

## UNIT 3

### VAT POLYMERIZATION AND DIRECTED ENERGY DEPOSITION

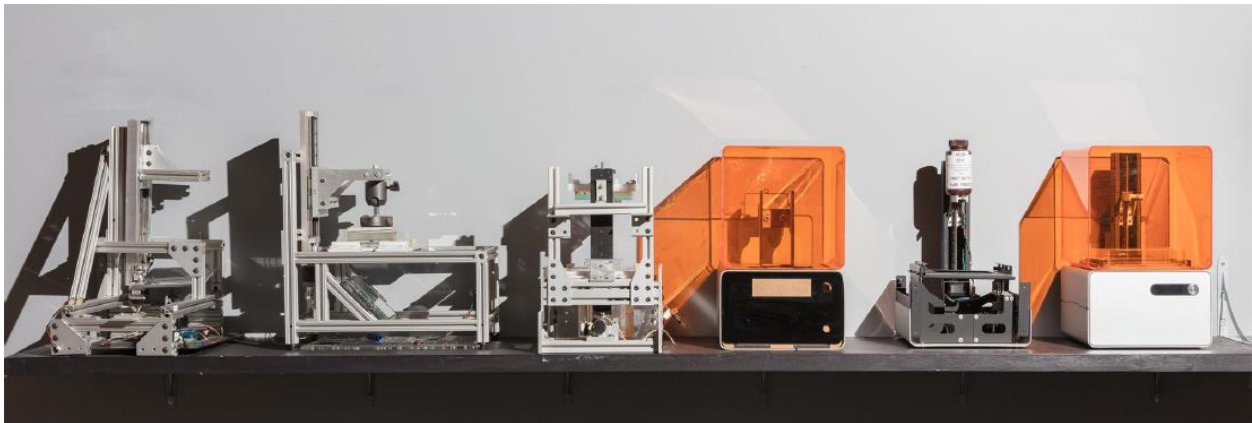
#### 3.1 STEREO LITHOGRAPHY (SLA)

##### 3.1.1 Introduction

Stereolithography (SLA) is an additive manufacturing — commonly referred to as 3D printing — technology that converts liquid materials into solid parts, layer by layer, by selectively curing them using a light source in a process called photopolymerization. SLA is widely used to create models, prototypes, patterns, and production parts for a range of industries from engineering and product design to manufacturing, dentistry, jewelry, model making, and education. In this comprehensive guide, you'll learn about the different SLA systems, various materials and their characteristics, and how SLA compares to other technologies on the market.

##### 3.1.2 History

The SLA process first appeared in the early 1970s, when Japanese researcher Dr. Hideo Kodama invented the modern layered approach to stereolithography of using ultraviolet light to cure photosensitive polymers. The term stereolithography itself was coined by Charles (Chuck) W. Hull, who patented the technology in 1986 and founded the company 3D Systems to commercialize it. Hull described the method as creating 3D objects by successively “printing” thin layers of a material curable by ultraviolet light, starting from the bottom layer to the top layer. Later, the definition was extended to any material capable of solidification or alteration of its physical state. Today, 3D printing and additive manufacturing (AM) describe numerous individual processes, which vary in their method of layer manufacturing, material, and machine technology used.



