SOP's

Standard operating procedures and guidelines for Wiki - In development

TL;DR

For more info: https://www.bookstackapp.com/docs/user/content-overview/

And: https://demo.bookstackapp.com/books/bookstack-demo-site/chapter/content-examples

Embedded images are public and accessible by anyone (e.g. by direct link)
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Revisions are fully visible by anyone with access to page (e.g. public users)
If a revision was made to occlude information, please remember to clear the revision history.

Eventually

Pages published are visible immediately - Hold the page in **Draft** form until you are ready to display it.

There is no similar option for Books or Chapters. Eventually

Website timestamps are in PST

WIP - Wiki content plans

Physical motion system
  - Belts
  - Pulleys
  - Bearings
  - Grease
  - Solid Lubricants
  - Linear Rails vs Ball Screws vs Lead Screws
  - > And comparisons, and like tradeoffs between 2 carriages/etc.
  - Other motion systems (V-Wheels, dovetails, etc?)
  - Bellows
  - Shafts and clearances
  - CrossXY/etc. motion systems

Beds
  - Mag-beds, bed sheets, etc.
  - Flatness metrics and how 'flat' do they have to be, really
  - Kinematics
  - Alignment of Bed(Powered tilt, manual, spring loaded, etc.)

Wiring
  - Zip-ties
  - cable sheaths
  - Crimps & Crimping/QC
  - Wire Sheathing, uv-resistance, flex, water permeability, etc.
  - Gage selection
  - Strand count standards, flexibility, repeated-flex ratings

Electrical systems
  - Motors
  - Encoders, closed/open loop systems
  - 3DP Boards
  - LED Lights
  - ADXL's/Crampon
  - Probes, Beacon/inductive/etc.
  - Strain Gauges
  - ESD, Grounding, Shielding, and Noise
  - > Wire twisted stranding, analog/digital sensors, and a bunch more......
  - Screens, touch screens, WiFI/etc.

Filament
  - Manufacture and QC
  - Drying, Storing, and Annealing filament

> Loadcells to detect filament remaining
> Optical to check filament measurements
> Re-spooling & Spools
Waterproofing 3D Prints (Dichtol/dwh etc.)
Filament database w required printing temperatures
Specialized filaments (ceramic, CNT, etc.)
Common ones used for X purpose etc.

Resins/Glues/Pastes/Silicones/TIM(thermal interface materials)
    Thermal Conductivity (inasmuch practical limitations) of these pastes/etc.
    Storage, Degassing, Potting, and Curing considerations
    Shore hardness and Electronics
    Another DB w associated common uses/etc.
    Discussions on Filament/Epoxy/resin Tg/CTE/Crystallinity/etc.
    Usefulness of technical data and testing
    This one has a lot of overlap w resin/filaments idk......

Air, Water, and Vacuum systems
    Piping/flaring/etc.
    O-Rings/seal election/vacuum grease/etc. Loctite choice.
    Approx. vacuum requirements
    Recommended oil-free pump types
    Pressure and Vac sensors
    Gas and Water permeability of plastics/plastic tubing/etc.
    Fans and Part cooling
    Liquid Cooling
    Air/Oil/VOC Filtration
    > and Resin PPE

Thermometry: Thermistors, RTD's, TC's.
    Their measurement, accuracy, etc.
    PID/MPC and other algorithms

Insulation and Construction
    Tapes (Mica/PTFE/Fiberglass/etc.)
    IR insulative
    Heat insulative
    VIP's
    Selection of foams, boards, blankets, and flashing
    VOC's, aging, oxidation, etc.

Heat:
    Safety circuitry and fire-suppression/prevention systems
    IR Lamp, silicone, PCB, cartridge heaters. quartz lamps. MCH. PTC. etc.
    Kanthal/Nichrome alloys/wiring/selection, winding tools/tips
    Wattage and density
    > IDK where to mention, if at all: Hermetic seals, dielectric breakdown/shunt-currents, etc.

