

## The Ultimate Guide to Stereolithography (SLA) 3D Printing

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.



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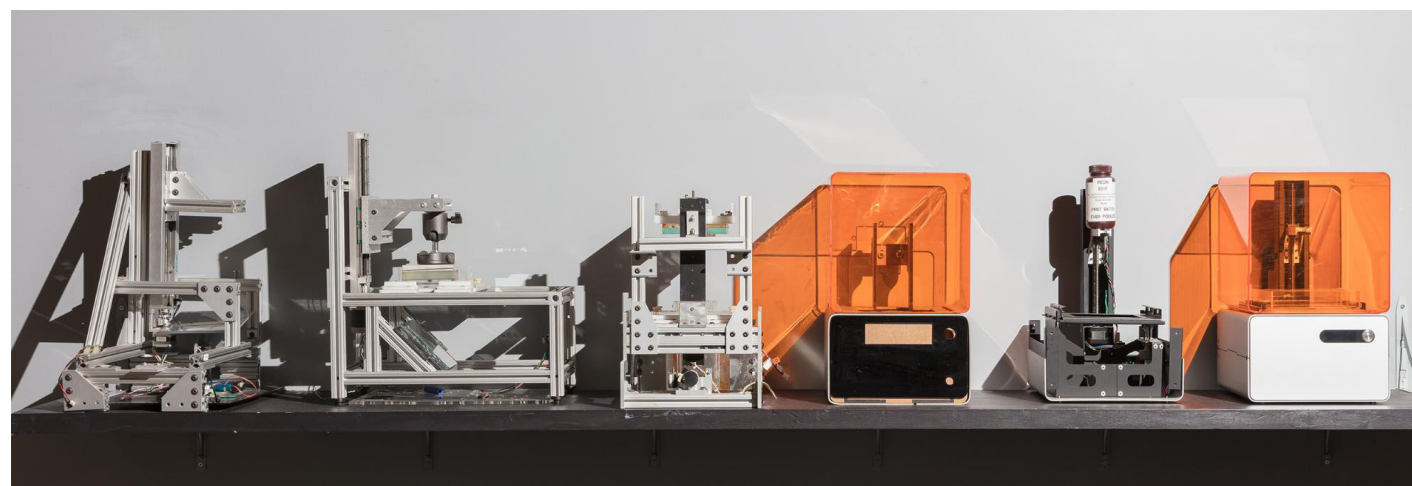
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## Brief History

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.