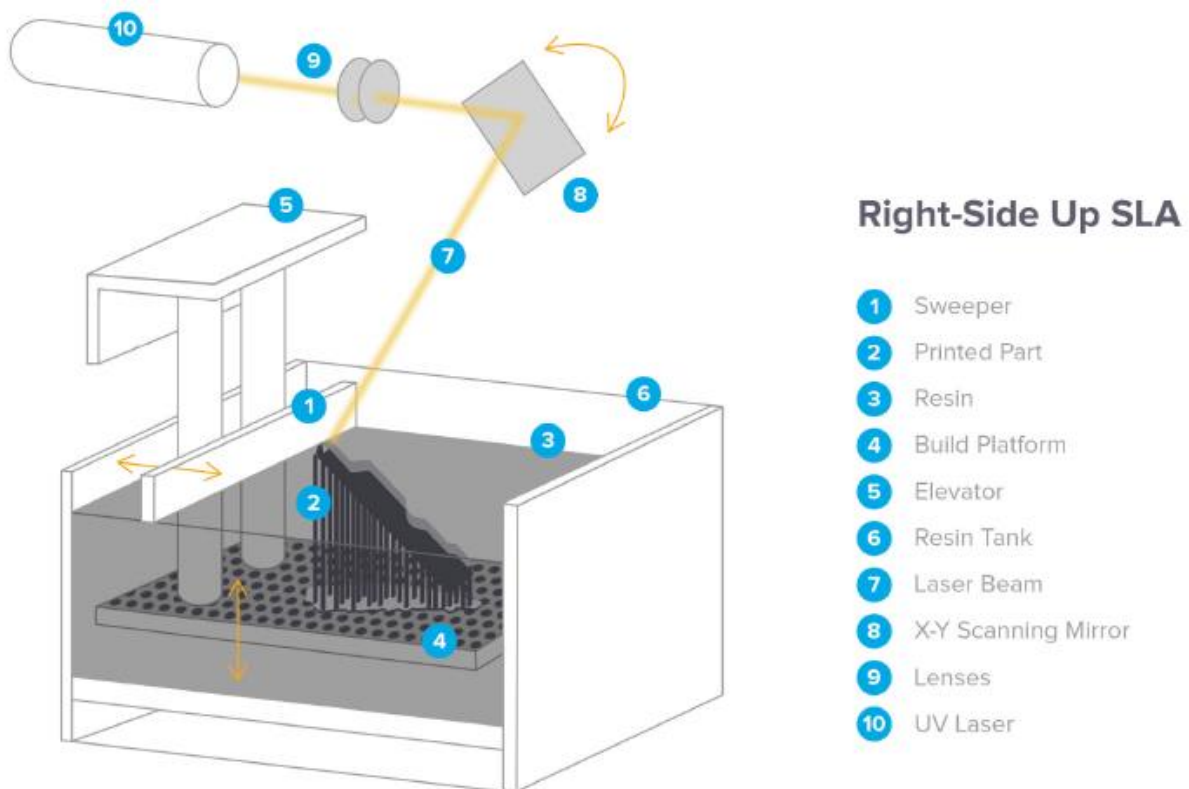
As patents began to expire at the end of the 2000s, the introduction of desktop 3D printing widened access to the technology, with fused deposition modeling (FDM) first gaining adoption in desktop platforms. While this affordable extrusion-based technology aided the widespread use of 3D printing, the quality of these parts has limited the use of these machines, since repeatable, high-precision results are crucial for professional applications.

### 3.1.3 SLA Systems

SLA belongs to a family of additive manufacturing technologies known as vat photo polymerization. These machines are all built around the same principle, using a light source UV laser or projector to cure liquid resin into hardened plastic. The main physical differentiation lies in the arrangement of the core components, such as the light source, the build platform, and the resin tank.

#### Right-Side SLA

Right-side up SLA machines are built around a large tank containing the liquid photopolymer (resin), and the build platform. The UV laser focuses onto the surface of the resin, tracing a cross-section of the 3D model. The build platform then descends a distance equal to the thickness of a single layer, and a resin- filled blade sweeps across the vat to recoat it with fresh material. The process builds consecutive layers on top of the others until the part is finished.