Firmware: Klipper/RRF
  - How they handle motor feedback (closed/open, command buffering, etc.)
  - Pressure Advance
  - Acceleration/Deceleration options (Square velocity etc.)
  - PID/MPC

Slicers and You:
  - Detailing of useful features e.g. z-seam controls or what not.
  - Slicer Idiosyncrosies
  - Adjustments for improved part prints

Extrusion
  - Nozzles: Types/Quality/Effect of nozzle orifice
  - Hotend general design and limiting factors
  - Extruder choices, backpressure, gearing, gimbal, direct, remote drive, etc.

Print 101:
  - Prioritized tuning guide (Reduce # of dials to adjust!)
  - Macros to improve integration between Slicer/Firmware/Printer, general UX
  - Mainsail/etc.
  - Printer specific starter configs
  - Combined wiring diagrams for specific boards/printers/etc.
  - Cross-linking to pages e.g. 'What filament you want, to what temp you need, to printer etc.'
  - Common Failures/Failure gallery lol
  - Safety 101

Alloys
  - Alloy selection for bed material (Deformation under heat, porosity, stress cracks, etc.)
  - Alloy selection for Hotend, heat break, and so on.
  - Commonly used alloys and their recommended uses (e.g. 3003 alu flashing)

Vendors & Sourcing
  - Rails/Motors/yadayada
  - More specific details and such, rail profiles, pulley/belt mesh quality
  - General vendor QC and elaboration on e.g. Gates unitta/etc.

  NOTE: Most sourcing pages to be written up in e.g. 'Belt's chapter
  Then cross-linked into this book for easier access.

Assembly
  - Preferred bolts (stainless vs carbon 10.9, hex vs torx etc.)
  - Drilling, Reaming, and Tapping
  - Bending sheet metal, rivets, etc.
  - Basic metrology and tools/methods to align 3DP
  - Torque (NASA guides/what not)
  - Specs to torque Rails/etc.

Cross-Ref> belt tensioning, regreasing bearings, etc. etc.
Selection and choice of Loctite components for 3DP uses
> Thermal aging, curing, etc.

Design

Joint Stiffness
Maintainability
Concept to part
CNC/SLM/3DP etc.
Titanium vs Steel vs Aluminum stiffness/weight for part choice
Deformation, Temperature, Air flow modeling
Watersheds for materials/3D printer components, wiring, etc.
This one is tricky since we want to have ONE source of truth for temp ratings
No duplication of hard data like that, makes impossible to reference and clean up later.

OVERLAPS:

- Bellows, wiring, insulative materials. Fiberglass tape etc.
- Permeability of plastics, VOC's.
- Drying/Vacuum/Annealing, Psychrometry/humidity measurement, etc.
- Properties of materials, especially Alloys, have a lot of overlap.
  Resins/Filaments/etc.
- Design for obv reasons overlaps a lot with the others e.g. Slicers, etc.
- Loctite overlaps bcz applicable to many areas
  Same for glues/pastes (for silicone heater, or sensors, potting, etc.)
- Fans for chamber control, part cooling, etc. also technically slicer related.....
- etc. etc.

Hotends

Hotends

The purpose of the hotend of a 3D printer is to melt the plastic that is fed into it, and deposit it in a controlled manner.

A hotend consists of a "cold side" which keeps filament as straight and cold as possible until it is fed into the "hot side", where the filament gets heated past its melting point via conduction from the heater block around it. Below the heater block is the nozzle, which reduces the diameter to its final width immediately before extrusion.

Key aspects of hotends to consider are:

- Cooling of the cold side
- Minimizing conduction of heat from the hot to the cold side
- Control of the heater block temperature against the cooling effect of cold filament going in and part cooling airflow
- Prevention of leaks on the hot side
- Wear resistance
- Rigidity
- Length of meltzone
- What nozzles are available

Structure

Cold Side

The cold side of the hotend is very simple: filament is guided through a narrow tube just larger than the diameter of the filament, and this tube is surrounded by (or itself made from) conductive metal (aluminum or copper) to draw heat away.