*Prototypes of the Form 1, the first desktop SLA 3D printer*

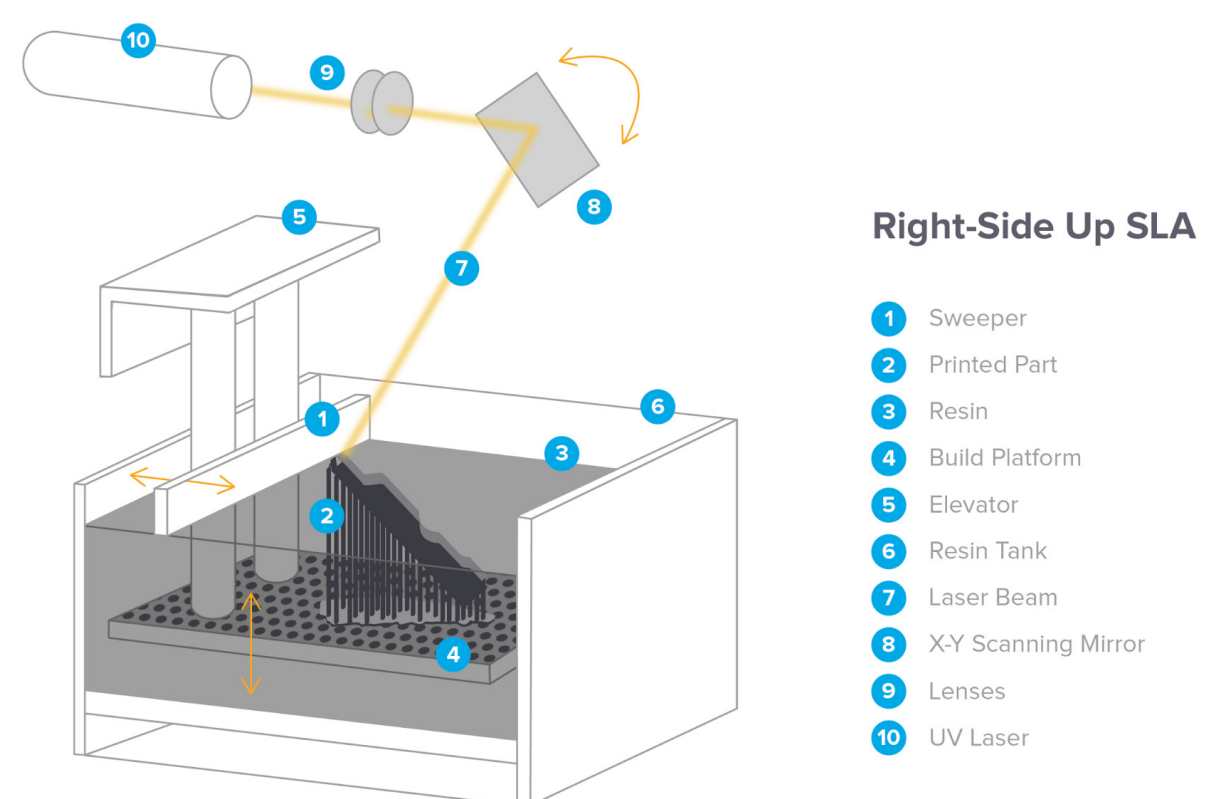
SLA soon followed FDM to the desktop, when Formlabs adapted the technology in 2011. SLA brought the promise of high resolution 3D printing—previously limited to industrial systems—in a much smaller and more affordable setup, with a wide range of print materials. These capabilities made 3D printing accessible for a variety of custom applications, including engineering, product design and manufacturing or the dental and jewelry industries.

## SLA Systems

SLA belongs to a family of additive manufacturing technologies known as vat photopolymerization. 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.



Schematic of the right-side up SLA systems.

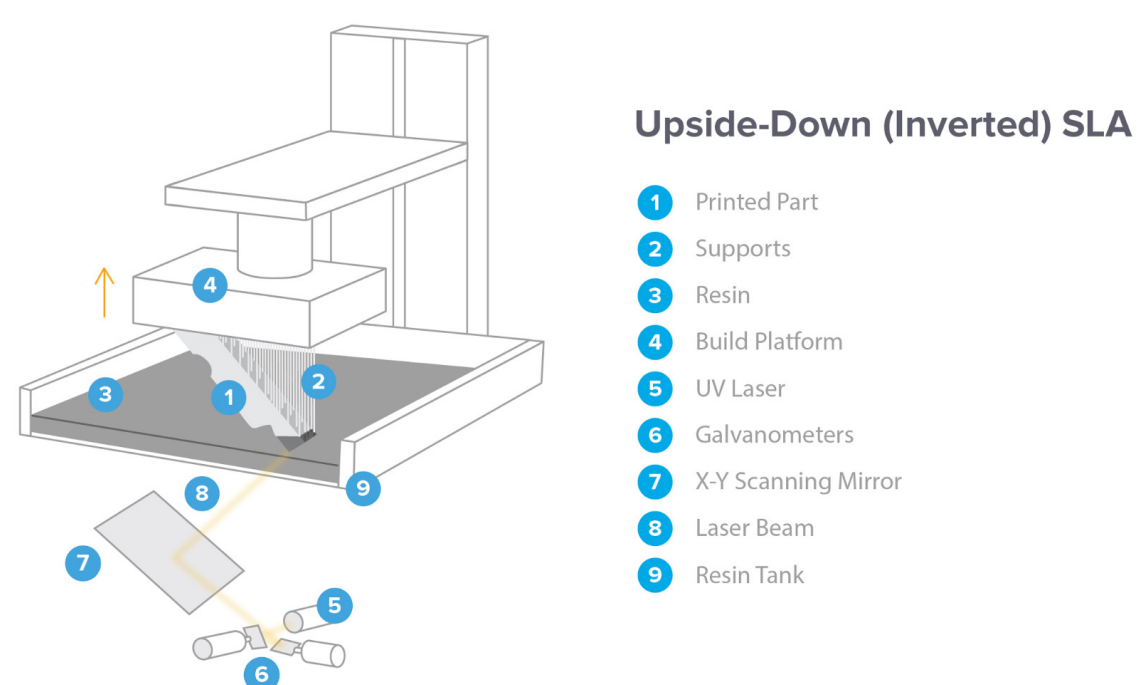
This approach mostly appears in large scale industrial systems, and before the appearance of desktop systems it was the standard approach to stereolithography. Its benefits include some of the largest build volumes in 3D printing, low forces on the parts during the print process, and in turn high detail and accuracy.

