BETTER BE RUNNING!

TOOLS TO DRIVE DESIGN SUCCESS

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EXCERPT FROM
Better Be Running!: Tools to
Drive Design Success

Chapter 2

Stereolithography

THE LION'S SHARE OF RAPID PROTOTYPING

"Rapid prototyping makes heroes."

QuickSMART

Definition: Stereolithography (SL) means to print in three dimensions (stereo: three-dimensional; lithography: to print). SL is the first and most popular liquid-based AF system that produces plastic parts from cross-sectioned CAD data. Electronic CAD design data is converted to an STL (Standard Tessellation Language) file format. Special software slices the CAD model into thin layers and creates build instructions for the machine. Layer by layer, the Stereolithography Apparatus (SLA) machine replicates a plastic physical model out of photo-curable resin. The resin turns into hard plastic wherever touched by an ultraviolet (UV) laser.

Why You Need It: To reduce design cycle time by 50%; to ensure part functionality; to eliminate design changes late in the manufacturing cycle; to quickly create a single physical model or family of parts to touch and feel; to see how the part interacts with its environment; and to check physically/geometrically because drawing interpretation is prone to human error.

Ideal Uses: Trade show models; CAD verification; proof-of-concept; conceptualization; visual aids for marketing and planning; form, fit, and function testing; flow analysis, stress analysis, mock-up for testing, clearance checking, patterns for tooling and casting; tooling production, reproducing snap fits, assisting collaborative design, engineering, and manufacturing team in planning and decision-making; and a powerful communicator that provides complete information and understanding to all parties so they don't have to rely on guesswork or CAD data.

Stereolithography Background

As the forerunner of the latest Industrial Revolution which began in the early '90s, SL allows you to create a 3D plastic object from a CAD model in several hours. Prior to this technology, conventional prototyping methods could take days or even weeks. Whether you are a design engineer wanting to verify your concept, or a manufacturing engineer needing form, fit, and function feedback, SL gives you and your team a quick, accurate way to convert virtual data into real objects. It allows you to test designs in their physical environment before committing to expensive tooling.

If you are new to the exciting world of AF, which includes rapid prototyping (RP), rapid tooling, and low-volume production manufacturing, you have a strong cost incentive for remembering all the acronyms associated with these revolutionary processes. Lucky for you, there really are only three AF processes we are including in the Product Developer's Toolbox. Of course there are dozens of other processes that exist with varying degrees of utility to product development. The first we are discussing is SL, considered the pioneer of the AF industry.

Stereolithography was the watershed in manufacturing. It was invented by Charles Hull and made commercially available by 3D Systems, Inc., in 1988. Because 3D Systems was the first to market the SLA machine, many folks frequently misuse the term SLA to generically describe all RP techniques and any liquid-based, UV AF process. Within the industry, SLA has become as widely misused as the name Kleenex. One example of a process that produces parts that are similar to SL is made by Objet Geometries, Ltd. Objet machines produce parts using a different technique known as PolyJet. This technique jets or sprays a photopolymer resin instead of using a vat of the resin and solidifies this resin with a UV bulb instead of a laser beam. However, the parts are similar to parts made by SL, but have much smoother surfaces. Since 1988, over 40 AF systems have entered the worldwide market, competing to serve product designers, tool manufacturers, manufacturing engineers, and ultimately, the end consumer.

An informed customer knows that an SL part's strength, accuracy, and surface finish depend on variables of layer thickness, materials, and post-processing. Other parameters influence the performance and functionality of the parts, including the physical and chemical properties of the resin; resolution of the optical scanning system; laser type, power, wavelength, and spot size; the recoating system; and the post-curing process.

When using service providers, it's important to remember the variables, as the production of your SL part can be more of an art than a science. You need to thoroughly understand the process and parameters before cutting a purchase order to the service provider. **Many times customers don't know what they don't know.** They end up getting exactly what they asked for, which is not at all what they really wanted. Once informed, you will realize the benefits of these relatively new technologies that dramatically lower your product development costs and reduce your time to market.

SL Process—Inside the "Replicator"

Design engineers jokingly refer to the SL process as *Star Trek*'s "Replicator"—a machine that converts energy into matter—producing spare parts quickly to avoid starship disasters. A very apt comparison, SL converts virtual models to reality in short order, saving your company considerable budget and time. This laser-based process produces plastic parts by curing photo-curable resin with a UV laser system. The SL process is classified as AF due to the process of producing a physical part with successive layers. The SLA system consists of a UV laser, a vat of photo-curable liquid resin, and a controlling system. Your CAD data provides cross-sectioned build information to the SLA system. Layering technology is performed by computer software that slices the CAD data into layers, called slices, and outputs the slice data to the SLA.

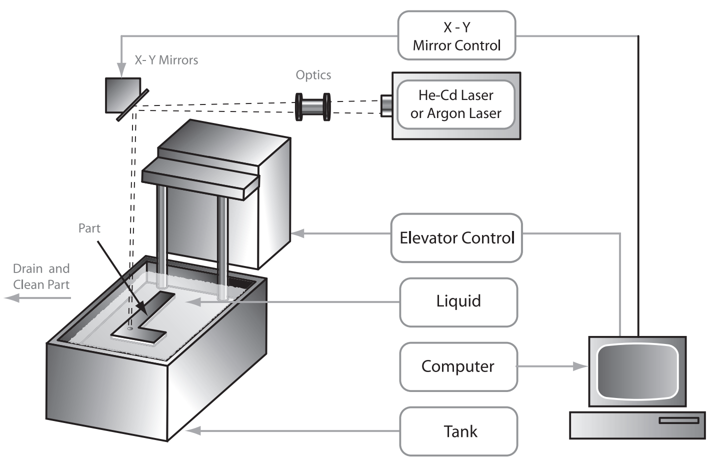
Step by Step with SL

First, an operator loads the STL file from your CAD data into proprietary software, which digitally slices the model into thin layers of approximately 0.005 inch (five thousandths), and produces a removable, stabilizing structure to support the part during the build. Next, the physical build process begins with a vat of photo-curable liquid resin and an elevator table in the vat, set just below the surface of the resin.