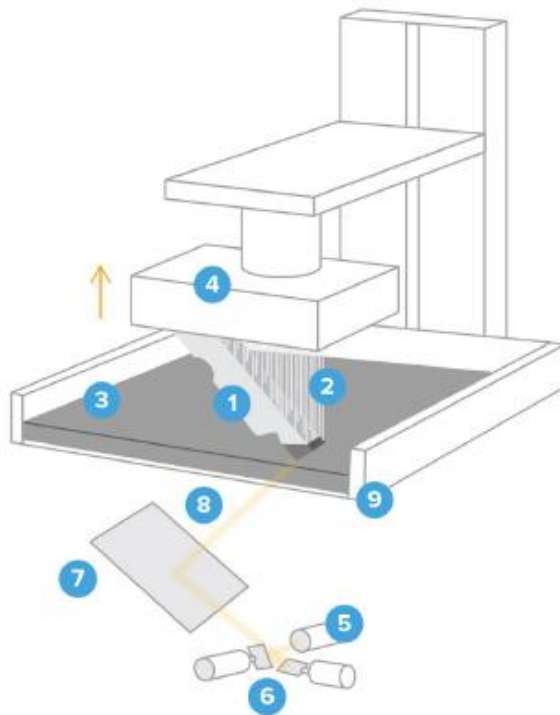


This approach mostly appears in large scale industrial systems, and before the appearance of desktop systems it was the standard approach to stereolithographic. Its benefits include some of the largest build volumes in 3D printing, low forces on the parts during the print process, and in turn high detail and accuracy. Due to the large setup, maintenance requirements, and material volume, right-side up SLA requires a high initial investment and is expensive to run. The entire build area must be filled with resin, which can easily mean 10-100+ liters in raw material, making it a time consuming task to handle, maintain, filter and swap materials. These machines

are highly sensitive to being stable and level, any inconsistency can lead to the recoater toppling the part, leading to print failure.

### Upside-Down (Inverted) SLA

As the name suggests, in inverted stereolithographic, the process is turned upside down. This method uses a tank with transparent bottom and non-stick surface, which serves as a substrate for the liquid resin to cure against, allowing for the gentle detachment of newly-formed layers. A build platform is lowered into a resin tank, leaving space equal to the layer height in between the build platform, or the last completed layer, and the bottom of the tank.



### Upside-Down (Inverted) SLA

- 1 Printed Part
- 2 Supports
- 3 Resin
- 4 Build Platform
- 5 UV Laser
- 6 Galvanometers
- 7 X-Y Scanning Mirror
- 8 Laser Beam
- 9 Resin Tank

The UV laser points at two mirror galvanometers, which direct the light to the correct coordinates on a series of mirrors, focusing the light upward through the bottom of the vat and curing a layer of photopolymer resin against the bottom of the tank. A combination of vertical build platform and horizontal tank movement then separates the cured layer from the bottom of the tank, and the build platform moves up to let fresh resin flow beneath. The process repeats until the print is complete. On more advanced systems, the tank is heated to provide a controlled environment, and a wiper passes across the tank in between layers to circulate resin and remove clusters of semi-cured resin. An advantage of this upside-down approach is that the build volume can substantially exceed the volume of the tank, since the machine only requires enough material to keep the bottom of the build vat continuously covered with liquid. This makes it generally easier to maintain, clean, swap materials, and also allows for a much smaller machine size and lower cost, making it possible to bring SLA to the desktop.

Inverted SLA comes with its own set of limitations. Due to the peel forces affecting the print when it's separated from the surface of the tank, the build volume is limited, and larger

support structures are required to keep the part attached to the build platform. Peel forces also limit the use of more flexible materials Shore hardness below ~70A, because the support structures become flexible as well.

### Understanding Supports

Both right-side up and inverted SLA systems require the use of support structures for most parts, depending on their design. In right-side up systems, these supports hold parts at a precise location to ensure that all details have something to attach to, and resist lateral pressure from the resin-filled blade. Inverted SLA uses supports to attach overhanging parts to the build platform, prevent deflection due to gravity, and retain newly created sections during the peel process. Most software automatically creates supports during the preparation of the 3D models, but they can also be adjusted manually. Once the printing process is completed, these supports must be removed from the finished product manually.