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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 stereolithography, 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.



Schematic of the upside-down (inverted) SLA systems

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.

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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



Both SLA systems use support structures to attach parts to the build platform.



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

Comparison is based on a Formlabs desktop SLA printers and industrial SLA systems by 3D Systems.

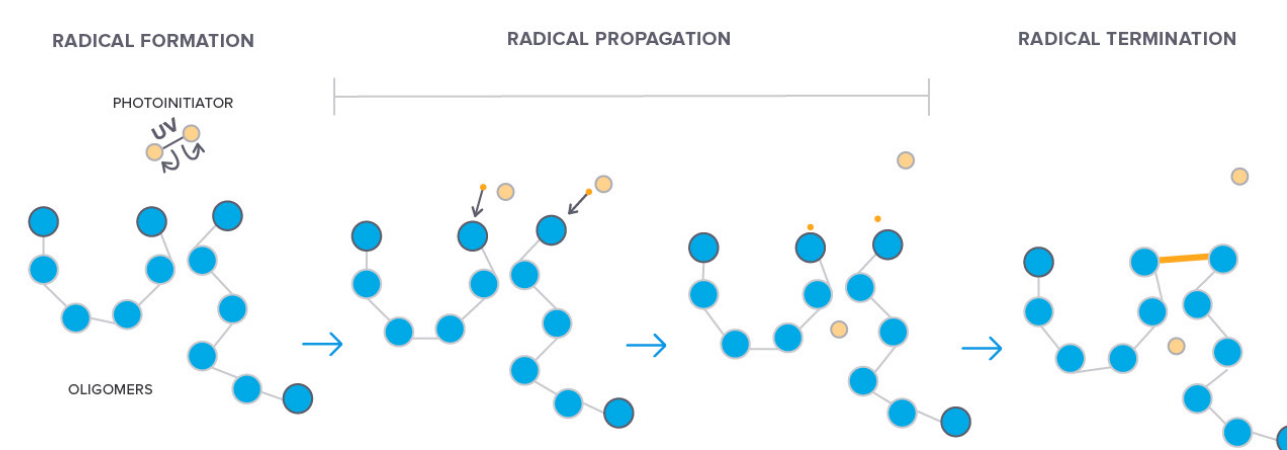
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## Materials

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 photopolymerization 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



Steps of the polymerization process.

in the resin have active groups at their ends. When the resin is exposed to UV light, the photoinitiator 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

Different resins consist of different backbones and side groups—different combinations of long and short monomers, oligomers, photoinitiators, 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.