A computer-controlled optical scanning system directs the focused laser beam so that it solidifies the 2D cross section corresponding to the slice on the surface of the photo-curable liquid resin. The laser's depth of penetration is greater than the desired layer thickness, and is known as overcure. Overcure plays an important role in producing solid SL models and it also affects the build time of the part.

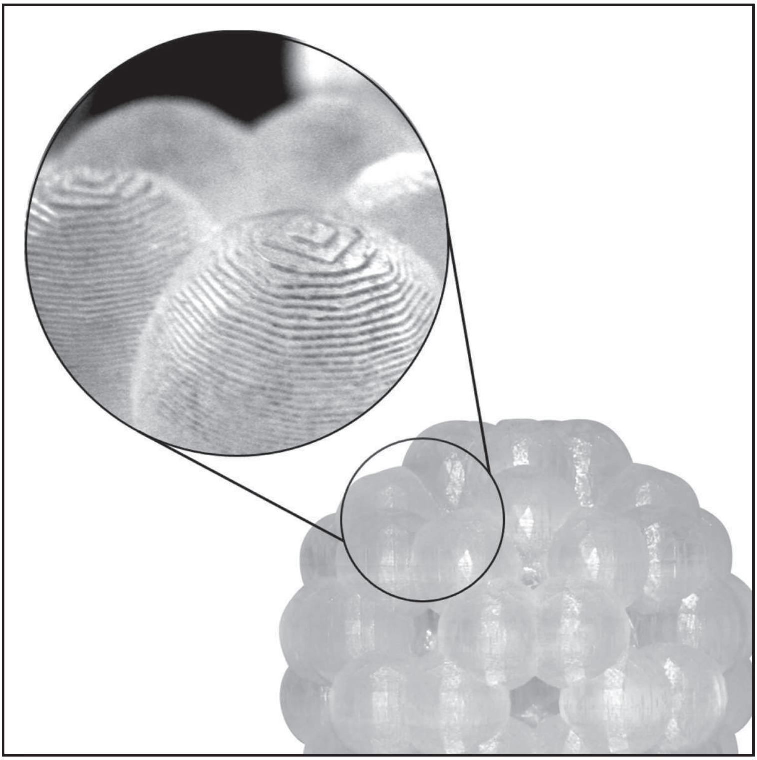
After a layer is complete, the elevator table lowers enough to cover the solid polymer with another layer of the liquid resin. A leveling wiper system moves across the surfaces to recoat the next layer of resin on the surface. The laser then traces the next layer. In simple terms, the energy of the laser "flips" the liquid material to a solid material upon contact. As chemistry buffs know, this is called a phase change in the resin. This process continues in successive layers, building the part from the ground up, until the system completes it. The elevator then rises from the vat, and the operator removes any excess, uncured liquid polymer from the part.

STEREOLITHOGRAPHY (SLA)



Finally, the part is placed in a UV oven for final curing. The part is then hand-finished to remove the support structure and to smooth the minute "stair-stepping effect" seen from building the part in multiple layers.

STAIR STEPPING



It is difficult to predict the cumulative impact of chemical properties and operating parameters on a build, subject to the ever-changing aspects of cross sections and geometries. Therefore, developing easy-to-use pricing algorithms has always been a challenge. The industry-accepted approach is to use geometric information in secondary formulae to predict cost and "guess-timate" the true build time of a part.

SL Applications—Stop and Smell the Plastic

Look around you. Almost everything you touch throughout your day was made using a specific prototyping process: cell phones, keyboards, pen caps, gearshift handles. Rapid prototyping has already reached every sector of your day-to-day life. As a result, a firefighter's mask fits better, your steering wheel grips tighter, and your office furniture looks smarter. The virtual-to-reality evolution makes room for organic shapes, compressed time cycles, and quick physical replicas. Home or office, work or play, most of the things you touch were designed and produced using the SL process.

Industry Overview—A Nerd's Eye View

The innovative solutions made possible by SL technology are energizing the conventional design and engineering culture worldwide. According to the *Wohler's Report 2006,* in the last year, millions of parts were made by service providers and end-user companies combined. That's amazing growth for a teenage technology.

With SL's ability to produce finished solid objects within hours, the feedback loop is much faster, and approval time is shortened to days. In every boardroom around the globe, engineering managers are evangelizing the wonders of RP, as it frequently cuts tooling costs by 50% and reduces overall development times by as much. So the question is: **Why wouldn't you use RP?** The answer: lack of knowledge or corporate superstition. Maybe you tried it once and your expectations were not aligned with reality. In the world of RP, it's easy to ask for the wrong thing without knowing it.

In a young industry, product development leaders are very excited to see the best minds in design and engineering take ownership of these powerful tools and come up with a new generation of evolutionary applications. Pick up any manufacturing trade journal to find hundreds of fascinating case studies about SL applications across a wide spectrum of users.

Resolution—The Nitty Gritty

Understanding part types as a function of resolution is very important as resolution affects tolerance, surface finish, and cost. As a customer, you have several choices of resolution when creating your SL part. Applications fall into three basic types of SL parts as defined by resolution: The standard layer thickness for SL parts is 0.005 to 0.006 inch (five to six thousandths), the thickness of a sheet of paper. High-resolution parts are grown at 0.002 to 0.004 inch (two to four thousandths), one-third as thick as a sheet of paper. Machines made by Objet Geometries produce the highest resolution layer thickness of 0.0006 inch (six ten-thousandths), not visible to the naked eye.

The resolution offered by three different process types dramatically impacts the accuracy and feature capability of your parts. Different geometries require a certain level of resolution. The thinner and more fragile part features are, the higher the resolution required. If your part has no highly detailed areas, standard resolution is sufficient.

If you are creating a part that is mostly simple with a few complex features, for example, a housing with buttons, you can build the complex features in high resolution and build the housing in standard resolution to realize a cost savings. While it would look great, building the entire assembly in high resolution would be considered overkill for the part type and would be very expensive. Typically speaking, the super-high resolution processes cost twice as much as the high-resolution process, and four times more than standard.

