karim Rashid, esteemed industrial designer who uses Dimension for various projects, creating such things as trophies for an MTV AIDS awareness awards program and 50 one-of-a-kind sculptures for an art gallery showing.

Where to learn more

Visit http://wohlersassociates.com to access more than 200 pages of additional content. The site also includes links to more than 125 articles, technical papers, reports, and other documents on additive fabrication, prototyping, tooling, 3D printing, CAD/CAM/CAE, reverse engineering, and rapid manufacturing. All 125 documents are available to read online, free of charge.

The website also offers links to more than 200 system manufacturers, CAD vendors, service providers, universities, and other organizations focusing on rapid product development. Many use this site as a starting point for exploring additive fabrication and related products and services worldwide.

Global Alliance of Rapid Prototyping Associations

The Global Alliance of Rapid Prototyping Associations (GARPA) was formed to encourage the ongoing exchange of information across international borders. Members of GARPA include groups and associations in Australia, Canada, China, Denmark, Finland, France, Germany, Hong Kong, Ireland, Italy, Japan, Korea, the Netherlands, Portugal, South Africa, Sweden, the UK, and the USA.

GARPA members from around the world participate in activities that include technical presentations at major industry conferences, the publication of application case studies, business meetings, social events, and the formal and informal sharing of information. For more information on how to become a member of one of GARPA's groups or associations, visit www.garpa.org and click on the proper link.

Rapid Technologies and Additive Manufacturing Community

The Rapid Technologies and Additive Manufacturing Technical Community (RTAM) of the Society of Manufacturing Engineers (SME) provides opportunities to learn about the latest advances and share best practices with others who share similar technical interests. For more information on RTAM, visit www.sme.org/rtam.

Unlimited potential

The application of additive fabrication is vast and unlimited. Perhaps the most significant barrier to realizing new applications and powerful benefits is our reluctance to change. Established processes and procedures are difficult to displace. When forward-thinking individuals apply additive processes in new and exciting ways, however, it is possible to achieve astonishing results.

The breadth of additive fabrication applications is impressive. The technology has been applied to fields as varied as medicine, dentistry, architecture, geographical information systems (GIS), and mapping. Others include microsystems, forensics, space exploration, filmmaking, and entertainment. Additional examples include:

- Burn masks with better fit that improve recovery.
- Components for the world's smallest autonomous robot.
- Full-size automobile instrument panels made in one piece.
- Recreation of a murder victim's likeness.
- On-demand creation of components for a self-designed droid.
- Action figures for Hollywood films.
- Components for exploration submersibles.
- Skulls of accident victims to prepare for reconstructive surgeries.
- Color models, revealing areas of stress through finite element analysis.

If change is welcomed, it is inevitable that many more applications of additive fabrication, once inconceivable, will begin to emerge.

Module 1
Review & Assignments

Key Terms

o Additive Fabrication
o CAD (Computer-aided-design)
o CNC (Computer numerical control)
o Rapid Manufacturing
o SLS (Selective Laser Sintering)
o SL (StereoLithography)
o SGC (Solid Ground Curing)
o FDM (Fused Deposition Modeling)
o ECO (Engineering change order)
o Ergonomics

Questions

o What is additive fabrication? What are its benefits?
o What is the term for applying additive fabrication to the production of finished products?
o What is the input format used by RP systems? How does it work?
o Explain the differences among Selective Laser Sintering (SLS); StereoLithography (SL); Solid Ground Curing (SGC); and Fused Deposition Modeling (FDM).
o What two closely related features can all benefits of additive fabrication be traced to?
o How is additive fabrication used to improve communication?
o What are the costs of engineering changes at each phase of product development?
o How many raw ideas, small projects, major developments and product launches does it take to deliver a successful product?
o What are some examples of how additive fabrication is used for ergonomics?
o What are the barriers to using additive fabrication for the manufacturing of parts?

MODULE 2

3D PRINTING

OBJECTIVE:
Provide an understanding of the history, mechanics and applications of 3D printing.

3D Printing

Recently introduced is a new generation of RP machine technology that some are referring to as 3D printing. This class of machine is targeted at the design engineer for concept modeling and early design review and approval. Rather than submit an RP job and wait for days, as people do now, 3D printers bring the technology within reach, literally, of design groups running CAD solid modeling software. These office friendly machines sit next to CAD workstations, office copiers, and fax machines.

An RP part usually costs a few hundred to more than a thousand dollars, and takes days to a week or longer to produce and finish. 3D printed parts generally cost under $50 and take less than a day or two to build. 3D printers are designed for speed and ease of use, so you are not given the range of software build parameters, nor are you given a choice of materials. 3D printers that are available today offer one material only, but most designers are willing to sacrifice flexibility for such significant time and cost savings. You should think of it as a rough draft model that helps designers more quickly iterate and advance the design before going to more expensive prototyping options. The life of an RP part is often days or weeks, but the life of a 3D printed part may be only minutes or hours.