These can dissipate heat in three ways: a finned heatsink, a water cooling block, or conduction into a larger metal structure that acts as a heatsink.

At the top of the cold side is often the mounting structure for attaching the hotend to the toolhead, unless the hotend is more deeply integrated into the design of the toolhead.

At the bottom of the cold side, the filament gets delivered to the filament heatbreak, and any additional structural support for the hot side is attached.

Filament Heatbreak

The filament heatbreak moves filament from the cold side to the hot side, with the goal of minimizing heat transfer and preventing leaks.

On many older hotend designs, the filament heatbreak also is the sole support for the hot side, creating a conflict between maximizing structural strength and minimizing heat transfer.

Very old hotends have the heatbreak lined by a PTFE tube that goes all the way down to the heater block itself, which reduces friction and drastically reduces heat creep, but is a wear item and reduces the maximum temperature of the hotend.

The connection from the heatbreak to the hot side is an important consideration for reliability and performance.

- Thread-in heatbreaks: these occupy the top few millimeters of the heater block. If the heatbreak is monolithic then this somewhat reduces the effective length of the melt zone. If the heatbreak is bimetallic (a thin low-conductivity tube press-fit into a threaded copper slug) then melting performance is improved but this can potentially be a source of leaks.
- Brazed-in heatbreaks: these minimize the thickness of the low-conductivity metal along the filament path of the meltzone, but reduce repairability in the case of failures.
- Press-fit heatbreaks: often used in integrated heatbreak nozzles, these are similar to brazed-in heatbreaks but are a leak risk.
- Press-on heatbreaks: these do not intrude into the hot side at all and are pressed downward from the cold side onto the top of the hot side. These maximize the meltzone with minimal compromise, but if the pressure is insufficient then they could leak.

If the heatbreak is too conductive, the cold side will warm up too much, causing heat creep. Also if the heatbreak is too short, even if low conductivity, the cold side will also warm up too much, causing heat creep. Conversely, if the heatbreak is too long, the temperature transition between the hot and cold sides will be too gradual, resulting in mild amounts of heat creep that will increase required extruder force for a given flowrate even if it doesn't fully jam.

Structural Heatbreak

Older or more basic hotends use only the filament heatbreak to support the heater block, but this reduces the strength and stiffness of the hotend, increasing deflection of the nozzle tip under high acceleration and making the hotend susceptible to damage when tightening nozzles or if the nozzle rubs on the bed or print.

To mitigate this issue, some hotends are designed with additional structural reinforcement.

There are several methods for this.

- Stainless steel tubes in compression with screws in tension (Mosquito)
- Standoff screws made of titanium (Rapido 2)
- Tensile filament heatbreak with tubes or zirconia columns in compression (Dragon ACE)

- Truss (v9, Tricorn)
- Titanium tube with cutouts (Chube)

Heat Block

The heat block has four main considerations: length, material, heater type, and temperature sensor.

The longer the meltzone, the better the hotend will be at bringing filament to temperature before it reaches the nozzle tip. In addition to enabling higher peak flowrates, longer meltzones enable you to have more consistent temperature when flowrates vary (reducing variation in sheen on surfaces) and also let you run lower temperatures for a given flowrate, which can be good for high temp engineering plastics. Longer meltzones will require more PA and will ooze more if the filament isn't perfectly dry.

The material affects usability more than melting performance. Aluminum heater blocks should not be used above 270 degrees C because strength falls off dramatically. Copper has high thermal conductivity and matches the coefficient of thermal expansion (CTE) of brass and copper. However, it is expensive and more difficult to machine. Steel heater blocks have great hardness and high temperature capabilities but they match the CTE of brass nozzles poorly, matching better with tungsten carbide. It has lower thermal conductivity, which can make temperature regulation more difficult.