Benefits—The Buzz is Real

Over the past five years, trade journals such as *Rapid Prototyping Report, The Edge*, and *Wohlers Report* have created a huge industry buzz by citing hundreds of success stories using SL. Whether you are designing a new engine block for Mercedes-Benz or a shoulder replacement for a human being, SL technology is radically compressing developmental cycles, saving millions of dollars, and opening new doors to innovative solutions. SL makes for almost magic stories with happily-ever-after endings.

One dental company heavily employs SL technology to create invisible braces to treat hundreds of thousands of patients. A major automotive company realized a cost savings of 45% by using SL for rapid tooling of small parts. A jet engine blade project, typically taking nine months with standard tooling and machining, took only one month using SL solutions. Design time for an orthopedic implant was reduced by 15 months. Design cycle times and production cycle times for an electric power system were reduced by 40%. One tooling project that would have cost $1,700,000 using conventional methods cost only $40,000 with SL because it drastically reduced the errors in tooling. Competing architects designing options for the new World Trade Center used SL extensively for highly detailed, full-color miniature models of their visions. A number of motion picture companies use 3D modeling and SL on a daily basis. To emphasize a sign of the times, the motion picture *Small Soldiers* featured an animated SL machine in its opening sequence, to the delight of product developers around the world.

SL technology continues to revolutionize manufacturing in all key industries of automotive, aerospace, military, machinery, biomedical and dental, consumer products, shoe-making, architectural, and aesthetic and artistic products. Additional industries along with entertainment and filmmaking include: forensics, space exploration, microsystems, geographical information systems, and mapping. The application of SL technology holds unlimited potential and is a challenge to every designer's imagination. It's easy to understand why **RP makes heroes.**

A day in the life of our humble hero, Johnny Quickparts, further details more advantages and limitations of the SL process. Let's stop by the perennially stressed-out Acme Design Corporation and see how Johnny is going to save his boss, Bob Overrun.

A Very Tall Tale—Johnny Quickparts and the Olympic Torch Challenge

Deep in the basement of Acme Design Corporation, the product development team was playing solitaire and waiting for its next crisis. Fast asleep in his cubicle, the humble super-geek Johnny Quickparts, P.E., was having another work-related nightmare: to the drone of an antiquated air conditioner, Johnny watched as his engineering manager used medieval methods of hand-modeling to solve another emergency design problem. As the telephone rang, Johnny woke up, stretching and yawning, prepared for his next weird work experience. It was his boss Mr. Overrun in a panic.

The client needed a plastic model of an Olympic torch for a tradeshow by Monday or Acme Design would lose the account! If they drew it in 2D and whittled a prototype by hand, it would take three weeks to get approval. Mr. Overrun was willing, at last, to try Johnny's new "quantum thinking." Mr. Overrun pleaded, "If you can save this account, Johnny, I'll let you touch my Harley!"

Johnny rubbed the sleep from his eyes and began cogitating. He loved hanging up on his boss without saying a word. It made them both feel very manly. He opened a can of Pringles and thought of all the times he had seen the Olympic runner carry the early Grecian torch to start the games. Johnny swelled up with pride for finally connecting to the ancient past, the belly of Western Civilization where heroes were honored for their strength, flexibility, and speed, just like the little-known rapid prototyping processes he lauded. This was his one chance to perform an Olympic challenge, so he started a new 3D SolidWorks file, put on his headset, and cranked up the music, the theme from *Chariots of Fire*.

Atop the mist-covered Mount Olympus in his mind, Johnny drew an excellent 3D torch in about an hour. He wanted this torch to be way more than cones and cylinders. His torch would be curvy, freeform, and darn-near pretty. Johnny's torch would out-torch all others in wind-resistant and aerodynamic features! He had watched enough *Flintstones* episodes to make it organic-looking and ergonomically correct.

Toward completion, Johnny checked his file to make sure the data had no bad facets or holes. He hollowed it out to save on materials and build time. He made sure that there were no freaky undercuts or fragile features that might be difficult to build. Double-checking his work, he carefully eyed where the parting line for the eventual mold would be. Then he converted his CAD file to STL format.

Choking down a really bad cup of coffee, Johnny considered his options for making a physical torch, such as Computer Numerically Controlled (CNC) milling the part out of metal, foam, plastic, or wood, or using an additive process such as Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM), or Stereolithography (SL). He chose SL over the other processes because he needed a smooth finish with metallic paint, something glossy. He was not really shopping for durable plastic. For a show model, he was willing to trade functionality for excellent appearance. He imagined that the SL process would deliver the goods quickly but he wasn't completely sure.

Suddenly the frosty Queen of Procurement, Sally Savealot, dressed in a tiger-print dress, graced Johnny's doorway. She eyed him up and down with her famous "engineering disdain" look, designed to vaporize the majority of problems and people that came her way. "For today's crisis," she spoke coolly, "just use a credit card and quit wasting my time!" Then she vanished.

Johnny knew she didn't mean it and submitted several requests for quotes (RFQs) the old-fashioned way. He then flew onto the World Wide Web and Googled Stereolithography, just for kicks. Then a truly mysterious thing happened. He noticed a company that shared his own last name...Quickparts! A believer in synchronicity, Johnny wondered if he was somehow related to a company that used all of his favorite technologies. Duty called and he could not tarry, so he shrugged off this name coincidence for the time being. He logged in and quickly uploaded his torch file to Quickparts.com and got an instant quote.

Within 10 seconds his phone jingled in an unusually warm, sweet way. It was Helen Helpalot from Quickparts, following up on his quote. When Johnny heard her velvet voice spiked with real enthusiasm, his left brain simply melted. She was already on his side and she would never lie or leave him. She even told Johnny that, as her customer, HE was indeed the heart of the part. Life was suddenly a blaring carnival for Johnny. He reached for his heavy gold crown to make sure it was on straight. Maybe he had inadvertently downed champagne instead of orange juice for breakfast.