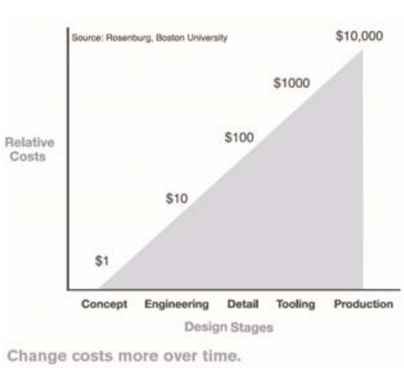


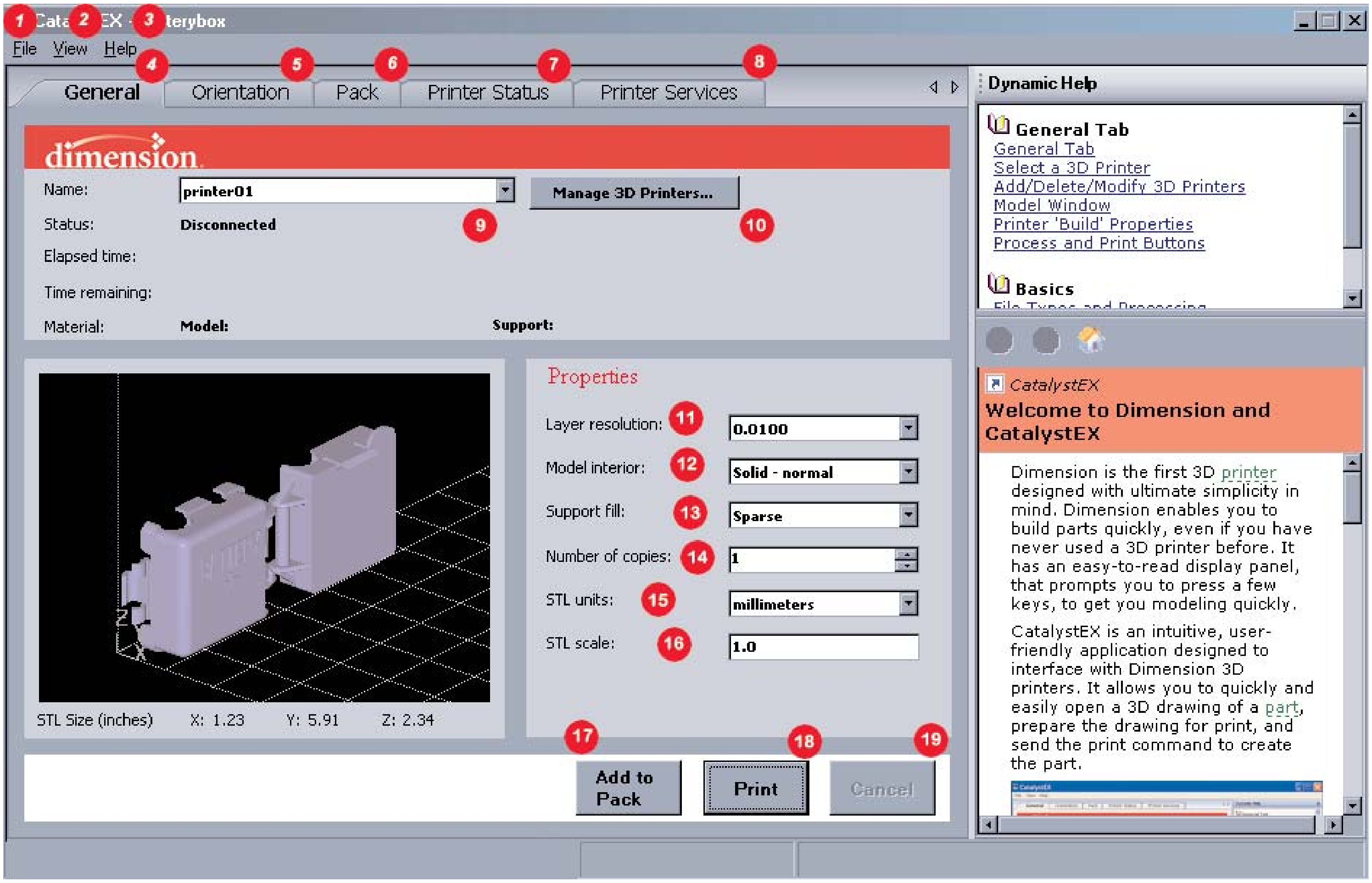
Figure 1

3D printing helps to reduce the number of costly engineering changes. The cost of an engineering change increases roughly by an order of magnitude (see Figure 1) as the design progresses from one significant development phase to the next. Making changes and refining the design as early as possible in the design process reduces cost and improves product quality and time to market. 3D printing enhances communication between the designers and the tooling experts, giving the tooling department a chance to influence the design when changes are inexpensive.

Will 3D printing replace 2D drawing/prints? In many cases, it will reduce the need for complete 2D documentation. Companies can instead focus on supplying critical-to-function drawings that include only those drawings and dimensions that are critical to the function of the part. Combining these drawings with a 3D printed model results in a very powerful communication package.

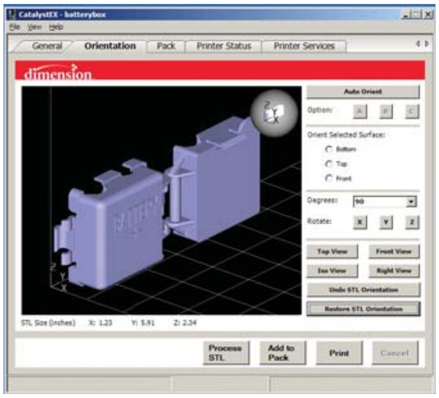
Using your Dimension 3D Printer

Dimension 3D Printers are designed to be easy-to-use, easy-to-maintain, and just a single step process for students and instructors to explore multiple design concepts in durable ABS plastic. This section will give you some tips and tricks for navigating around in Catalyst software as well as working with your Dimension 3D Printer. Use this section as a guide, but always refer to your Dimension 3D Printer User Manual for technical information.



Navigating Catalyst Software

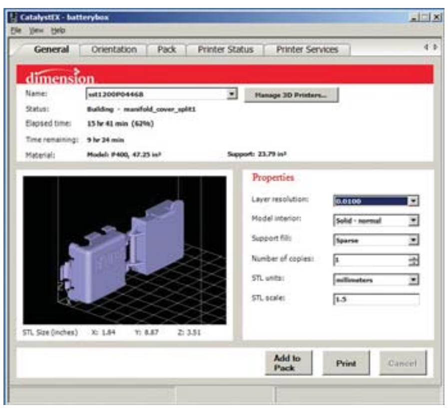
1. File:	Open/Close, Save/Save As, Print, Preferences, Options, Print Screen
2. View:	Preview Display, STL, Single Layer, All Layers, Change Camera View
3. Help:	Contents, Dynamic Help, About
4. General:	General, Printer Choices, Model Views, Job Properties
5. Orientation:	View, Orient, View Layers and Process a Part
6. Pack:	Pack Related Tools
7. Printer Status:	Printer Information and Management Options
8. Printer Services:	Printer History, Update Software, Manage Printer Password
9. Name:	Printer Name
10. Manage Printers:	Add/Delete/Modify Printers Set IP Address
11. Layer Resolution:	Select Layer Resolution
12. Model Interior:	Select Part Interior Style
13. Support Fill:	Select Support Style
14. Number of Copies:	Select Number of Copies
15. STL Units:	Select Inches or Millimeters for Measurment
16. STL Scale:	Change the Size of the Part Within the Build Envelope
17. Add To Pack:	Add Files to Pack
18. Print:	Print
19. Cancel:	Cancel



Rotating a model:
Rotating your model is a common function in Catalyst software. Rotating your model within the build envelope can save you both time and money. You can select the orientation that will use the least amount of modeling and support material which can also cut down on the time it takes to build a model.

- on the "orientation" tab, you can enter in the number of degrees in which to rotate.

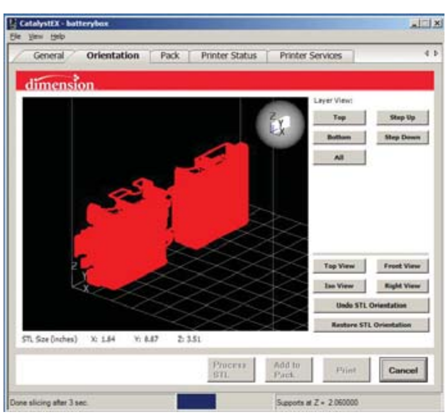
- you may also select which axis you would like to rotate around (x, y, & z).



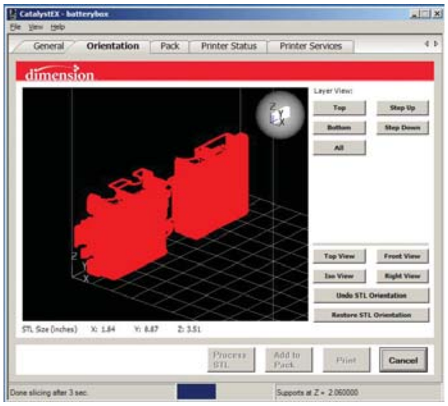
Scaling a model:
Equipped with up to a 10"x10"x12" build envelope, Dimension 3D Printers can build many models at full size. Scaling a model can be helpful when designing larger items. Scaling can be done with one simple click of the mouse.

- on the "general" tab enter the amount to scale next to "STL Scale". If 1 is entered the scale of your model will not change. If 2.0 is entered, your model will double in size.