Heaters are either sufficient or insufficient. Cylindrical cartridge heaters are versatile and easy to replace with cheap or high-end versions. They're somewhat bulky but perform well because their power doesn't change much with temperature, making temperature control simpler. PTC ceramic heaters are small and light, but their power drops off as temperature increases, which makes it more difficult to control temperature. They come in two forms: cylindrical ones that provide 360 degree heating of the filament but are more prone to breaking, and planar ones which don't heat as evenly but are more robust and replaceable. Nichrome or Kanthal wire is occasionally used. This is high performance with constant power, and it can fully surround the filament path, but it makes replacement difficult.

Draft Shield/Sock

Heater blocks are usually covered with insulation in order to improve temperature uniformity across the heater block, reduce the power required to maintain temperature, and reduce the cooling effect of part cooling air.

On almost all hotends for sub 300 degree C temperatures, this is a "sock" made of silicone that tightly fits around the heater block and usually attempts to cover at least some of the nozzle. The lifespan of silicone is basically unlimited at lower temperatures, but it gradually degrades at temperatures approaching 300 degrees C.

For higher temperatures, the hotend can be wrapped in fiberglass or mineral wool, which is then secured with Kapton or aluminum tape, or silicone tubing. Alternatively, low-thermal-conductivity metals like stainless steel or titanium can be used to deflect cooling air without conducting much heat away while resisting unlimited temperatures.

Nozzle

Different hotends use different nozzles. E3D V6 is the most common standard, but there are many variations. Some nozzles come with integrated heatbreaks and even integrated heatsinks, which eliminates the need for hot tightening but can still leak from manufacturing defects. Some nozzles are also integrated into the heater block, which can improve thermal control of the nozzle itself but limits selection.

Issues

Heat Creep

Heat creep occurs when filament is allowed to reach its softening temperature on the cold side of the hotend.

When this occurs, as the filament gets pressed from behind by the extruder, the softened filament bulges and jams against the walls of the filament path. No matter how hard it is pushed, flow will completely stop.

Inexperienced 3D printer users may think it's a clogged nozzle but there is actually no obstruction in the nozzle opening.

Heat creep can be caused by insufficient cooling (or actual heating) of the cold side, from a filament heatbreak that is too conductive, too short, or counterintuitively too long..

Leaks

The pressures inside a hotend are absolutely monstrous. If the interfaces sealing the molten plastic in are not joined closely enough, filament can and will leak out and form large blobs of plastic that can destroy the hotend and even the entire toolhead.

When the nozzle and heater block materials are significantly different in thermal conductivity, it's important to tighten at or above operating temperature so that they don't loosen up.

Softer materials are easier to deform and create tight seals with, but they more easily fail completely. Use an appropriate torque wrench or torque screwdriver to tighten nozzles, as there can be a fine line between leaking and damaging, especially with CHT nozzles.

Structural Failure

On hotends where the filament heatbreak is the only structure supporting the heater block, it can easily be damaged. The only sure way to avoid this is to avoid hotends without sufficient support.

Nozzles

Nozzles

Nozzles are where the rubber meets the road, so to speak.

To some extent almost any nozzle *can* print, but better quality nozzles will produce better surface finish, achieve higher flowrates, or last longer before wearing out.

External Geometry

Orifice Size

The key parameter of any nozzle is the orifice size.

This sets a tradeoff between detail and print speed. Larger nozzles have higher filament flowrates, while smaller nozzles can produce narrower lines, enabling the reproduction of finer surface features.

Most product lines of nozzles are available in a range of sizes, so you can pick what you need.

But you will seldom find hardened material nozzles in small orifice sizes because the filled filaments that need the wear resistance would likely clog the orifice. Likewise, you'll never find high-flow geometry nozzles in small sizes because filament melt rate is extremely far from being a bottleneck in small sizes.

If you want to use a very small nozzle, you need to make sure that your hotend is particularly good at avoiding heat creep.

Tip Geometry

Around the orifice before the conical surface begins, there is a small flat that helps maintain surface quality.

If you buy premium nozzles, this will always be nicely machined, but cheap nozzles with uneven flats may tear up the surface and cause poor print quality.

