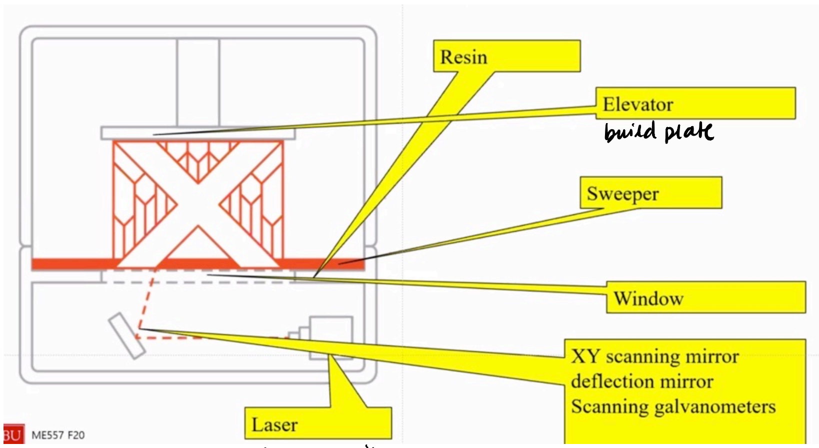
Vat Polymerization

- class of methods for creating a solid part
- traditionally use SLA for prototyping, now can use SLA/vat polymerization for prototype tooling
- dental molds, dentures, hearing aids industries have been transformed and almost all use SLA/vat polym.
- custom shoes w/ lattice design
- Formlabs bought patent; invested a lot in biocompatible materials



Laser hits resin

Two types of printers

- top down
  - need to have entire vat of resin (more $)
  - industrial
  - don't have peeling force so easier to take off
- bottom up
  - smaller print area
  - a lot of peeling force
  - lower cost

Thermoplastic vs. Thermoset

Thermoplastic: can melt down

Thermoset: chemically set; can't melt down or will get material degradation

Guest Speaker – Craig Broady from Form Labs

- Formlabs Profile – 1
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- Reinventing SLA at Formlabs – 3
- Covid-19 swab case study – 4

1- Formlabs Profile

- create reliable, accessible 3D printing systems for professionals
- form 3B – biocompatibility where wash + cure

2- SLA: Stereolithography Overview & 3- Reinventing SLA at Formlabs

- additive man. process where light cures a photopolymer resin
  - laser + galvanometer *
  - DLP (projector)
  - LCD
  - right side up
  - inverted *
    - pull part from resin upside down, requires less resin, need less precision

at Formlabs

- wherever the laser hits, it solidifies/cures resin

Advantages	Disadvantages
Advantages vs right side up • Less resin required • No leveling required • No precision recoated required • Lower cost machine	**Disadvantages vs right side up** • **Support structure removal** • **Dimensional accuracy for large parts** • **Maximum print size**
Advantages vs DLP • Cost—Blu-ray players dropped the price of 405nm laser diodes • Smaller machine size • No resolution / print size trade-off	**Disadvantages vs DLP** • More development time required • Print speed for high volume parts
Advantages vs FDM • *High resolution* • *Dimensional accuracy* • *Superior surface finish* • *Material properties**	**Disadvantages vs FDM** • Cost • Material handling • Speed • Material properties*

Resin can cost ~ $150/liter

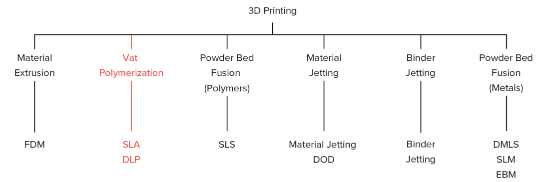
right side up
- easier to peel
- good for very fragile parts

Low Force Stereolithography
- keep laser diameter consistent

4- Covid-19 swab print test case

- NP swabs (nasopharyngeal)

<u>**What is SLA?**</u>

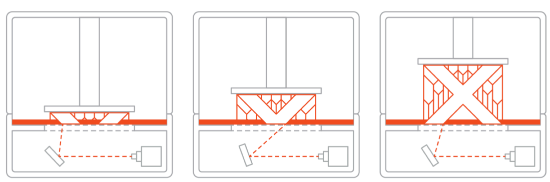


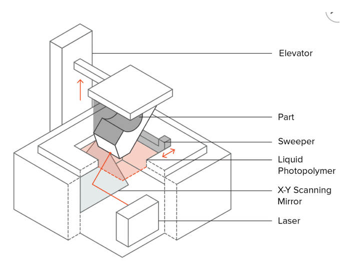
Stereolithography (SLA) is an AM process that belongs to the Vat Photopolymerization family

- object is created by selectively curing polymer resin layer-by-layer using UV laser beam
- materials use in SLA are photosensitive thermoset polymers that come in liquid form
- SLA famous for being the first 3D printing technology