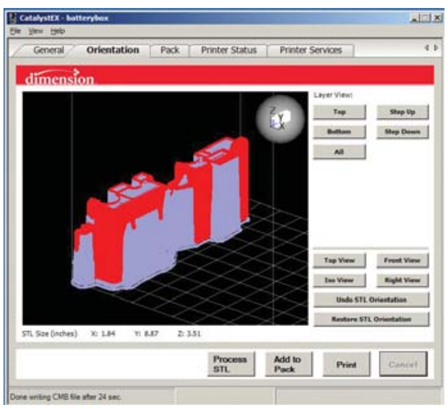
- scaling can also be accomplished on the "orientation" tab.



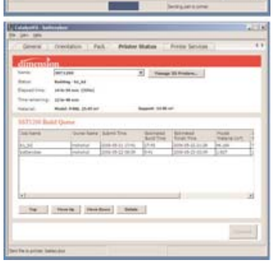
Processing a Model:
Once you've selected your modeler, determined the layer resolution, assigned a part surface style, selected a part interior style & support style, rotated and/or scaled your model, you are ready to send it to the printer. Simply click on the "process STL" button on the bottom of your screen.



Processing a Model:
Here is what you'll see on the screen when processing the model. The software automatically slice the file, generate any necessary support structures, write boundary curves, generate toolpaths and create the CMB file. You can do all of this with just one click of the mouse.

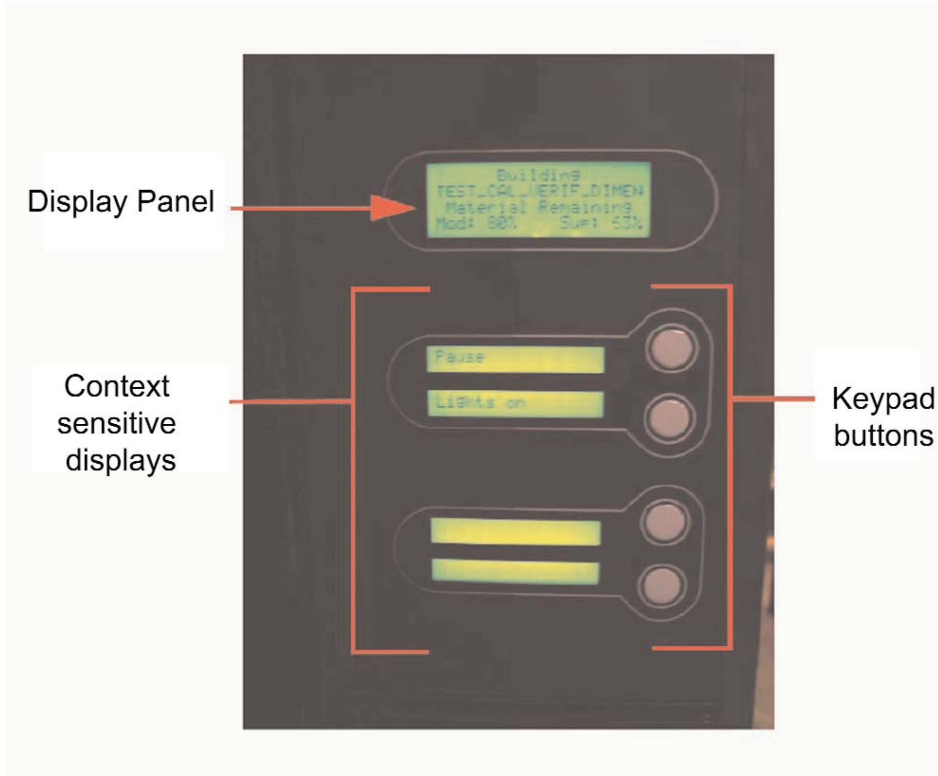


Processing a Model:
The image to the left shows you where support structures are being placed. The red items are built with modeling material and the purple are where your suport structures are being built.



Print:
Once you have processed your file, you may add it to the pack. You can place as many files in the build platform as you can fit. Once you have arranged your pack, simply click “print.”

Operating Your Dimension 3D Printer



Display Panel & Keypad

The Dimension display panel and keypad is very basic and simple to use. It consists of a larger multiple-line LCD display on top, and four single-line context-sensitive displays, each with one button (or key). The top line in the large display always reveals the machine status. The remaining three lines give details related to the current operation.

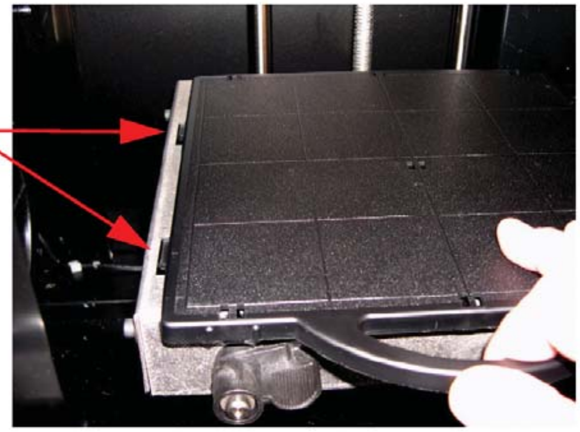
Normally there will be an item blinking in the lower (contextsensi-tive) displays. The blinking item is usually the most logical selection.

Inserting Model Bases

Prior to inserting a plastic modeling base (substrate) into the tray, remove any material buildup on and behind the Z-platform and around the lead screw. Failure to do so could cause the modeling base to be unlevel or, if the buildup is large enough, cause the Zstage to jam at its upper limit.

Set the modeling base down on the Z-platform allowing the four outer tabs to drop into the cutouts in the sheet metal tray. Slide the modeling base forward until it is flush with the front edge of the tray. Secure the base with the two retainers.

Slide modeling base into the side tray guides (2 on other side).



To reuse a plastic modeling base:
The square outlines on the modeling base represent modeling areas. The base is intended for single-use on each modeling area. Building on a used modeling area may cause a part to curl or break loose from the modeling base.

Before inserting a used modeling base into the machine, make sure that all material above the previous part.s first layer is removed from the base.

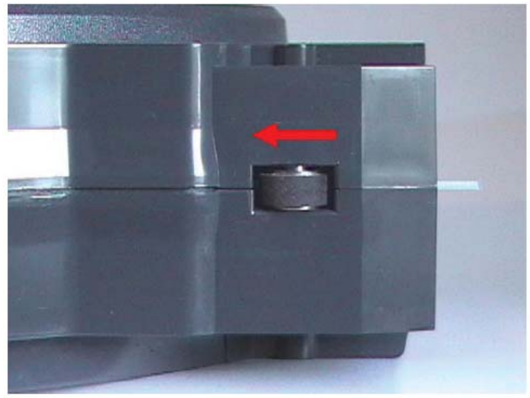
Failure to completely remove all other layers from a previous part build can cause a head collision and result in damage to the system. A modeling base may become worn or distorted after using it several times. The machine performs a modeling base levelness check at the beginning of every part build; upon detection of a faulty modeling base, the machine will pause and allow you to install a new one.

Inserting Modeling & Support Material

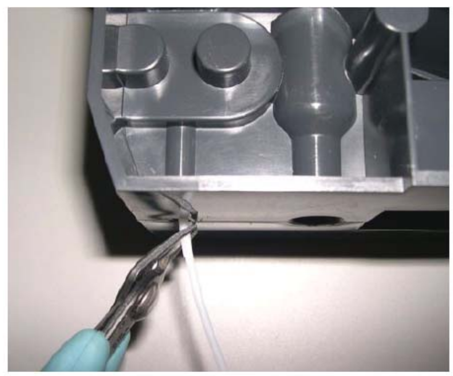
Material cartridges are factory packaged in a box and an anti-static, moisture-proof bag to preserve shelf life. The material inside the cartridge will stay humidity free for at least 30 days after opening. Shelf life is more than one year if cartridge package remains sealed.