In a matter of minutes, Helen guided him through his technical specs to make sure that SL was indeed the right process for him. Johnny shuddered at the ecstatic experience of dealing with this unusually wonderful sales rep. He loved the clarity of her lightning speed response. Not only was Johnny in love, but he would also get his torch the

NEXT DAY! Bam! Done! Sold! This was big.

After the call, Johnny sank to his knees and took a long drag on a candy cigarette from his Halloween stash. He kept shaking his head, muttering, "Holy Cornflakes." This was a whole new universe of dynamic customer service with someone who really understood what he needed and actually cared about his part! By the time the other competing quotes finally came crawling in, Johnny was already on his way home to watch *Star Trek* reruns and think about Helen Helpalot. He almost dialed her up again but gave himself a noogie to snap out of it.

The next day at work, Johnny noticed the other quotes were bland and confusing. The prices were disparate and the lead times made no sense at all. None of the other service providers had even called him, and he wasn't going to call them. Clearly, Helen Helpalot was fueled up on the breakfast, lunch, and dinner of champions. He crunched the other quotes into a ball and slam-dunked them, just as the FedEx man brought in his SL package and grunted for Johnny's chicken-scratch. Johnny was so happy he threw his bony arms around the meaty, silent type in sunglasses who was apparently used to public displays of affection from total strangers.

Johnny now held a gleaming SL replica of a lifelike silver Olympic torch in his hands. He rolled it over and over in his palms, amazed at a vision made real. He could hear the roar of the coliseum crowd chanting,

"Go Johnny go! SLA all the way!!!"

The smooth, metallic-looking torch looked and felt absolutely real.

With the torch held high above his head, Johnny sprinted 100 meters to Bob Overrun's mega-cubical. Mr. Overrun was beside himself with glee. The torch was way better than what he had envisioned. Johnny had saved his boss again and was now wearing the proverbial gold medal. He began to teach Mr. Overrun the basic magic behind his latest success, if for no other reason than to spice up his cocktail party repertoire.

Johnny was glad he had taken good notes from his conversation with Helen Helpalot. His shaky handwriting was a memento of their very first conversation but it would also help him justify his purchase to Sally Savealot in Procurement. After meeting Helen, Johnny considered abandoning his 10-year effort to win over Acme's Goddess of Purchase Orders. After all, his valentine of pink tulips had only made her tougher.

Johnny learned a great deal about the SL process from his torch project; and yes, the customer was triple-wowed. In fact, they ordered four more plastic torches for a fraction of the cost—thanks to "family build" savings! That night, Johnny went home satisfied and celebrated with a new tuna melt recipe for one. He kept thinking of the motto of the Olympics, "*Citius, Altius, Fortius*," and how it relates to the world today.

Boring but Necessary—Understanding Stereolithography Limitations

Part Features

Knowing how to select an AF process for your part's feature limitations is very important. Every part is a series of features. Basic parts start off as simple prismatic shapes, such as cubes and cylinders. From these basic geometric shapes, a designer creates features. For example, a housing starts out as a box or cube and then is shelled out to reduce material. The CAD designer uses rounds, curves, and fillets to make the part more sculptural and organic.

Additional features are bosses, or attachment mechanisms, that interface with other parts. Features have thickness, fragility, and shape—characteristics that must be considered when using AF. So, if you are designing a diamond ring, you need a high-resolution process for thin, fragile prongs on the mounting piece. Those fine features steer you toward a high-resolution SL process that uses very thin layers of 0.002 inch (two thousandths) and steers you away from standard resolution manufacturing processes with a layer thickness of 0.005 inch (five thousandths). If you have robust features greater than 0.030 inch (thirty thousandths), a standard SL process is adequate. A wall thickness less than 0.030 inch is risky business because it won't fill up or form well in the SL process. A requirement for super-high resolution 0.0006 inch (six ten-thousandths), steers you toward the Objet process.

Unique part features are very important to consider when building a part. Typically, a part feature is integrated within the part and is not required to be analyzed independently for build or cost impact, but there are situations that require special consideration of the features. Some of these features include cylinders, such as tubes and cups, as well as rounded or sloped surfaces. How these features are handled will impact the cost of the part.

Tolerances and Accuracy—Real World

The accuracy of the part is an important factor in building useful models. When using AF processes, there are typically no drawings or tolerance studies provided to determine whether a part is within tolerance. Therefore, the base dimensions are actual dimensions in the CAD model, which is mathematically perfect. The limiting constraint becomes the ability of the technology being used, such as SL, to produce the part.

In manufacturing, there is no such thing as a perfect part. Skillful engineers know it is necessary to apply tolerance, the permissible limit of variation in a dimension, to the design. What many engineers typically don't know is that SL is not an exact manufacturing process. Even the high-precision coordinate measurement machine (CMM) has tolerances. Its "1-inch" diameter pin is really 1.00005 inch.

With any manufacturing process, there are tolerances inherent to the process itself. Standard SL tolerances are ± 0.005 inch (five thousandths) for the first inch, and ± 0.002 inch (two thousandths), inch for inch on most parts and features. Understanding this is critical, especially when mating the parts made with the same SL process.

Tolerances and accuracy for SL are dependent on the geometry and orientation of the part. Engineers expect perfection because they design parts in the mathematically perfect world of CAD. However, once virtual comes into physical reality, we find that materials and geometries interact and affect the outcome. The perfect-fitting tolerance you had designed will most likely “behave badly” at a minute level in physical form due to residual stresses driven by part geometry. This is why **a designer must design to the process and material being used.** Minute residual stresses, determined by geometry, are introduced into an SL part when liquid turns into solid form. These residual stresses will cause the part to bend in a certain way. Outcomes can vary greatly from part to part, and process to process.