<u>**How does SLA work?**</u>

I. build platform positioned in tank of liquid photopolymer, distance of one layer height for the surface of the liquid
II. UV laser creates next layer by selectively curing solidifying photopolymer resin —> laser beam focused in predetermined path using set of mirrors (called galvos) and the whole cross-sectional area of the model is scanned so the produced part is fully solid
III. when layer finished, platform moves at safe distance and sweeper blade re-coats surface —> process repeats until part is complete
IV. after printing, part is in a green, no-fully-cured state and requires post processing under UV light if very high mechanical and thermal properties are required



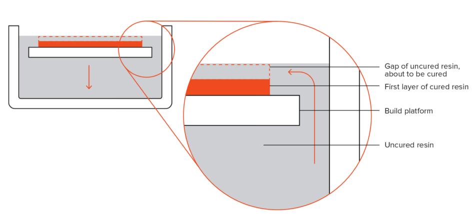


Liquid resin is solidified through a process called ***photopolymerization*** — during solidification, monomer carbon chains that compose the liquid resin are activated by the light of the UV laser and become solid, creating strong unbreakable bonds between each other

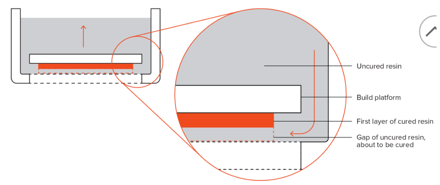
- the process is irreversible
- when heated, they will burn instead of melting
- this is because materials used for SLA are made of thermoset polymers as opposed to thermoplastics that FDM uses

<u>**Printer Parameters**</u>

- in SLA systems most print parameters are fixed by the manufacturer and can’t be changed
- only inputs are layer height and part orientation (which determines support location)
- typical layer height ranges between 25 and 100 microns
- lower layer heights capture cure geometries more accurately but increase the build time and cost and probability of a failed print
- 100 microns is suitable for most common applications
- build size depends on the SLA machine: two main types, top-down and bottom-up
    - ***top-down SLA printers***: place the laser source above the tank and part is built facing up; build platform begins at the very top of the resin vat and moves downwards after every layer



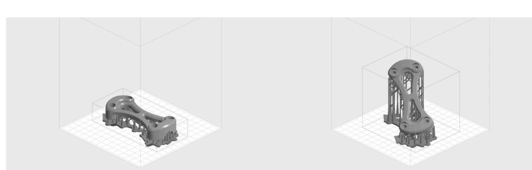
  - ***bottom-up SLA printers***: place light source under the resin and part is built facing upside down; after every layer the cured resin is detached from the bottom of the tank as build platform moves upwards, called the peeling step



- bottom-up orientation is mainly used in desktop printers like Formlabs while the top-down is generally used in industrial SLA systems
- bottom-up SLA printers easier to manufacture and operate but build size is limited as forces applied to part during peeling step might cause print to fail; while top-down printers can scale up to very large build sizes without a big loss in accuracy

	Bottom-up (Desktop) SLA	Top-down (Industrial) SLA
Advatages	+ Lower cost + Widely available	+ Very large build size + Faster build times
Disadvantages	− Small build size − Smaller material range − Requires more post-processing, due to extensive use of support	− Higher cost − Require specialist operator − Changing material involves emptying the whole tank
Popular SLA printer manufacturers	Formlabs	3D Systems
Build size	Up to 145 x 145 x 175 mm	Up to 1500 x 750 x 500 mm
Typical layer height	25 to 100 microns	25 to 150 microns
Dimensional Accuracy	± 0.5% (lower limit: ± 0.010 - 0.250 mm)	± 0.15% (lower limit ± 0.010 - 0.030 mm)

Support Structure
- always required in SLA, must be manually removed after printing
- orientation of part determines location and amount of support
- recommended that part oriented so that visually critically surfaces do not come in contact with the support structures
- in top-down SLA printers, support requirements similar to FDM: usually printed flat to minimize support, can do steeper overhang angles though (30 degrees)
- in bottom-up SLA printers, more complicated:
  - overhangs and bridges still need supports but minimizing the cross-sectional area of each layer is the most crucial criterion
  - the forces applied to the part during the peeling step may cause it to detach from the build platform
  - these forces are proportional to the cross-sectional area of each layer
  - why parts are oriented in an able and the reduction of support is not a primary concern



On the left, a part oriented for a top-down SLA printer (minimizing support). On the right, a part oriented for a bottom-up SLA printer (minimizing cross-sectional area)

Curling

- similar to warping in FDM
- during solidification/curing, the resin shrinks slightly upon exposure to the printer's light source
- when shrinkage considerable, large internal stresses develop between the new layer and the previously solidified material which results in curling of the part

Layer Adhesion

- SLA printed parts have isotropic mechanical properties
- because single UV laser pass is not enough to fully cure the liquid resin
- in SLA, curing continues even after the completion of the printing process
- to achieve best mechanical properties, SLA parts must be post-cured by placing them in a cure box under intense UV light
- this improves the hardness and temperature resistance of the SLA part (but it does make it more brittle)
- leaving part int he sun will also induce curing; extended exposure to UV light has detrimental effect on physical properties and appearances —> may curl, become very brittle, change color —> why recommended to spray coat with clear UV acrylic paint before use