To load material cartridges:
1. Remove packaging and find the end of the material filament taped with a flag.

Important - Be careful when touching the pinch roller on the side of the cartridge. If you roll it backwards, you can inadvertently withdraw the material into the cartridge. If this occurs, there is no way to retrieve the filament without opening the cartridge and exposing the material to humidity, which reduces shelf life to a few days.



2. Pull filament out of cartridge to expose about 12 inches of material. You should be able to pull the material easily out of the cartridge.
3. With the cutter provided in your Startup Kit, snip the filament at an angle, leaving ¼” (6 mm) of material protruding from the cartridge.



4. Press the Material Load button, which will be blinking. The panel first displays Unloading and then it instructs you to insert the cartridges with the prompt Replace Both Cartridges.
5. Insert each cartridge. The panel then displays Ready to Load.
6. Press Load. The panel then displays Loading. After the material loads, the panel displays Material Loaded.

Note:
You might get the message, Model cartridge not replaced or invalid. This occurs if you do not insert the new cartridges within 30 seconds. In this case the cartridge will not lock into its slot. You must press the Retry button before continuing the process.

7. Watch the extrusion tip to see if material extrudes (or purges) after loading. The panel will then display Did material purge?
8. Press Yes or No as appropriate or press Purge Again if you are unsure.

Unloading Material

The model and support material cartridges may be replaced separately or at the same time. In idle, load, or build-related modes, the panel displays the percentage of material remaining in the cartridges. If the machine is to be operating unattended for a long period and the material level is getting low, you may want to replace the cartridges before starting a new part. Of course, you will also need to replace the cartridges when they are empty.

To unload material cartridges:

1. Press Material Load.
The panel reads Load material and prompts with, Replace model?

2. Press Yes.
The panel displays Replacing model, and asks if you want to replace the support material also. It also displays the remaining percentage of support material.

3. If you want to replace the support material cartridge also, press Yes. The panel displays Unloading for approximately 15 to 20 seconds, and then displays Remove cartridge.

4. Remove the model material cartridge by first pushing it forward gently, and then pulling it out of the slot.

5. Remove the cartridge(s) and approximately 6 feet (180 cm) of material.

6. To store a partially used cartridge, place a small flag of tape on the filament near the cartridge, and strip off and discard the remaining material. The tape flag ensures the filament does not roll back into the cartridge.

Module 2

Review & Assignments

Questions

· What is the software the Dimension 3D Printer uses?
· When preparing your design for printing, why rotate your model on the computer screen?
· What size is the build envelope for the Dimension 3D Printer?
· What five steps need to happen before you send a model to the 3D printer for processing?
· What does the Dimension display panel consist of?
· What step needs to occur before you insert a plastic modeling base into the tray? Why?
· What is the shelf life for a material cartridge?
· How can you store a partially used cartridge?

Module 3

Basic Design: Theory of Shapes

Objective:

- Provide an understanding of orthographic projections

Prerequisites:

- Intro to 3D printing
- Drafting equipment, media and reproduction
- Basic drafting
- Introduction to computer aided design (CAD)/2D-3D Skills

Assignment #1: *Demonstrate understanding of normal surfaces*

1. Choose one part from figures 1-5, and create a 3D CAD file of the part. Convert the CAD file to an STL file.
2. Send the file to the 3D printer and print the part.
3. Measure and record key dimensions identified in figures 1-5.
4. Compare to orthographic views from page 32

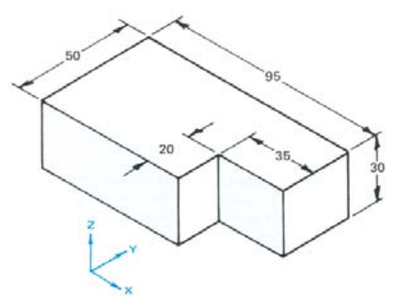


Figure 1: Stop Block

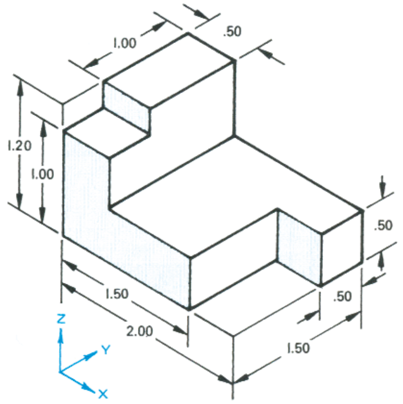


Figure 2: Angle Bracket

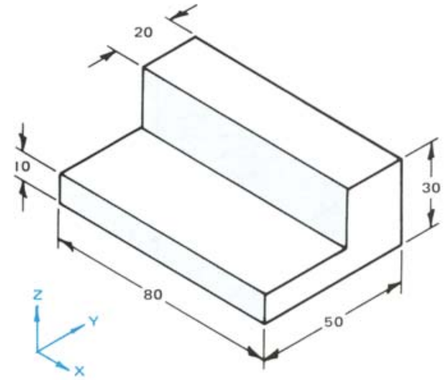


Figure 3: Step Block

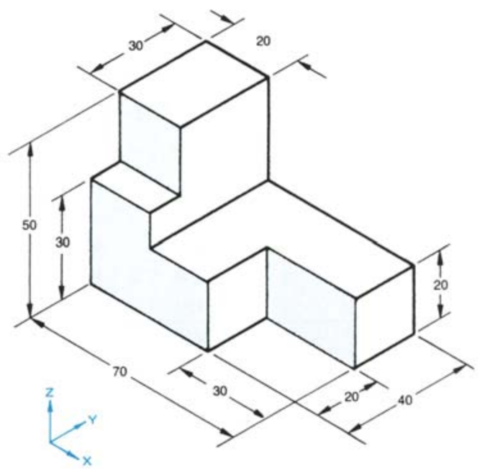


Figure 4: Corner Bracket

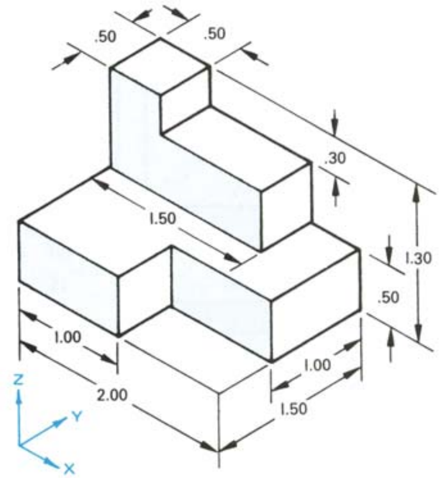


Figure 5: Locating Block

Assignment #2: ***Demonstrate understanding of centerlines, circles and arches***

1. Choose one part from figures 6-11, and create a 3D CAD file of the part. Convert the CAD file to an STL file.
2. Send the file to the 3D printer and print the part.
3. Measure and record key dimensions identified in figures 6-11.
4. Compare to orthographic views from page 32