Of special consideration are those tolerances of two or more interfacing parts, produced in the same manufacturing process such as SL. Good engineers always specify the largest possible tolerance while maintaining proper functionality. But a clear understanding of how materials and geometries affect SL tolerances is most likely one thing they didn’t teach in engineering school. Parts must be designed to distribute or relieve residual stresses. For example, a long bar will react differently than a housing part. While both designs look perfectly flat in CAD, they will both warp slightly, factoring together residual stresses, material properties, and build orientation.

A typical SL failure occurs due to the underestimation of tolerance stacking. Tolerance stacking occurs when mating more than one part because different parts have varying geometries that react differently rather than homogenously. While tolerances are somewhat less critical in the real world, applying special SL tolerances is highly critical, especially with mating SL parts where the interface may not mate at all due to distortion inherent in the process.

SL materials have a low tolerance for heat with typical heat deflection temperatures around 110 to 120°F. Tolerances may also be affected by splitting a part. Shrink factor is a component of accuracy and should be accounted for by your service provider operator.

Part Orientation—How to "Grok" XYZ

Informed customers get better pricing and better solutions. To play this game well, you have to understand what orientation really means. The time required to build a part depends on its orientation in the machine vat while being produced. Factors include the number of layers required to be processed as well as specific layer-dependent parameters that can affect the time required to complete a layer.

Depending on part geometry, there can be a major cost and time difference in parts built vertically versus horizontally. Vertical builds get better definition and require a longer build time, and therefore, cost more. If you don't need perfection on your first draft, you may choose to build horizontally, and save 50%. However, when you are ready for a best quality SL, build in a vertical orientation to get better definition on your part.

> **QuickTip:** "GROK" (rhymes with "walk") is a fun, friendly science fiction verb, coined by author Robert Heinlein. It means "to understand something so well that it is fully absorbed into oneself." Example: If you can grok this important material, you will become a hero in your company!

There is also a tradeoff between the surface finish requirements of a part and its build time. Typically, surface finish is the more critical factor because a part with poor surface finish may not be useful to the user, regardless of how long it took to build the part.

Size Matters—Are We Surprised?

In almost every category of life, size does indeed matter. Some of us have learned about machine size issues the hard way. 3D Systems machine names SLA-250 and SLA-500, actually denote their real build platform size. The SLA-250 platform is 250 x 250 millimeters, or approximately 10 x 10 inches. The SLA 500 platform measures 500 x 500 millimeters, which is approximately 20 x 20 inches. However, for the more recent models, SLA-5000 and SLA-7000, meaningful size denotations were dropped and a few zeros were added to make the machines sound “bigger and badder,” though they are essentially the same as their predecessors.

The point is to be careful about machine size. So, if you have to produce a 21-inch rod in SL and you are dealing with a fly-by-night SL provider, he may suggest that, due to platform size limitation, he would cut the rod in half, build two SL parts, and then rejoin them with adhesive, a more costly solution. While it is true that SL machines offer only two choices of platform size, 10 x 10 inches or 20 x 20 inches, there is a better way to handle this problem. Look at the build platform space in a new way. Instead, turn the 21-inch rod diagonally in the larger vat so that it fits on the hypotenuse of the platform space. **Avoid splitting parts whenever possible.**

In other words, part size should determine machine selection. If your part has a dimension greater than 20 inches, you have to figure out how the part can best be oriented to make a single piece. Make sure that your service provider has a large-frame machine. If they only have a small machine, your part will be split, which adds cost. If you don’t ask them about machine size, they probably will not tell you.

To produce parts as a single piece, the SLA 500 platform has the limitation of approximately 20 x 20 x 20 inches. But for larger parts, it is possible to split and join them after production with special adhesives and resin directly from the machine. For example, if you need to make a 40-inch tube in SL, cut your CAD model electronically and design the split with a special tongue-and-groove connection. An ordinary slacker would use only dowel pins as connectors, but a super-engineer takes the guesswork out of rejoining to make the tube halves fit perfectly together for durability and lasting quality. **Be proactive and determine the fate of your own parts.** Do not leave it up to a service provider who might just glue the halves together in a sloppy way.

QuickTip: Make sure your service provider uses a large- frame SLA machine for big parts.

A part is composed of many attributes, such as volume and the overall dimensions of the part. Obviously, these attributes have an impact on the part production cost, but there are extremes that have to be considered: very small parts and very large parts. Very small parts are, in essence, parts that require few resources to produce from the system. They require very small amounts of raw material, and their build times are very short in comparison to times for normal parts (measured in minutes). From a cost estimation evaluation, the cost of these parts will be insignificant and always default to some predetermined minimum part cost value, such as the direct cost of just starting the equipment.

The other extreme is very large parts, again very subjective. In SL, there are no constraints for the volume of the part. However, large volume parts could be outside the spectrum of the cost estimation algorithms. The value of the large volume would likely be in the range of 50 to 100 cubic inches, and all parts that exceed this limit would be subject to additional scrutiny in their cost estimation. Smart engineers know there is plenty of room to negotiate on big parts due to the huge variance in "guesstimates" on labor and materials. You can pay anywhere from $3,000 to $8,000 for the same part. Obviously, the primary factor affecting parts of this size is the actual build time to produce the parts, which can extend to days or even weeks. The best way to save money is to **negotiate with price matching from other lower quotes from equal quality providers.**

Materials Are a Nightmare

Johnny Quickparts' boss, Bob Overrun, had a negative impression of SL. Ten years ago he had ordered an SL part, dropped it on the floor, and watched in slow motion as it shattered into a hundred pieces. Needless to say, his customer was not happy with the invisible part or the new industrial revolution. Johnny did his best to convince his boss that these once brittle materials have come a long way in a decade.

The truth about materials is that there is no truth. Materials are a nightmare. To push ahead of the competition, plastics companies continually release "new and improved" plastics and resins, making shopping very confusing. Plastics marketing professionals have a tough time pitching new products as stronger, stiffer, brighter, bouncier, or somehow sexier plastic. Basically, it's all gooey gunk. Some of it is toxic, some of it isn't. The performance of materials is geometrically dependent on design; orientation can determine the success of your build.