#### COMPOSITION OF PHOTOPOLYMER RESIN

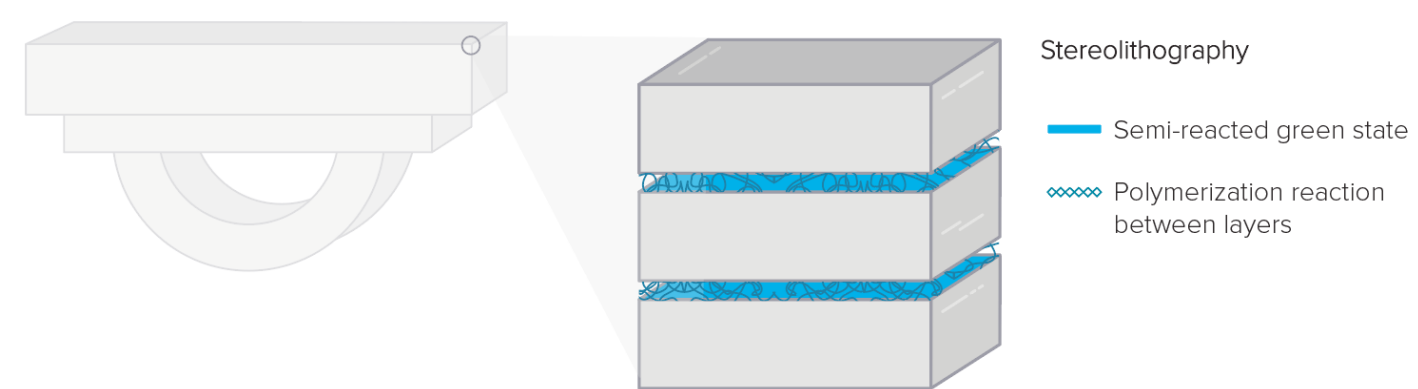
Component	Role
Monomers and Oligomers	The core of the resin; carbon chains that will make up the solid parts.
Photoinitiator	Molecules that react when exposed to UV light, initiating the reaction.
Additives	Visual and functional supplements, such as pigments or dyes.

#### 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.



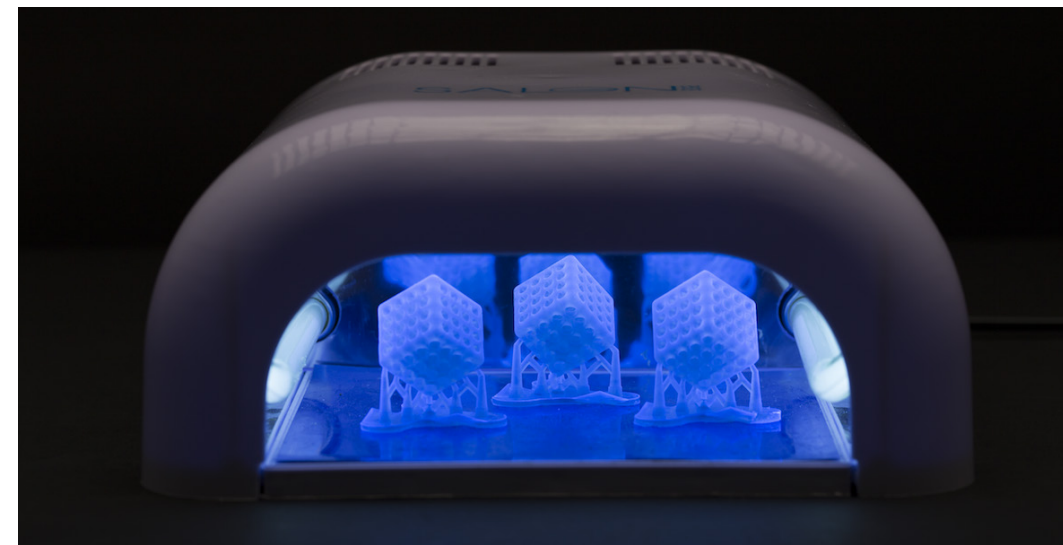
*In SLA prints, there is no difference between the Z-axis and the XY plane in terms of chemical bonds. Each continuous part printed on an SLA machine is a continuous polymer network.*

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.

[Learn more about isotropy](#), and see test results of SLA 3D printed 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.



*SLA prints in a UV-curing station. UV post-curing finalizes the polymerization process and stabilizes the mechanical properties.*

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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.

Find test results and read more about how post-curing influences mechanical properties in our [white paper](#).

#### 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 photoinitiator. 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



Interchangeable lens camera, produced entirely using Standard Resins, including the optically transparent lenses. [Learn how it's made.](#)

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.

[Compare Standard Resins](#) →

ENGINEERING



Parts printed with Engineering Resins, including thermoforming and injection molds, flexible shoe sole, and consumer products.

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.

[Compare Engineering Resins](#) →



DENTAL



*Dental model and biocompatible surgical guide, printed on the Form 2.*

Dental materials allow dental labs and practices to create a range of personalised 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.