Some nozzles will round the corner between the flat and conical surface to improve surface finish even further.

Tip Shape

Most nozzles have a fairly blunt conical tip to maximize heat transfer in the presence of part cooling air, but some specialty nozzles are extra pointy with no significant flat for the purposes of nonplanar printing and use at angles for belt printers.

Material

Eventually, as a nozzle gets oodles of filament squeezed through it, and its tip is dragged long distances over the layers of prints in progress, the geometry changes.

This causes both the orifice size to increase and the tip flat to be worn back, significantly affecting print quality.

Different materials resist wear differently, but they present performance tradeoffs.

Single-Material Nozzles

- Brass nozzles are the cheapest you can get. Brass itself is inexpensive, easy to machine, and has good thermal conductivity. Additionally, it matches well with the thermal expansion coefficient of copper heater blocks. However, it is soft and wear-prone, and it becomes less strong at temperatures above 300 degrees C.
- Copper is an upgrade over brass with better thermal conductivity and higher temperature limits, but that isn't extremely impactful because the limiting factor is the rate of heat transfer within the plastic.
- Hardened Steel is an inexpensive material with greater hardness for minimizing wear. However, steel has much lower thermal conductivity than brass, so the hotend temperature may need to be set 10-15 degrees higher than with brass nozzles. It's also not completely impervious to wear, so it will still need periodic replacement.
- Tungsten Carbide is extremely hard and strong, with thermal conductivity almost as good as brass. Additionally, it has incredible temperature resistance letting you blowtorch them to clean out clogs if necessary (though this can damage some coatings). Because they're sintered from powder, solid tungsten carbide nozzles can be made with unique internal geometries that would be extremely difficult to produce in normal metals, such as the fins in Bozzle or the slot in Nanoflow. However, they often have not-so-great surface finish in the nozzle bore and this can cause trouble with tuning pressure advance. Additionally, they are fairly expensive.

Multi-Material Nozzles

Sometimes it's not possible to manufacture an entire nozzle with the material you want to use. To get around this, many nozzles are assemblies of a brass or copper threaded portion, for machinability and thermal conductivity, and a hard material used only for the tip.

These can offer the best of both worlds, but they also add a failure point where a leak may occur.

- Hardened Steel: These have less of the thermal downsides of single-piece hardened steel nozzles, but less of the upsides of better insert materials.

- Tungsten Carbide: These are more economical than full carbide nozzles, but cannot be blowtorch cleaned and thermal expansion differences can cause leaks.
- Sapphire (or Ruby): These inserts offer extreme hardness, even better than tungsten carbide, but worse thermal performance and the monocrystalline tip can crack under high forces. Sapphire-tipped nozzles are fairly expensive.
- Silicon Carbide: Silicon carbide is even harder yet than sapphire, and has excellent thermal conductivity. The only reason it's not used for entire nozzles is because it cannot be machined or sintered the way metal or tungsten carbide nozzles are. Like sapphire, it is vulnerable to cracking and fairly expensive.
- Polycrystalline Diamond (PCD): These are made of the hardest possible material with as good a thermal conductivity as you can get. Additionally, they have low friction, which reduces the amount of plastic that sticks. The polycrystalline material is also more crack-resistant than sapphire or silicon carbide. However, they are extremely expensive, and do not have the blowtorchability of solid tungsten carbide.

Internal Geometry

When trying to print quickly, one of the limiting factors is how fast you can get heat to the core of the filament to melt it. There are several approaches for enhancing the performance relative to a straight cylindrical bore, and they involve reducing the distance to the center.

Flow Splitters (aka CHT)

One prominent high flow geometry splits the flow of plastic into two or more narrower passages that reduce the distance to the center of the filament, before rejoining just before the nozzle tip. Because the splitter heats from the center outward, it is branded as Core Heating Technology by Bondtech.

If the filament is fully melted but not at the desired temperature before reaching the splitter, then CHT greatly improves heat transfer to the melt pool.