### Comparison of Sla Systems

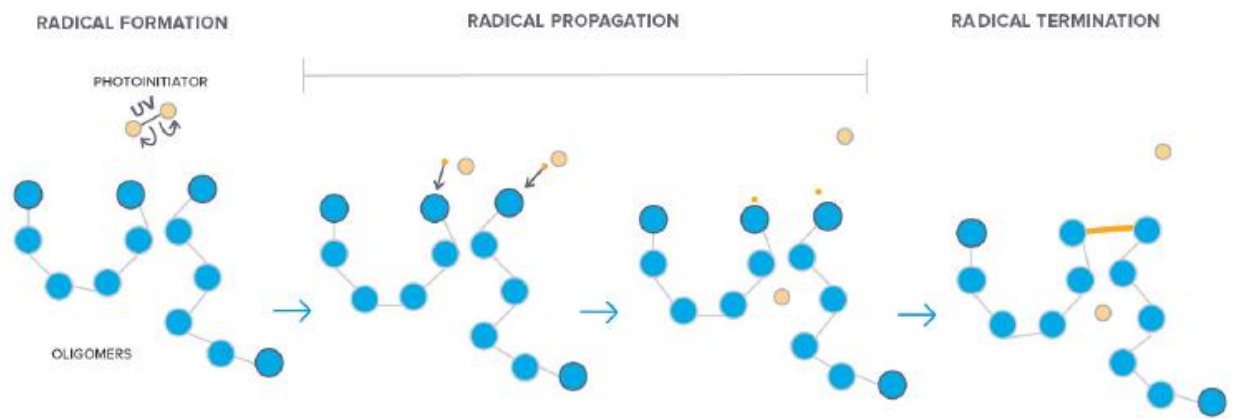
	Desktop SLA: Inverted	Industrial SLA: Right-Side Up
Price	Starting at \$3500	\$60,000-\$1,000,000+
Print Volume	Up to 145 x 145 x 175 cm	Up to 1500 x 750 x 550 mm
Pros	Affordable Easy to use Low maintenance Small footprint Easy material swapping	Large build volume High production rate Extensive material options
Cons	Average build volume	Expensive machinery High maintenance Operator required

#### 3.1.4 Materials

SLA 3D printers provide the tool, but it's the materials that empower stereolithography to create a wide range of functional parts for different industries. In this chapter, we'll look into the photo polymerization process and its raw material, the resin, from its unique characteristics to the various compositions for specific applications.

## The Polymerization Process

Plastics are made out of long carbon chains. The shorter the chain, the less solid or viscous the plastic. Resin is a plastic composed of short(er) carbon chains from 1 carbon to a few thousand carbons. It has all of the components of the final plastic, but hasn't been fully polymerized yet. When the resin is exposed to UV light, the chains join together to create much longer and therefore stiffer chains. When enough chains have reacted, the result is a solid part. Let's break this process down even further. The monomer and oligomer chains in the resin have active groups at their ends. When the resin is exposed to UV light, the photo initiator molecule breaks down into two parts, and the bond holding it together becomes two very reactive radicals. These molecules transfer the reactive radicals to the active groups on the monomers and oligomer chains, which in turn react with other active groups, forming longer chains. As the chains get longer and create cross-links, the resin begins to solidify. The entire process, from liquid to highly polymerized solid state, takes place in a matter of milliseconds.



## Characteristics of Resins and Plastics

Component	Role
Monomers and Oligomers	The core of the resin; carbon chains that will make up the solid parts.
Photoinitiator	Molecules that react when exposed to UV light, initiating the reaction.
Additives	Visual and functional supplements, such as pigments or dyes.

Different resins consist of different backbones and side groups' different combinations of long and short monomers, oligomers, photo initiators, and additives. This provides unique freedom to create

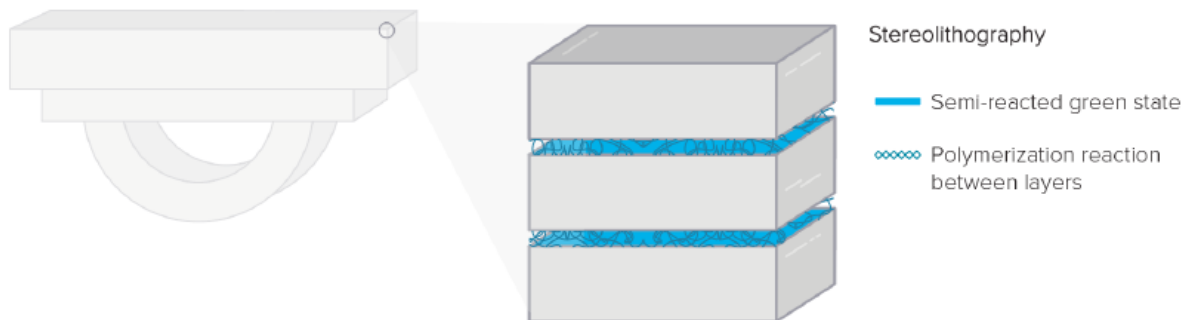
various formulations with a wide range of optical, mechanical, and thermal properties, from clear to opaque and colored, flexible to rigid, and tough to heat resistant.