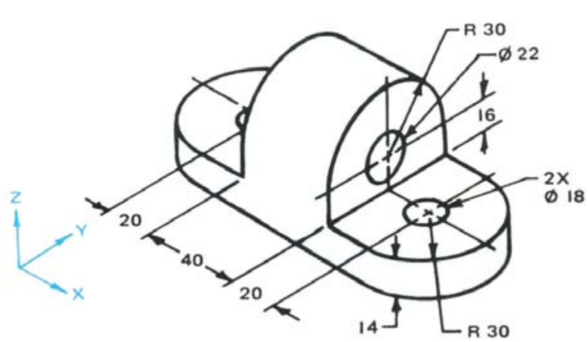


Figure 6: Pillow Block

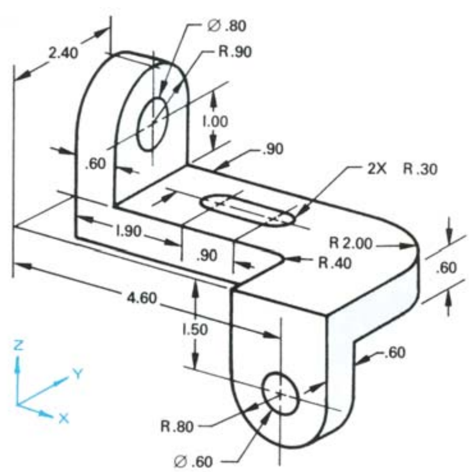


Figure 7: Guide Bracket

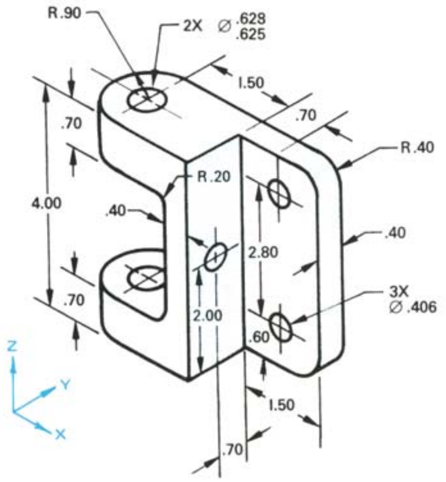


Figure 8: Hinge Fixture

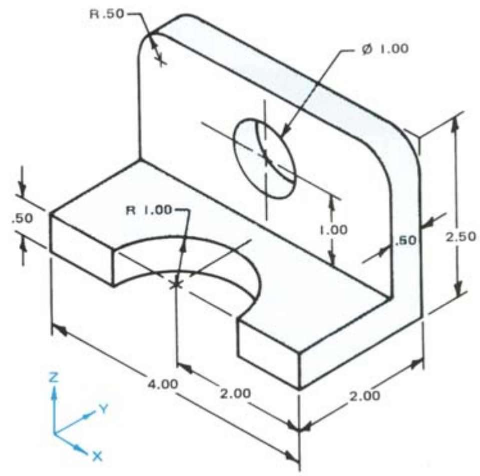


Figure 9: Rod Support

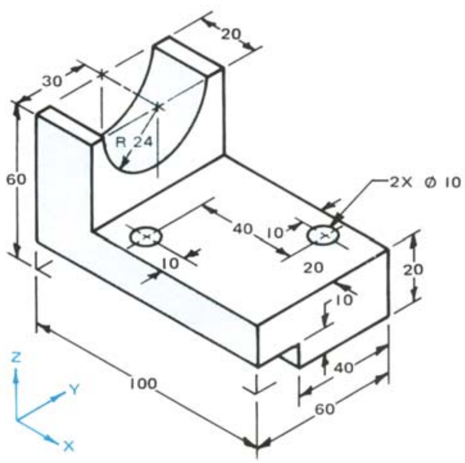


Figure 10: Cradle Support

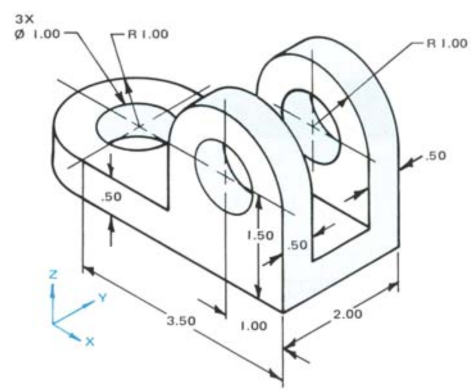


Figure 11: Rocker Arm

Assignment #3: *Demonstrate understanding of slopes and angles*

1. Choose one part from figures 12 and 13, and create a 3D CAD file of the part. Convert the CAD file to an STL file.
2. Send the file to the 3D printer and print the part.
3. Measure and record key dimensions identified in figures 12 and 13.
4. Compare to orthographic views from page 32

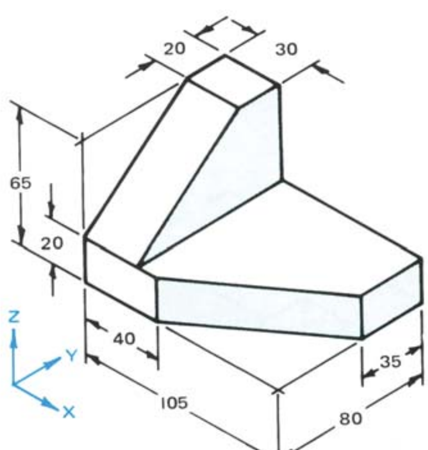


Figure 12: Angle Plate

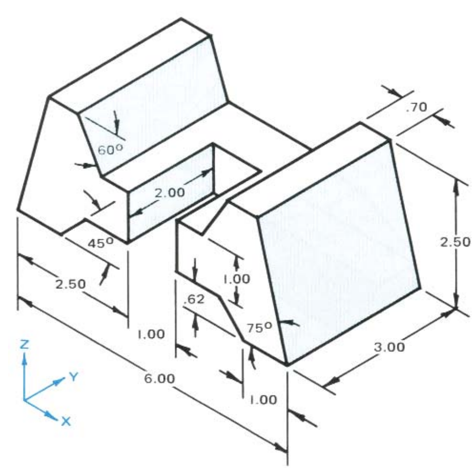


Figure 13: Stand

Orthographic Views

Use figures 1-13 to complete #4 on assignments 1,2,3 of this section.