Common SLA Materials

- thermosets are used, more brittle than materials produced with FDM or SLS (thermoplastics)
- SLA parts therefore not usually used for functional prototypes that will undertake significant loading

Benefits & Limitations of SLA

+ SLA can produce parts with very high dimensional accuracy and with intricate details
+ SLA parts have a very smooth surface finish, therefore ideal for visual prototypes
+ specialty SLA materials are available, such as clear, flexible, and cartable resins
- SLA parts generally more brittle and not suitable for functional prototypes
- mechanical properties and visual appearance of SLA parts will degrade overtime when parts exposed to sunlight
- support structures are always required and post-processing is necessary to remove visual marks left on SLA part

Rules of Thumb

- SLA best suited for visual prototypes with very smooth surface and very fine details from range of thermoset materials
- desktop SLA ideal for manufacturing small (smaller than a fist) injection molded-like parts at an affordable price
- industrial SLA machines can produce very large parts, as big as 1500x750x500 mm

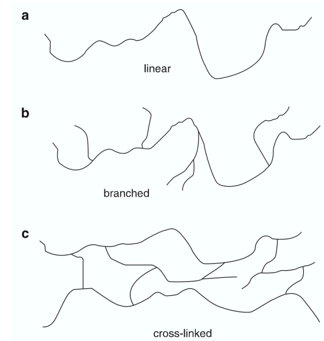
	Stereolithography (SLA)
Materials	Photopolymer resins (thermosets)
Dimensional Accuracy	± 0.5% (lower limit: ±0.10 mm) - desktop ± 0.15% (lower limit ± 0.01 mm) - industrial
Typical Build Size	Up to 145 x 145 x 175 mm - desktop Up to 1500 x 750 x 500 mm - industrial
Common layer thickness	25 - 100 microns
Support	Always required (essential to producing an accurate part)

— **<u>Vat Photopolymerization Processes</u>** —

- photopolymerization makes use of liquid, radiation-curable resins, or photopolymers
- upon irradiation, materials undergo chemical reaction to become solid and this reaction is called photopolymerization
- mid-1980s by Chuck Hull; term VP is general term that encompasses SL and related processes
- three configurations for photopolymerization process
  - (1) vector scan — point-wise approach, typical of commercial SL machines
  - (2) mask projection — layer-wise approach, irradiate entire layers at one time
  - (3) two-photon approach, essentially high-resolution point-by-point approaches

<u>UV Curable Photopolymers</u>

- various types of radiation may be used to cure commercial photopolymers, including gamma rays, x-rays, electron beams, UV, visible light
- in SL systems, UV radiation exclusively used
- while thermoplastic polymers are typically in injection molding and have a linear or branched molecular structure that allows them to melt and solidify repeatedly, in contrast *VP photopolymers are cross-linked* and as a result don't melt and exhibit much less creep and stress relaxation
- most SL resins commercially available today are epoxides with some acrylate content



<u>Overview of Photopolymer Chemistry</u>

- VP photopolymers are composed of several types of ingredients: photo initiators, reactive diluents, flexibilizers, stabilizers, and liquid monomers
- when UV radiation impinges on VP resin the photoinitiators undergo a chemical transformation and become reactive with the liquid monomers to start a polymer chain
- subsequent reactions occur to build polymer chains and then to cross-link which is the creation of strong covalent bonds between polymer chains
- polymerization is term used to describe process of linking small molecules (monomers) into larger molecules (polymers) composed of many monomer units
- two main types of photopolymer chemistry commercially evident: (1) free-radical photopolymerization (acrylate) and (2) cationic photopolymerization (epoxy and vinylether)
- SL resins used to be only acrylate
- acrylate photopolymers exhibit high photo speed (react quickly when exposed to UV radiation) but have a number of disadvantages including significant shrinkage and a tendency to warp or curl —> now therefore rarely used without epoxy or other photopolymer elements
- resin suppliers create ready-to-use formulations by mixing oligomers and monomers with photoinitiator as well as other materials to affect reaction rates and part properties
- photosensitizes often used in combo with photo initiator to shift absorption towards longer wavelengths

<u>Photoinitiator Systems</u>

- role of photo initiator is to convert physical energy of incident light into chemical energy in form of reactive intermediates
- photoinitiator must exhibit strong absorption at the laser emission wavelength and undergo a fast photolysis to generate the initiating species with great quantum yield

<u>Laser Scan Vat Photopolymerization</u>

- laser scan VP creates solid parts by selectively solidifying a liquid photopolymer resin using a UV laser
- physical parts are manufactured by fabricating cross-sectional contours, or slices, one on top of another
- slices are created by tracing 2D contours of a CAD model in a vat of photopolymer resin with a laser
- laser scanning of part is the phase that actually solidifies each slice in VP machine
- after building part, part must be cleaned, post-cured, and finished