### Isotropy vs. Anisotropy

Due to the layer-by-layer nature of 3D printing technologies, in many cases material properties vary to some degree according to the direction in the material in which they are measured, a condition referred to as anisotropy. For example, a 3D printed object may have different elongation at break or stiffness in the X, Y, and Z directions.

During the SLA 3D printing process, the components of the resin form covalent bonds. This provides high degrees of lateral strength, but the polymerization reaction is not driven to completion. Rather, the print process is modulated in a way that keeps the layer in a semi-reacted state called the “green state.” This green state differs from the completely cured state in one very important way: there are still polymerizable groups on the surface that subsequent layers can form covalent bonds with.

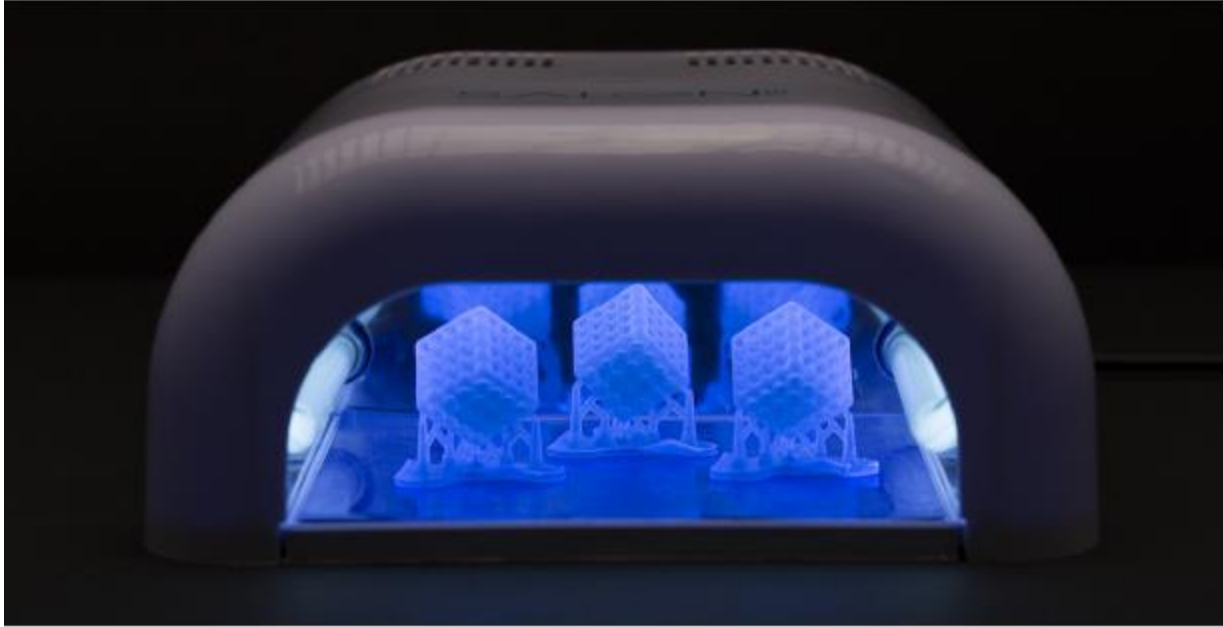
As the next layer is cured, the polymerization reaction includes the groups on the previous layer, forming covalent bonds not just laterally, but also with the previous layer. This means that on a molecular level, there is little to no difference between the Z-axis and the XY plane in terms of chemical bonds. Each continuous part printed on an SLA machine is isotropic.



Isotropy has both mechanical and optical benefits. Isotropic parts are ideal for engineering prototyping applications, since they reflect the range of properties associated with common injection-molded thermoplastics and don't suffer from delamination or surface porosity. The chemical bonding process and the lack of visible layer lines inside the parts allows for printing of optically clear parts.