[Compare Dental Resins](#) →

JEWELRY



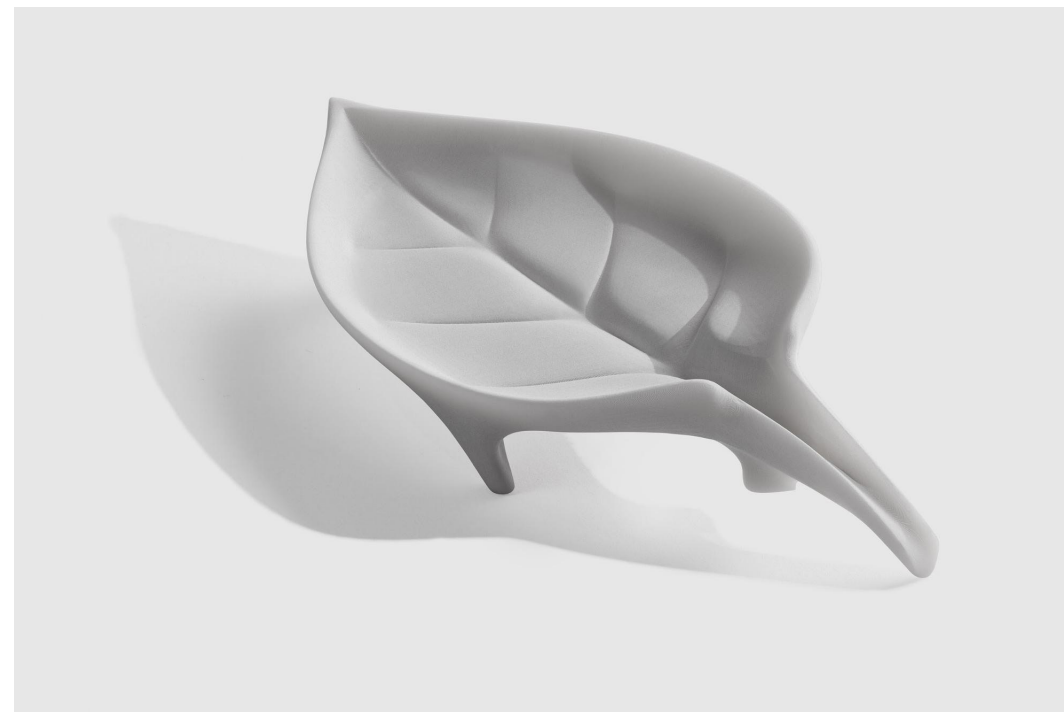
*Jewelry printed from Castable Resin for direct investment casting, and the finished ring.*

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.

[Compare Jewelry Resins](#) →



EXPERIMENTAL



*Soap dish printed from Ceramic Resin, and post-cured for distinctive aesthetics.*

Various formulations using additives and composites in the resin open up possibilities for new experimental materials. [Ceramic](#) produces post-cured prints with a distinctive aesthetic, that looks and feels like traditional ceramics. After firing, prints become pure ceramic parts, suitable for glazing.

Experiment with adding epoxy dye and fragrance oil for [colorful, scented 3D prints](#).

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## 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.

XY resolution for most SLA machines is much higher—2.8 microns for the Form 2, compared to 12.5+ microns for FDM printers. The smallest possible detail is also much finer on SLA, given 140 micron laser spot size on the Form 2, in comparison with 250–800 micron nozzles on FDM machines.



Rooks printed at 100 micron layer height on an desktop and industrial FDM, desktop SLA (Form 2), industrial SLA and industrial SLS 3D printers.

The smallest possible detail is also much finer on SLA, given 140 micron laser spot size on the Form 2, in comparison with 350 microns on industrial SLS printers, and 250–800 micron nozzles on FDM machines.

[Read more about what resolution means in 3D printing.](#)



#### ACCURACY AND REPEATABILITY

SLA printers can create accurate parts with repeatable dimensions. This is essential for functional applications, such as 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, model geometry and support generation. In a recent testing on the Form 2, 95% of prints measured within 240 µm or less of the designed dimensions.

For a [in-depth study on accuracy](#), download our free white paper.