The best way to get to learn about materials is to feel samples with your own hands, compare their properties, talk to the experts, and try out a new material on your next project. The materials used by SLA equipment are mostly epoxy-based resins that offer strong, durable, and accurate models. These characteristics make SL an excellent all-around choice for prototypes. Informed users know that Objet Geometries typically uses an acrylic-based material that can be brittle and not that user-friendly. Some acrylic-based materials are potentially carcinogenic and less stable. However tempting, please do not eat the parts!

In materials selection, try to identify the material that supports the function of the prototype itself, which in turn can support the function of the part in the real world. Sometimes you will have to compromise, but companies offer a litany of SL materials to cover capabilities from rigid to durable to flexible. When shopping for plastics, you need to know the basic material types.

Material Types—It's All Gunk

Rigid materials, similar to polystyrene or Acrylonitrile Butadiene Styrene (ABS)-like materials, are used for things like a computer mouse, cell phone, or electronic shroud. For harder parts that require no flexibility, rigid material is tough and can withstand rugged environments. In the industrial world, a handheld scanner that may be dropped or knocked around in an industrial environment needs a rigid material. Holding up to wear and tear, rigid resin ensures your part a long life.

Durable materials, closest to polypropylene, are used for parts that require a snap fit. Durable materials flex without breaking, but be cautious when building a part that requires flexing. Make sure that your part is oriented properly to support and strengthen the snap feature. A vertical build will add strength to a flexing snap feature, but the horizontal build is innately weaker due to horizontal layering. **Mistakes are commonly made due to lack of knowledge about part orientation.**

Semi-flexible material, like polyethylene, is lightweight and easily deforms. It is used for some bottles and lids. Flexible material, such as elastomeric, is rubbery and used for connecting pieces like gaskets, washers, and boots, which often require a watertight seal. Elastomeric is highly flexible and forms strong seals and interfaces. Water sealant can be added to make parts, such as flexible nozzles on liquid dispensers, water-resistant. Special materials are available for high-temperature SL usage.

Save yourself months of research by understanding that there are only a few basic materials that really exist. However, plastics and their distant relatives are marketed with more flavors and hype than Baskin-Robbins, Ben & Jerry's, and Häagen-Dazs combined.

Water-Resistant—Glub, Glub

SL material will absorb liquid and cause it to deform. If you need a water-resistant SL, use water sealant as a secondary process. The best SL choice for water testing is the rigid material. Please note that the SL becomes water-resistant but not waterproof. Therefore, only limited use in water—an hour or two—is recommended.

Temperature—Some Like it Hot, But Not Stereolithography

Standard SL materials are temperature sensitive and will not withstand more than 120 to 130°F before they start to breakdown, deform, and warp. In other words, don't leave SL parts in your car in the middle of summer. In only a few hours, those parts will twist and warp, as Johnny found out on a searing August afternoon. A quick errand turned into an extended sales pitch for Acme. His prize possession, a 1970 cherry red Camaro, got so hot that it torched his Velveeta sandwich and his SL part in about two hours. Thanks to extraordinary precognition, Johnny had ordered an extra SL part that cost only pennies thanks to economies of scale. No mistake was ever wasted on Johnny. He ate his drippy cheese sandwich and twisted the gooey SL gob into a perfect likeness of his dog, Attaboy. A resilient learner, Johnny would soon discover high-temperature materials used in SLS, allow parts to withstand temperatures up to 200°F.

How Will My Part Look?

A critical part feature is the surface, meaning the part surface as it comes off the SL machine. You want it to look and function at its very best, so additional finishing, a physical alteration, is almost always required. Trained craftsmen do all post-processing hand-finishing of SL parts. Informed engineers know that finishing and post-processing involves taking the part off the SL machine, removing the support structures, and sanding down the part—all of which affect lead times. Both detailed parts and bigger parts take longer to sand, but typically finishing takes as long as building the part.

Prior to manufacturing, part orientation needs to be planned to eliminate the undesirable stair-stepping effect, evidence of the layering process. Therefore, it is important to orient the part to minimize the stair-stepping effect that all current AF systems produce. Stair-stepping is most often apparent on sloping or curved surfaces, but can also occur on flat surfaces, depending on part orientation. In certain cases, stair-stepping may be impossible to eliminate.

After manufacturing an SL part, sandpaper finishing is typically used to smooth a part's surface. Skilled craftsmen fill tiny holes and sand down cured SL material to get a smooth polish.

The importance of surface finish depends on the specific use of your part. Because craftsmen have different skills, the human factor is introduced here. An inexperienced operator might remove or "subtract" too much, whereas a skilled craftsman will be more precise. **A craftsman's skill level can affect your part's tolerance and accuracy.**

Because there is a lot of science to a part, there are several causes of build failure. Bad CAD files and wrong orientation can crash a build. Machine parameters, such as truncated wait times between layers, can ruin the build. A power outage or a dead power supply also cause build failures. Johnny has personally observed that earthquakes, fires, floods, and temper tantrums never helped a build!

The cost of failure is absorbed by your service provider, but the loss of time hurts everyone. When a problem occurs, the whole part must be scrapped and rebuilt. That's why a service provider makes a resounding groan if a build that takes 10 hours fails in the last hour; the lost build time is non-recoverable all the way around.

• Finishes

Most parts require a standard finish. Some finishes are more functional than aesthetic. The finishes listed here are used when you need an SL model to evaluate your part for some reason. As a customer, you have a choice of finishes.

Primed SL parts have several coats of automotive-grade primer applied. This coating makes the parts paint-ready or mold-ready. Primer is needed when you want to make sure your part is tradeshow quality. After being primed, you can paint the part yourself.

Painted SL parts have several layers of paint applied to color the parts to your specifications. This is needed for fully functionally show models that have been filled, primed, and painted to look like actual parts. Painted parts are used for aesthetic or illustrative purposes.

Painting your parts increases the service provider's price only because it takes a long time to paint them, not because of any special paint used on them. Paint is one of the best and easiest ways to color SL parts.