However, at the limits of flow for the hotend, the cold core of the filament is forced down only one of the paths at a time, and this can result in temperature gradients across the flow, causing the flow out the tip to squiggle around. However, this usually isn't noticeable in actual printing.

Projections

Bozzle, a cemented carbide nozzle, tries to improve heat transfer to the core of the filament by having fins protrude inward from the walls of the nozzle bore. Even at high flow rates, this allows the cold core to pass close to the fins, picking up heat faster without hitting an obstruction.

Slot

Nanoflow, another cemented carbide nozzle, simply narrows the meltzone to a thin slot. This results in a short maximum distance from any plastic to the wall, improving heat transfer.

Coatings

Low-end brass nozzles are often uncoated, but higher-end nozzles are coated to reduce the tendency for filament to stick to the nozzle.

Some manufacturers claim that their coatings are enough to significantly improve wear resistance, but it is difficult to verify by how much.

Hotend Compatibility

Nozzles must fit your hotend.

Some hotends can accept multiple types of nozzles using adapters, though sometimes with length changes.

Standard Nozzles

- V6: E3D's V6 nozzle is the standard for enthusiast printers, and you can get any nozzle material or geometry you'd like for it. It has a 12.5mm overall length, 7.5mm of M6 threads and 5mm of tip.
- Volcano: Like E3D V6 but 8.5mm longer threads to extend the meltzone. All volcano-compatible hotends can fit V6 nozzles with an internal "volcano adapter" threaded in, and V6 hotends can use volcano nozzles with a nut threaded on to improve heat conduction. 21mm overall length, 16mm of M6 threads and 5mm of tip.
- Supervolcano: This E3D standard is a ridiculously long version of V6, very rarely seen because of flaws in the original hotend. 51.5mm overall length, with 46.5mm of M6 thread and 5mm of tip.
- Mk8: This is an older nozzle standard from Makerbot. It has a shorter threaded section and a longer hex+tip than V6, and it's overall 0.5mm longer. Mk8 nozzles can usually function with a V6 nozzle if the part cooling ducts have enough clearance, but V6 hotends usually cannot work with Mk8 nozzles. 13mm overall length, 5mm of M6 threads, and 8mm tip.
- FIN: This newer Slice standard, created in collaboration with Bondtech and Micro-Swiss with a prescribed tip geometry to allow the hotend socks to cover most of the nozzle, reducing unwanted convective cooling of the nozzle tip by part cooling airflow. It also uses a shorter, smaller-diameter threaded section to minimize the effects of differential thermal expansion between the nozzle and heater block. Not many hotends are available for it, but hopefully more are coming... 9.5mm overall length, 4.4mm of **M5x0.8** threads plus some clearance, and 5.1mm from the heater block to the tip. The hex has 150 degree conical surfaces to allow for firm contact with the silicone sock.
- And many others, including various different length extended Mk8-tip-style nozzles used by Creality, Sovol, and others.

Integrated Heatbreak

Some hotends use nozzles that have the heatbreak installed directly into the nozzle body, relieving the heater block of any need to seal.

This more or less eliminates user error from improper tightening of nozzles, whether that be undertightening causing leaking, or overtightening and snapping the nozzle.

- E3D Revo: The original integrated heatbreak nozzle, Revo has the nozzle thread into the heatsink, and uses a spring-loaded heater block to transfer heat to the nozzle.
- Prusa Nozzle (for Nextruder): This resembles V6 in meltzone length and tip geometry. The nozzle is snugly screwed into the heater block, then the cold side of the nozzle is held into the heatsink using a setscrew. The hotend can be used with V6 nozzles using an adapter (basically just a heatbreak with a compatible cold side).
- Micro-Swiss Flowtech: These nozzles thread into the heater block, which is loosely retained using two structural screws. The heatbreak is placed in compression and the structural screws in tension.
- Creality Unicorn nozzle: This is similar to the Prusa Nozzle but uses a rigidly mounted heater block that the nozzle is snugly screwed into.
- QIDI Plus4 nozzle: this is like the Creality Unicorn nozzle, but it has a zirconia filament heatbreak to better prevent heat creep, taking advantage of the rigid heatblock mount.