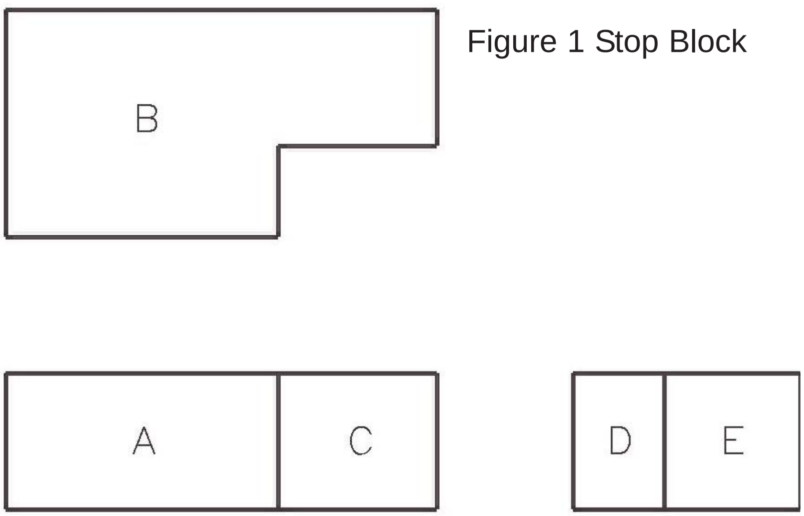


Figure 1 Stop Block

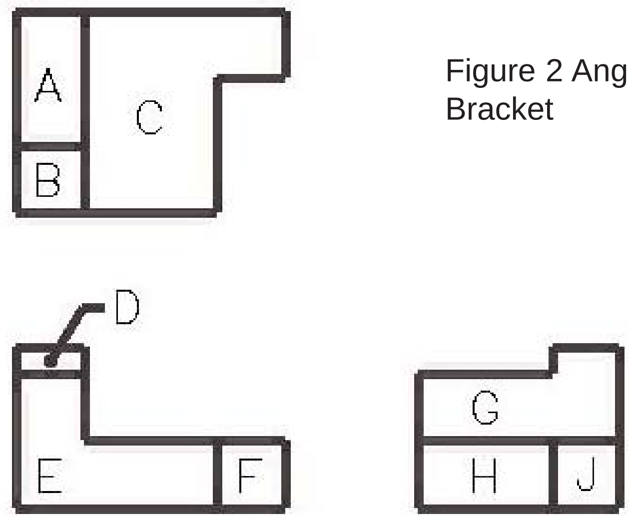


Figure 2 Angle Bracket

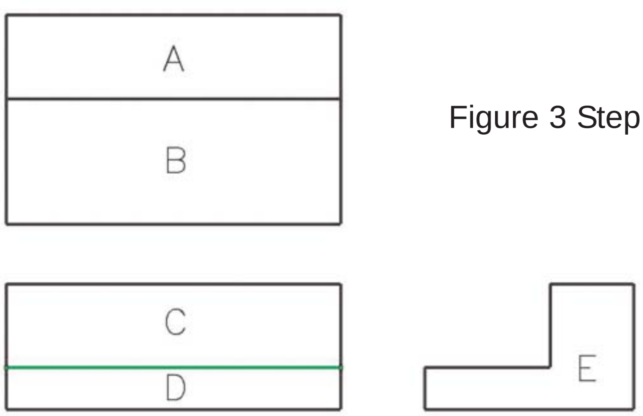


Figure 3 Step Block

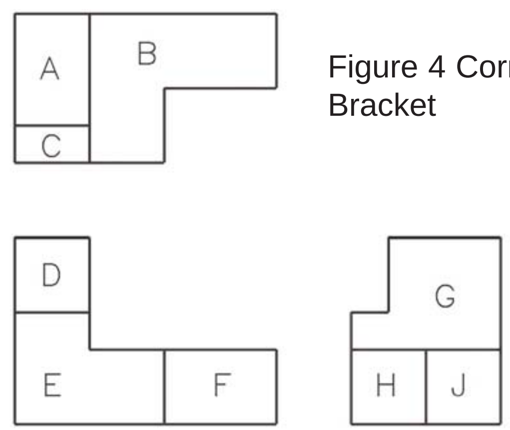


Figure 4 Corner Bracket

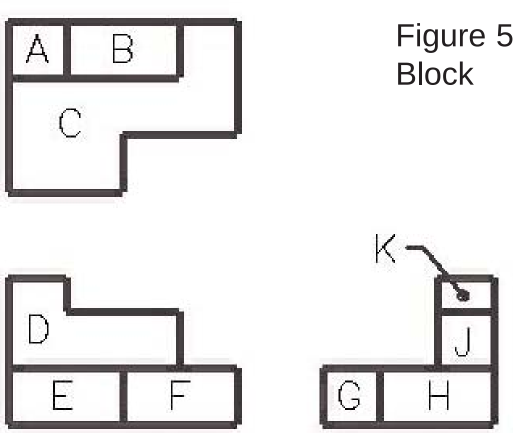


Figure 5 Locating Block

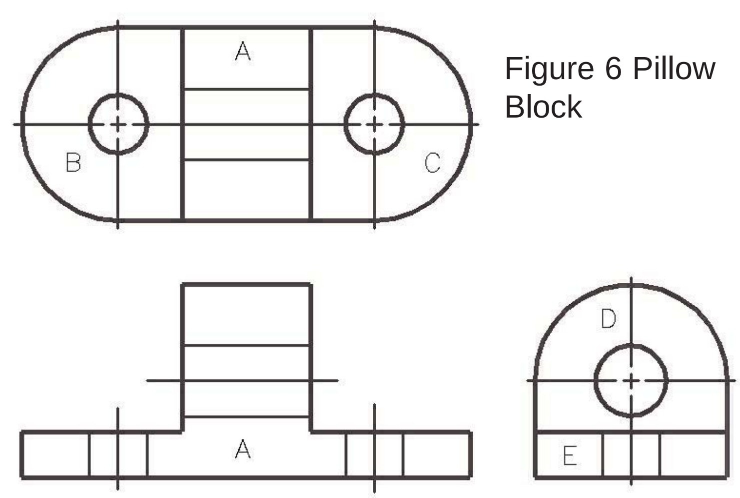


Figure 6 Pillow Block

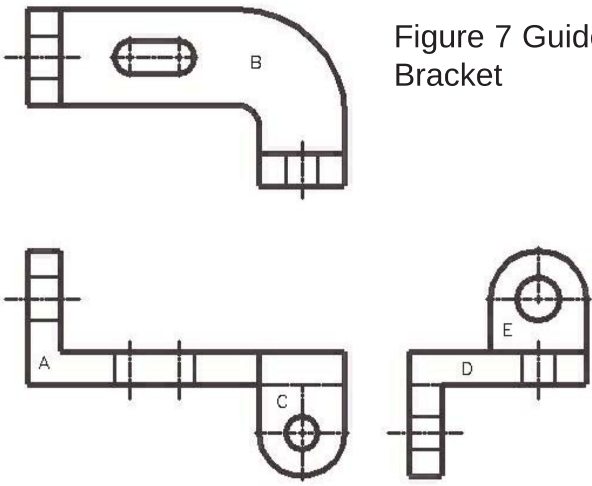


Figure 7 Guide Bracket

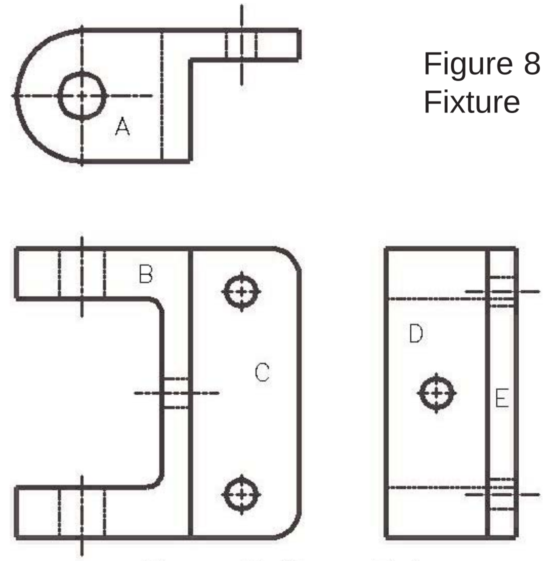


Figure 8 Hinge Fixture

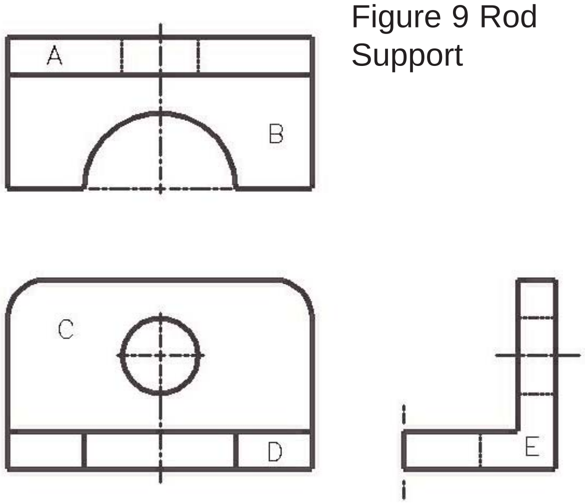


Figure 9 Rod Support

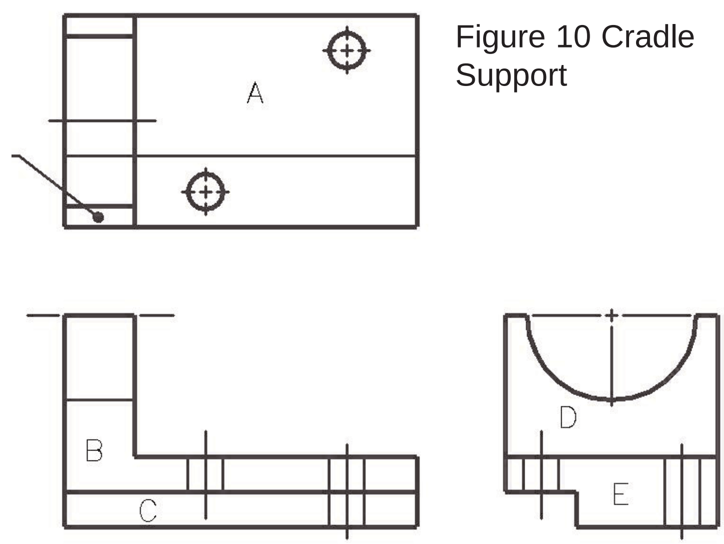


Figure 10 Cradle Support

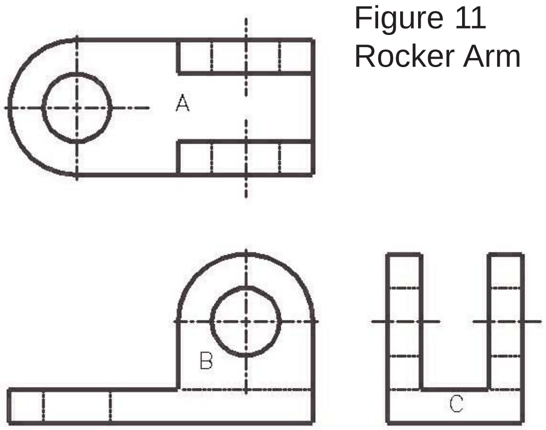


Figure 11 Rocker Arm

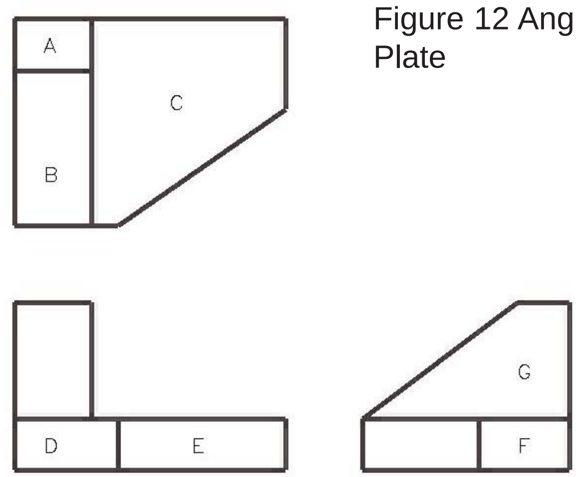


Figure 12 Angle Plate

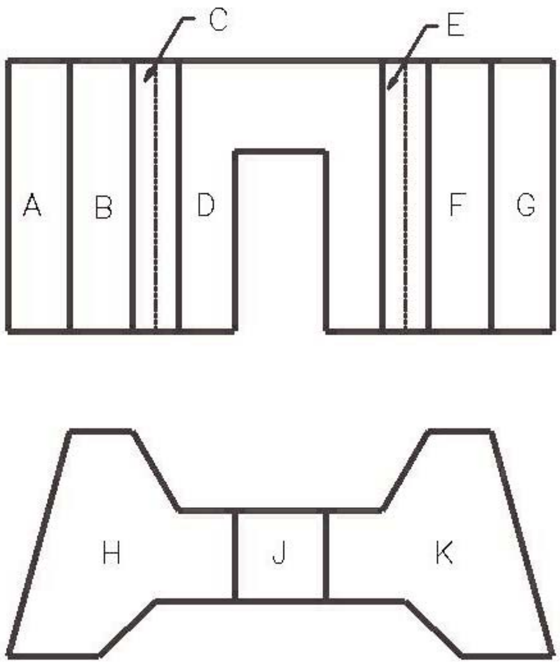


Figure 13 Stand

Module 4