### Post-Curing

Once the stereolithography process is completed, the printed parts remain on the build platform in the aforementioned green state. While they've reached their final shape and form, the polymerization reaction is not yet driven to completion, so mechanical and thermal properties are not fully set.



Adding a UV post-cure chamber to the printing process finalizes the polymerization process and stabilizes the mechanical properties. This enables parts to reach the highest possible strength and become more stable, which is particularly important for functional resins for engineering, dentistry, and jewelry. For example, successful burnout of Castable prints requires post-curing, and Flexible parts double their strength with post-curing.

### **Thermosetting vs. Thermoplastics**

Photopolymer resins are thermosetting plastics, as opposed to thermoplastics. Though they sound similar, their properties and applications can differ significantly. The primary physical difference is that thermoplastics can be melted into a liquid state and cooled multiple times to form various shapes, whereas thermoset plastics remain in a permanent solid state after curing.

Polymers in thermoset plastics cross-link together during the curing process to form an irreversible chemical bond. For the most common thermoset polymers, curing is induced by heat or suitable radiation, often under high pressure, whereas for stereolithography, the initiator is light and a photo initiator. Thermoplastics pellets soften and become fluid when heated, and the process is completely reversible, as no chemical bonding takes place.

### **SLA Materials by Application**

Stereolithography materials are generally formulated for specific applications or industries. Due to machine and process characteristics, proprietary materials tend to be limited to use in specific SLA systems. In the following, we'll introduce Formlabs' material selection for desktop SLA printers.

Standard Resins provide high resolution, fine features, and a smooth surface finish right out of the printer. While post-curing is recommended, it's not required for all uses, making these resins ideal for rapid prototyping, product development, and general modeling applications.



Engineering Resins simulate a range of injection-molded plastics, helping engineers and product designers conceptualize, prototype, test, and manufacture final products. With material characteristics like tough, durable, flexible, or temperature resistant these resins are used to create functional parts from assemblies to injection molds, soft-touch surfaces and consumer products.



Dental materials allow dental labs and practices to create a range of personalized dental products in house. These parts are based on the patient's scan intraoral, or CBCT scan, and designed for the treatment. Specific applications include orthodontic, diagnostic, and educational models as well as biocompatible parts like surgical and pilot drill guides.





SLA is ideal for prototyping and casting jewelry with intricate details. Standard modeling resins are recommended for prototyping to create an inexpensive “fitting ring” or “try on” piece to create excitement and deliver peace of mind to clients before casting. Castable resin is designed for direct investment casting, allowing jewelers and casting houses to go straight from digital design to a 3D print.



### **3.1.5 Why Desktop SLA?**

To help you decide if stereolithography is the right process for your application, we’ll now compare the benefits of stereolithography to traditional manufacturing methods and other additive manufacturing technologies.

#### **High Resolution and Smooth Surface Finish**

SLA creates parts with a smooth surface finish directly out the machine. This is ideal for applications that require a flawless finish, and also helps reduce finishing time, since parts can easily be sanded, polished and painted. Z-axis layer height is commonly used to define the resolution of a 3D printer. This can be adjusted in between 25 and 100 microns on the Form 2, with a trade-off between speed and quality. In comparison, FDM and SLS printers typically print Z-axis layers at 100 to 300 microns. However, a part printed at 100 microns on an FDM or SLS printer looks different from a part printed at 100 microns on an SLA printer. SLA prints have a smoother surface finish right out of the printer, because the outermost perimeter walls are straight, and the newly printed layer interacts with the previous layer, smoothing out the staircase effect. FDM prints tend to have clearly visible layers, whereas SLS has a grainy surface from the sintered powder.

#### **Accuracy and Repeatability**

SLA printers can create accurate parts with repeatable dimensions. This is essential for functional applications, such engineering assemblies, jewelry casting masters, or custom dental products from a patient’s scan. The combination of the heated resin tank and the closed build environment provides almost identical conditions for each print. Better accuracy is also a function of lower printing temperature compared to thermoplastic-based technologies that melt the raw

material. Because SLA uses light instead of heat, the printing process takes place at close to room temperature, and printed parts don't suffer from thermal expansion and contraction artifacts.