Make sure to ask your service provider if finishing supplies are automotive grade to provide the best finish possible. If you want to paint your own parts, be sure to use a sandable filler primer. Once the part is primed and sanded smooth, any type of paint will work fine. Parts must first be primed, prior to painting, so that the painted finish will look nice and last longer.

If you plan to submerge your SL parts in dyes to add color, keep in mind that SL parts do absorb liquid and can swell or warp under the conditions present in dyeing. Therefore, this method of coloring is not recommended.

The standard finish on SL parts is almost paint-ready. You could paint directly onto the standard surface; however, there are marks that will show through the paint unless you prepare the part by applying several coats of sandable filler primer.

Paint can be removed from an SL part. A quick bath in acetone or paint remover will begin the process; however, be sure to quickly wash the parts in water afterward to remove residual chemicals. Remember, SL parts absorb water. To completely remove all material, sand it away. Harsh chemicals will eat away at the SL material.

"Strip-and-ship" is not a psychological method for blasting obnoxious people out of your cubicle. Strip-and-ship refers to SL parts that look ugly because they have no finishing, other than the removal of support structures. Informed customers who are price sensitive can typically negotiate a 20% discount for this finishing level. If you are a cheapskate, like Johnny's boss Bob Overrun, the kind who doesn't want to pay for anything, please remember that you are asking for an unfinished part taken right off the machine. Strip-and-ship is not recommended because customers typically under-value all the labor that goes into making a standard finish. **With strip-and-ship, beware: what you don't see is what you get.**

The last choice of finish is WaterClear, a high polishing process. WaterClear gives white opaque plastic a mirror-smooth, clear-looking finish, needed for glass-like parts such as LEDs, bottles, lenses, and covers. WaterClear material cannot be tinted but it can be made optically clear, although it may have a slight yellowish hue.

How Long Does it Take to Get My Part?

Johnny hated it when Mr. Overrun yawned repeatedly during zealous reports of technical discoveries. Overrun would always interrupt and slur a question through the dark cavern of his yawning mouth, "Okay, Johnny, so how long does it take to get my parts?" We all want to know this: how quick is quick? Is rapid really rapid?

Typical lead times for SL parts are as follows. Most standard SL part orders are delivered in 3 to 10 days, depending on the size of your order and your service provider. WaterClear finishing and painted parts take a bit longer, approximately 7 to 14 days.

> **QuickTip:** In every case, companies save significant money by using their own shipping account information. Service providers buy bulk rates for shipping but charge you the commercial rate.

High-resolution parts also take a bit longer, approximately 5 to 14 days. Some service providers do offer next day shipping if you need parts fast.

If you are not in a rush, you may negotiate a 25% cost savings off the standard shipping cost if you order economy shipping service.

Along with cutting lead times and reducing your time to market, plan well in advance and extend lead times to match your real needs. Allowing your service provider longer lead times can save you money.

Saving Money—Saving Time—Saving Thousands with SL

"Computers aren't emotional. That's why instant quoting is good. They won't raise your price because of a bad mood."

After reading this book, you won't be a technical expert, but you will be an expert in saving time and money. No other book tells you how to be a hero using these processes. Here are some insider secrets to saving time and money using SL.

How Do I Save Money Using SL?

Fortunately, SL has some very powerful characteristics to help drive efficiencies which can save money.

- **Family Build Concept**

A powerful cost-saving secret of using SL is realized using economies of scale. Economies of scale refer to the decreased per-unit cost as output increases. In other words, the initial investment of capital is spread over an increasing number of units of output, and therefore, the marginal cost of producing a part decreases as production increases.

Engineering managers can save thousands of dollars using family builds. Be prepared to use this powerful knowledge when negotiating with service providers that may offer only traditional pricing. Teach your provider about economies of scale in the following way.

• How Family Build Works

A service provider's operational overhead is built into every minute of the manufacturing process. Machines do things step by step. In between those steps, there is wait time. For example, in SLA production, the vat of resin takes 30 to 60 seconds to settle after the elevator platform moves to create the next layer of your physical model. This wait time is a valuable resource that is either captured or becomes operational waste.

If you produce a single part in that vat, the wait time or operational waste is the same as if you run a family build of 10 different parts in the vat. But in the case of the family build scenario, that wait time is divided by the number of parts in the vat. Therefore, operational waste is much lower per part than when running a single part. Traditional pricing models would show that if a single part costs $200 then 10 parts x $200 each would cost $2,000.

With economies of scale, pricing is much less per unit. Imagine your single part costs $200 to produce. If you build the family of 10 different parts, the cost is $425 total! Using family build, your piece part price decreases from $200 to $42.50 because operational overhead is now distributed among all the parts.

> **QuickTip:** Buy a few more, save a lot more. Learn the magic of family build!

A service provider using economy of scale pricing is very advantageous to those who need lots of different parts. Track your quotes from service providers to see if the single part is much higher than pricing for groups of parts. This knowledge will also help you understand the often puzzling disparity between quotes from different providers. Look closely: A cheaper price per unit may be resulting from economies of scale, but our traditional thinking would equate a lower price with lower quality. However, this is not the case when using family build. A lower price will most likely get you quality equal to or better than other competing quotes.

- **Build Multiple Parts of Assembly Together**

A good way to capture family build savings is to identify multiple projects needing assemblies of multiple parts, such as cell phones, keyboards, or a housing with buttons. If all of the parts fit on the SLA platform, you can save up to 50% of your traditional pricing estimate.

- **Order Multiple Quantities**

Economy of scale savings also apply to ordering more than one of the same part. Imagine that you need a pen cap made in SL, costing $200. But others in the company, like marketing and the president, also need one. If you order more than one, each additional part will be dramatically lower than the first. Traditional pricing would say that three pen caps x $200 each is $600 total. A better family build price shows the first pen cap at $200, but three parts together are quoted as $250 total, or a piece part price of $75 each.

- **Use Single Material**

Try to use a single material when building SL parts to save money. Family build practices can extract all overhead from one material. If additional materials are used, overhead will be added to those as well. So, the overhead is the same for either one or more than one part when using the same material during the same build.