Basic Design: Dimensioning and Tolerancing

Objective:

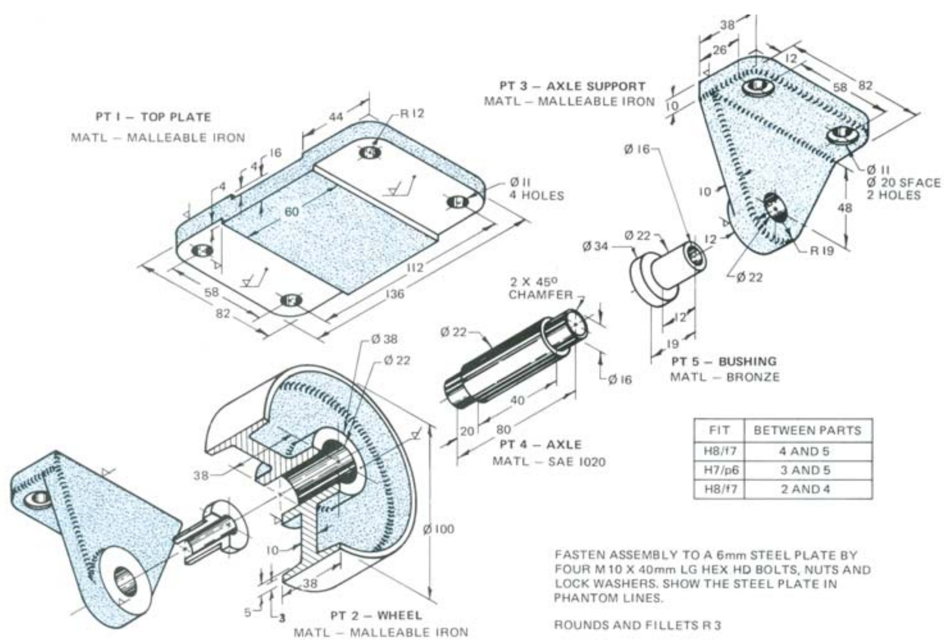
- Provide an understanding of basic dimensioning skills

Prerequisites:

- Intro to 3D printing
- Drafting equipment, media and reproduction
- Basic drafting
- Theory of shapes
- Introduction to computer aided design (CAD)/2D-3D Skills
- Auxiliary views/multi views

Assignment #1: *Demonstrate understanding of sectional views*

1. Create 3D CAD files of top plate, axle support pieces, wheel, axle and bushing as seen in Figure 1. Convert CAD files to STL files.
2. Send the files to the 3D printer and print the individual parts.
3. Measure and record key dimensions of each part.
4. Compare and verify prototypes with original design dimensions.
5. Conduct a trial assembly of the caster. Modify 3D CAD file and reprint prototypes (as necessary).
6. Once caster has been assembled, mount assembly.