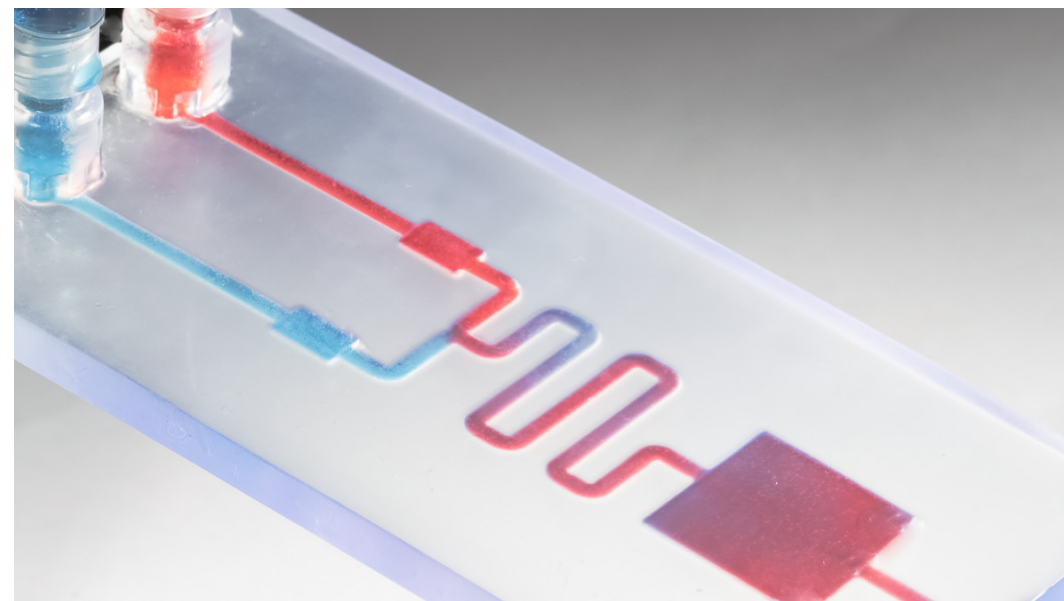
#### DESIGN FREEDOM

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 microchannels or cavities, which would not be possible with any other 3D printing process.





Microchannels that allow liquid transfer and mixing, printed using Standard Clear resin.

Read the detailed [design specifications](#) for SLA 3D printing.

#### 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.



Consecutive iterations of *Sutru*, an automated surgical suturing device prototyped on Formlabs SLA printers.

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.

Learn how to [manage multiple desktop SLA 3D printers](#) in our free white paper.



#### 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 personalised 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, 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.

For a [cost and time comparison](#) of desktop SLA printing, outsourcing, and injection molding for low volume production, check out our free white paper.



#### TECHNOLOGY COMPARISON

Three common technologies for 3D printing plastics exist today. Fused deposition modeling (FDM) melts a string of thermoplastic filament and lays it down on a printbed, stereolithography (SLA) solidifies liquid photopolymer resin with a light source, and selective laser sintering (SLS) uses a laser to sinter powdered raw material.

Each technology has its own set of benefits and drawbacks, and is therefore recommended for different applications.

	Fused Deposition Modeling (FDM)	Stereolithography (SLA)	Selective Laser Sintering (SLS)
<b>Pros</b>	Fast Low-cost system and materials	Great value High accuracy Smooth surface finish Range of functional applications	Strong functional parts Design freedom No need for support structures
<b>Cons</b>	Low accuracy Low details Limited design compatibility	Limited build volume on desktop Sensitive to long exposure to UV light	Expensive machinery Rough surface finish Limited material options
<b>Applications</b>	Low-cost rapid prototyping	Functional prototyping Dental applications Jewelry prototyping and casting Modelmaking	Functional prototyping Short-run, bridge, or custom manufacturing
<b>Price</b>	Mid-range desktop printers start at \$3,500, and industrial systems are available from \$20,000.	Professional desktop printers start at \$3,500 and large-scale industrial machines are available from \$80,000.	Industrial printers are available from \$100,000.

[Watch our webinar](#) for a detailed comparison of FDM, SLA, and SLS technologies and applications.

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## 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



*Use any computer-aided design (CAD) software to design your model, and export it in a 3D printable file format.*

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 an .STL or .OBJ file that's readable by the software that prepares the file for the 3D printer.