- **Orient-to-Fit**

Know the difference between building parts vertically versus horizontally. Vertical builds take longer, have more definition (based on geometry), and cost more. Be creative in fitting your part to the build platform for best result and cost. **Knowledge of part orientation will help you get the best deal.**

- **Instant Quoting**

Find sources that use instant quoting to literally save your company hundreds of man-hours of labor. Always use instant quoting for pricing because it has no greed factor and no human element. Instant quoting actually saves you money before you buy by helping you manage your quotes. An engineer's time costs a company about $100 per hour, so if you spend six hours getting a quote, you are losing money. If you decide to wait it out and get old-fashioned manual quotes, be sure to study them for mysterious markups.

- **Other Ways to Save**

Responding to the new age of quantum manufacturing, many companies hire an RP coordinator to assess departmental needs and place consolidated orders, saving their company thousands of dollars. They maximize savings with service providers by combining multiple projects when ordering SL parts, buying fixed hours on machine time in bulk, getting preference for volume discount by buying everything from one service provider.

How Do I Waste Money in the SL Environment?

It's easy to inadvertently waste money in the SL process if you are a newbie. Here are ways to avoid wasting money.

- **Wrong Orientation**

By now you know that wrong part orientation can foil your best intentions. Remember that vertical builds get you more definition and take longer, but horizontal builds cost quite a bit less and are good enough quality for a first draft. Keep in mind that building in the wrong orientation will result in an unusable part.

• Build the Whole Thing

Regardless of the part size, the natural tendency of engineers is to build the whole assembly when all they really need is the functional part. Only build the pieces you really need. Be conscientious of what feature set you are trying to identify with the part. For example, with a computer monitor frame, you may only need to test the button area. The solution is to electronically slice your CAD model to produce an SL of the featured button panel.

• Ordering "Onesies"

Single part ordering is not efficient. Operational waste racks up the cost very quickly, so plan ahead for multiple part orders.

• Use Multiple Materials

Switching materials during your process is very costly, due to operational waste incurred. Keep it simple and use one material at a time.

How Do I Save Time Using SL?

There are many easy things the engineer can do to save time, such as understand tolerances and materials.

• Tolerances

In the CAD world all things are perfect; in the SL world, a part can be off 0.005 inch (five thousandths) for every inch of the part. Tolerances affect interfacing parts. In your CAD design your two parts fit perfectly together, but once manufactured they won't fit perfectly. The engineer blames the SLA machine, but it was their responsibility to adjust for SL tolerances. Knowing this can save you puzzling mistakes and timely rework.

• Know Your Materials

For the SL process, investigate material choices thoroughly before you commit to one and request samples and data sheets well in advance of your need.

• Double-Check CAD

Make sure that your CAD file has smooth surfaces before uploading it for your service provider. Faceted files can crash your build and waste time and money. Also, as commonsensical as it may sound, always make sure you send the correct revision of your CAD file. Many times when engineers are burning the midnight oil, they send the previous revision to the service provider, and get a nasty surprise when the part arrives.

• Misnomers

Many people call all AF processes SL or SLA, even though they are referring to other processes such as FDM or SLS. Because SL has become an industry slang term for any AF technology, be sure you know the difference and call a process by its correct name.

• Use Instant Quoting

This incredible software tool actually saves you money before you buy. As mentioned earlier, the quoting process can eat up serious engineering man-hours. Imagine saving four to eight hours every time you need to quote on something. That's saving hundreds of hours and thousands of dollars per year in the quoting process alone!

How Do I Waste Time in the SL Environment?

The biggest time eaters in getting your SL made are caused by a lack of knowledge, which almost always results in costly rework. The safest approach is to increase your knowledge and avoid rushing through the steps for uploading files. To review, the most common time wasters are selecting the wrong material for the process, sending bad CAD data or STL files, building the wrong part version, based on a previous revision of a CAD file, using old-fashioned manual quoting, and selecting the wrong process for part.

The Keys to a Brand New Ferrari

By now you are revved up about SL technology and the dramatic time and cost savings it offers. You've heard numerous case studies of 50% savings or more with SL. You've made friends with our humble hero, Johnny Quickparts, the geek without guile who makes a dazzling technical contribution to his ho-hum corporation. You've seen Johnny beat a trade show deadline and use SL to verify his concept early in the design game, thereby eliminating expensive design changes late in the manufacturing process. You know that orientation, resolution, and tolerance are essential to building your SL parts successfully. You also know insider secrets on industry pricing. Finally, you've been forewarned about all those time eaters and shoulda-coulda-wouldas.

As Johnny would say,

"Let's drive this thing!"

About the Author

Ronald L. Hollis, Ph.D., P.E. is the President, CEO, and Co-founder of Quickparts.com, Inc. He provides experience, leadership, and knowledge in the development of a leading business in the product development market. With his vision and drive, he has been able to lead an innovative, entrepreneurial, and fast-growing company that helps product developers succeed.

Ron and his company have received many awards and recognitions including: 2005 and 2006 Deloitte Fast 500; Finalist Small Business Person of the Year from Atlanta Metro Chamber of Commerce and Atlanta Business Chronicle; 2004 Ernst and Young Finalist Entrepreneur of the Year; 2004 Innovator of the Year by Catalyst Magazine; Top 50 Entrepreneurs of Atlanta; Hot 100 List from Entrepreneur Magazine; 2004 INC 500 company.

Ron is a graduate of MIT/INC Birthing of Giants, the former President of the Atlanta Chapter of Young Entrepreneur's Organization (YEO), a member of Young President's Organization (YPO), a corporate sponsor of Hands-On Atlanta charity organization, and serves on the boards of other entrepreneurial companies.

He earned a BS in Mechanical Engineering from the University of Alabama, worked as a design engineer on Space Station Freedom for Boeing, earned an MS in Engineering and a Ph.D. in the management of technical business, and is a registered Professional Engineer. He is also a private pilot and enjoys boating.

Ron currently lives in Atlanta with his wife, Melanie, of more than 15 years and their son, Jackson.