FIT	BETWEEN PARTS
H8/f7	4 AND 5
H7/p6	3 AND 5
H8/f7	2 AND 4

Figure 1

Assignment #2: *Applying dimensioning and tolerancing team exercise*

1. Disassemble caster.
2. Breakout into teams of two or three: one component per team. Teams measure and record key dimensions of component.
3. Teams create CAD files of components.
4. Convert CAD files to STL files. Send files to the 3D printer and print component.
5. Measure and record key dimensions of the component.
6. Assemble caster and verify fit.
7. If assembly doesn't function properly, repeat steps 2-5 as necessary.

Module 5

Mechanics and materials: Fasteners

Objective:

- Provide an understanding of assembly process for plastic parts.

Prerequisites:

- Intro to 3D printing
- Drafting equipment, media and reproduction
- Basic drafting
- Theory of shapes
- Intro to computer aided design (CAD)/2D-3D skills
- Auxiliary views/multi views
- Sectional views
- Tolerancing

Assignment #1: *Snap fit and fastening exercise*

1. Measure key dimensions of part A and part B as provided by instructor.
2. Recreate part A and B utilizing CAD. Verify CAD data vs. part measurements.
3. Convert CAD files to STL files. Send the files to the 3D printer and print.
4. Measure output.
5. Verify assembly through snap fit and fastener.

Module 6

Mechanics and Materials: Casting

Objective:

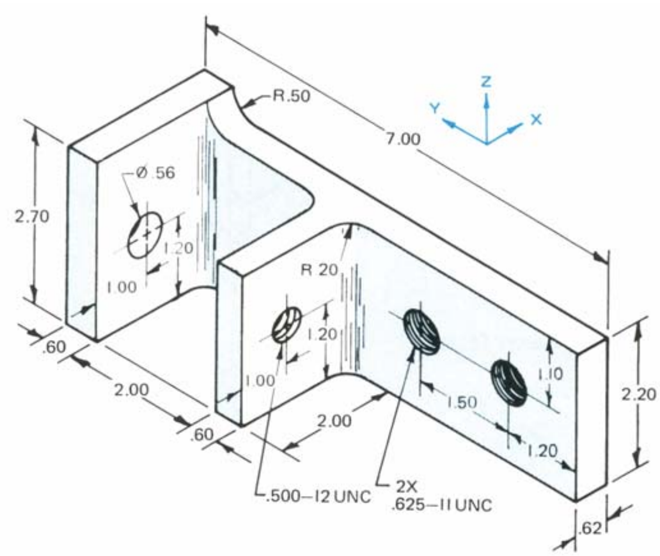
- Provide an understanding of redesign process for plastic molding.

Prerequisites:

- Intro to 3D printing
- Drafting equipment, media and reproduction
- Basic drafting
- Theory of shapes
- Intro to computer aided design (CAD)/2D-3D skills
- Shapes/geometric construction
- Auxiliary views/multi views
- Sectional views
- Tolerancing
- Fasteners
- Manufacturing materials

Assignment #1: *Create plastic part for molding exercise*

1. Using a plastic molding design, add threaded inserts to the part shown below. Use your judgement for dimensions not shown and the type and number of views required. Scale 2:1.
2. Convert 3D CAD file to STL file. Send files to 3D printer and print.
3. Verify your judgements using printed part.



Module 7

Mechanics and Materials: Ratchet Assemblies

Objective:
- Provide an understanding of working gear design

Prerequisites:
- Intro to 3D printing
- Drafting equipment, media and reproduction
- Basic drafting
- Theory of shapes
- Intro to computer aided design (CAD)/2D-3D skills
- Shapes/geometric construction
- Auxiliary views/multi views
- Sectional views
- Tolerancing
- Fasteners
- Manufacturing materials
- Working drawings
- Structural drafting
- Industrial process

Assignment #1: *Create ratchet wheel assemblies exercise*

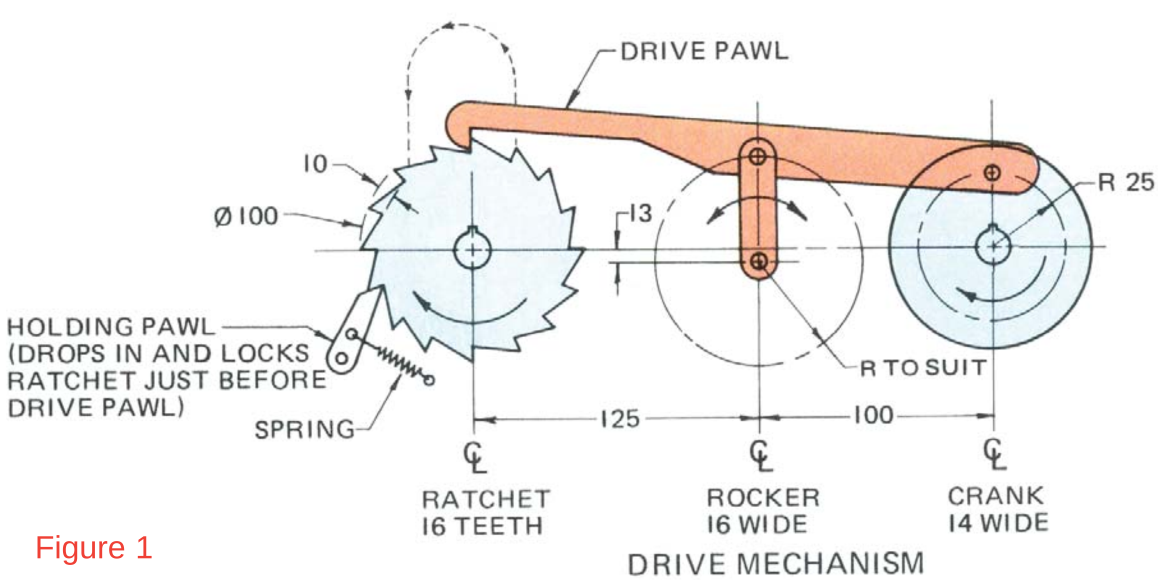


Figure 1

1. Lay out a ratchet assembly using a U-shaped pawl with a ratchet wheel. The ratchet wheel is to have 24 teeth; OD of 146 mm; hub 48 mm; shaft 32.5 mm; keyseat to suit; width of teeth 12 mm; depth of teeth 10 mm; and the hub is to extend 16 mm on one side. Scale 1:1. Show two views.

2. Ratchet and Crank Mechanism. Lay out a one-view drawing of the ratchet design shown in Fig. 1. Two pawls are used, a drive pawl as shown and a holding pawl held in position by a spring. Using crank rotation positions every 22.5 degrees, plot the path of the end of the drive pawl. Use your judgement for dimensions not shown. Scale 1:1.

3. Convert ratchet, drive pawl, and crank part files into 3D CAD files.

4. Convert CAD files to stl files. Send the files to the 3d printer and print each of the three components.

5. Mount assembly to wood as provided by instructor in working position using necessary additional materials.

6. Verify working assembly.

Additional Materials needed: Wood, holding pawl, spring.