General accuracy of SLA prints is 50 to 200 microns depending on size, resin, and model geometry and support generation. In a recent testing on the Form 2, 95% of prints measured within 240  $\mu\text{m}$  or less of the designed dimensions.

### **Design Freedom**

SLA has one of the most forgiving design specifications of all 3D printing technologies. Depending on part geometry, positive and negative surface features can be produced at 300 microns or less. This is essential for detailed applications such as intricate features on sculptures or tiny prongs in jewelry.

With stereolithography, there's no need to adapt models for 3D printing. Prototypes can be designed with the manufacturing process in mind. This allows for a seamless transition from prototype to traditional manufacturing, such as machining or injection molding. SLA prints are easy to clean and post-process. Resin is easy to wash out of internal channels, allowing for designs like micro channels or cavities, which would not be possible with any other 3D printing process.

### **Rapid Prototyping with Quick Iterations**

Stereolithography helps engineers and product designers quickly verify the look, feel, and function of a design. Mechanisms and assemblies can be tested and easily modified over the course of a few days, helping drastically reduce product development time and avoid costly tooling changes. Desktop SLA easily scales to significantly increase throughput and reduce user wait time. Teams working in multiple locations can print and collaborate on the same designs independently, sharing physical objects over digital channels and printing them on the same machines.

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## Functional Parts for a Wide Range of Applications

SLA resins provide a wide range of characteristics for applications from engineering to dental and jewelry. Material properties include heat resistance, biocompatibility, optical clarity or matching properties of engineering plastics. By creating chemical bonds that cross-link across layers, SLA results in fully dense, water- and air-tight parts that are isotropic their strength does not change with orientation.

## Costs and Value

Accurate prototypes, rapid iterations, and earlier discovery of errors all lead to better final results and less risk when moving from prototyping to production. In manufacturing, SLA reduces the need for expensive tooling, making small run or custom production such as bridge manufacturing, custom jewelry, or personalized dental products accessible. Industrial SLA printers can cost upwards of \$80,000 and require trained technicians and compulsory service contracts to operate. Desktop SLA offers the quality and functionality of industrial systems in a small footprint, with easy operation starting at \$2000.

In comparison to outsourcing or traditional machining, in-house 3D printing can reduce costs by 50-90% when factoring in all related costs like consumables (materials, tanks, and accessories), maintenance, labor, and the depreciation of the machine. Desktop SLA also has a turnaround time of hours, instead of days or weeks with outsourced production.

### 3.1.6 Printing Process

Now that we understand the theory behind stereolithography, let's explore what the printing process looks like on a desktop SLA printer.

## Design

As with all 3D printing processes, SLA starts with a three-dimensional model, the mathematical representation of any three-dimensional surface. This can be created using computer-aided design (CAD) software or developed from 3D scan data. The design is then exported as a .STL or .OBJ file that's readable by the software that prepares the file for the 3D printer.



## Prepare

Each SLA printer includes software to specify printing settings and slice the digital model into layers for printing. Adjustable printing settings include orientation, support structures, layer height, and material. Once setup is complete, the software sends the instructions to the printer via a wireless or cable connection.



## Print

After a quick confirmation of the correct setup, the printing process begins and the machine can run unattended until the print is complete. In printers with a cartridge system, the material is automatically refilled by the machine, while in other cases the user might need to add more material for large prints. Software that prepares the file for the 3D printer.



## Clean

Once the print process is completed, the build platform can be removed from the printer. The printed parts then require rinsing in isopropyl alcohol (IPA) to remove any uncured resin from their surface.



## Cure

After a quick confirmation of the correct setup, the printing process begins and the machine can run unattended until the print is complete. In printers with a cartridge system, the material is automatically refilled by the machine, while in other cases the user might need to add more material for large prints. Software that prepares the file for the 3D printer.



## **Finish**

After drying and curing, supports can be easily removed from the parts with flush cutters, and the remaining support marks sanded away for a clean finish. SLA parts can easily be post-processed for specific applications or the required finish, including machining, priming, painting, and assembling printed parts.