### PREPARE



*Prepare your model for printing in the SLA 3D printer's software.*

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



*Stereolithography printing in progress.*

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

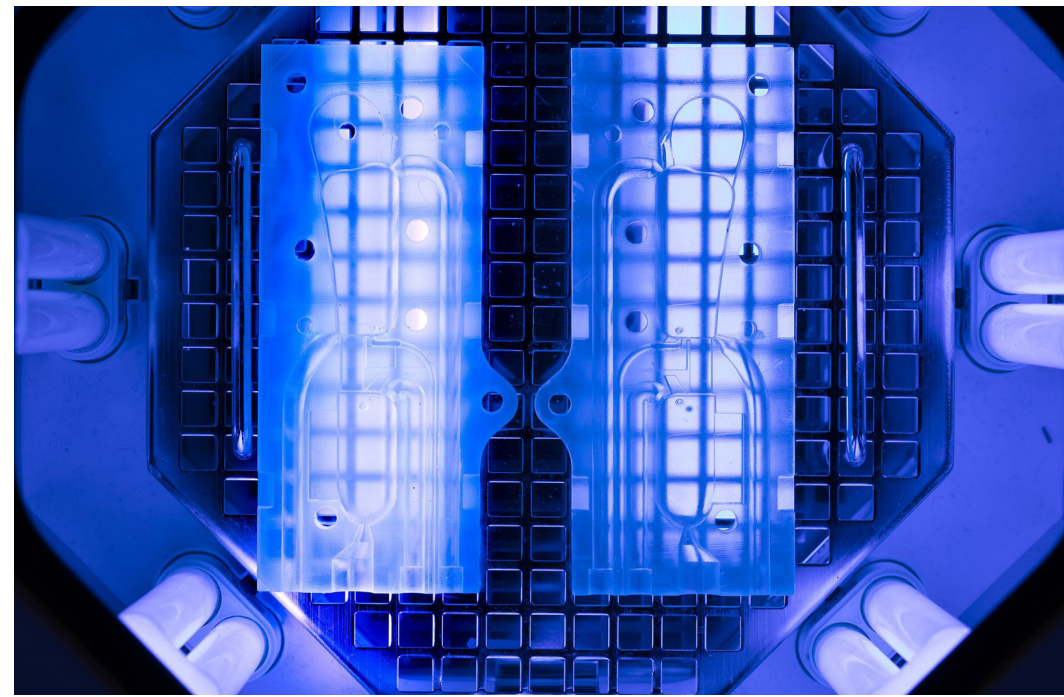


*Clean parts in isopropyl alcohol (IPA) to remove any uncured resin.*

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.



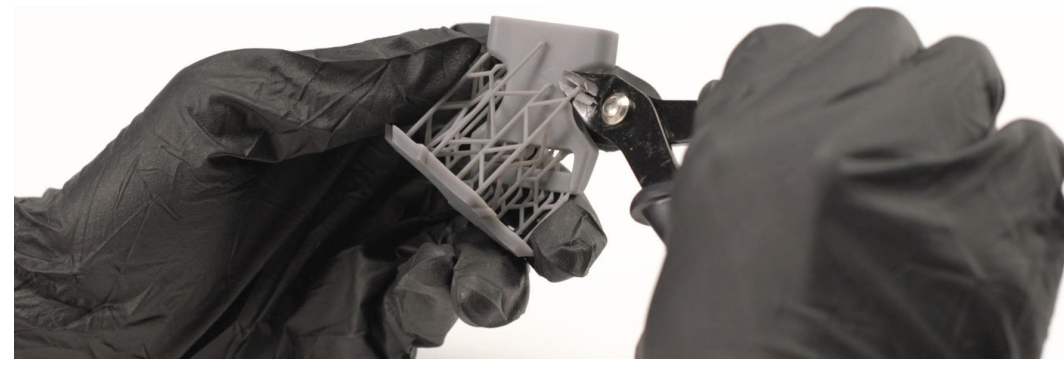
#### CURE



*Stereolithography printing in progress.*

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



*Remove supports with flush cutters, and sand away the remaining support marks for a clean 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.



### Get Started with SLA 3D Printing

Learn more about the [Form 2 desktop SLA printer](#), explore [stereolithography materials](#), or request a [free sample part](#) to experience the SLA quality firsthand.

See the Form 2