Integrated Heater Block

Some printers integrate the heater block itself into the nozzle and heatbreak, and sometimes even the heatsink.

- Bambu Lab X1/P1: These have the entire hotend including heatsink and heater block as one unit. Changing the nozzle involves the user installing the heater and thermistor with a steel clip and screwing in the cold side fan.
- Bambu Lab A1/H2: These have the entire hotend including heatsink and heater block as one unit. However, the heater block clips onto a hard-mounted heater with temperature sensor, simplifying the nozzle change process.
- Sovol SV08: This only integrates the heatbreak, heater block, and nozzle. Changing nozzles is similar to the X1 and P1 but the heatsink is separate and does not need replacement. Later models may have swappable nozzles?

Belted Kinematics

A 3D printer needs three axes of motion. Driving all three axes can be done in several different ways.

Bedslinger Cartesian

The simplest motion system, bedslinging moves the toolhead in X and Z, and the bed in Y.

This makes the two fast axes move completely independently. The X linear guide moves only slowly in Z, and the Y linear guides are completely stationary. This reduces friction when accelerating diagonally.

All belt runs are as short as possible for each axis with a minimum of idlers for low friction.

All motors are either stationary or slow-moving.

The motion itself is simple but the print itself moves and puts higher loads on the Y linear guide system. Additionally, the bed should be built as lightly as possible without losing rigidity.

One side benefit of bedslinging is that an air curtain mounted along the X rail can cool the entire print area without adding XY moving mass.

Box Cartesian (Serial X-Y)

Box Cartesian kinematics moves the X rail, together with the X motor(s), in the Y direction.

This allows the print to move slowly or not at all (depending on Z kinematics).

All belt runs are as short as possible for each axis, with a minimum of idlers for low friction, but there must be two Y axis belts.

The X motors move quickly in Y, making wiring an important consideration as well as their effect on the center of mass.

The X rail gets loaded during Y acceleration, increasing friction.

Cross Gantry

Cross gantry is a parallel cartesian kinematic that drives the toolhead using crossed linear guides that span the build area. The ends of the crossed guides are driven by simple short X and Y belt paths, and each end is supported by further linear guides.

This allows the print to move slowly or not at all (depending on Z kinematics).

All belt runs are as short as possible for each axis, with a minimum of idlers for low friction, but both X and Y need two belts each.

All motors are stationary or slow-moving.

This sounds ideal but there are several tradeoffs.

Cross gantry requires more hardware (at least 6 linear guides).

If only two guides are used to cross the build volume, at least one is misaligned with the center of mass of the toolhead, causing moment loads on the guides at the toolhead.

The two guides passing through the toolhead make toolhead design difficult regarding part cooling ducts and fan placement.

Finally, the multitude of linear guides make this prone to overconstraint, which leads to high friction with poor construction or in the case of thermal expansion mismatch.

CoreXY

CoreXY has two stationary motors with two P shaped belt paths combined to move both the toolhead in X and the X rail in Y. One motor changes X+Y and the other changes X-Y.

This allows the print to move slowly or not at all (depending on Z kinematics).

Belt runs are long in CoreXY, and differing tension between the two belts tries to rack the X axis out of square.

CoreXY has a lot of idlers on the belt path, causing higher friction particularly with higher belt tensions.

All motors are stationary or slow-moving.

HBot

HBot has two (or four) stationary motors with one H-shaped belt path that moves both the toolhead in X and the X rail in Y. One motor changes X+Y and the other changes X-Y.

This allows the print to move slowly or not at all (depending on Z kinematics).

The belt run is long in HBot, and any X acceleration causes belt tension that tries to rack the X axis out of square.

HBot has a lot of idlers on the belt path, causing higher friction particularly with higher belt tensions.

All motors are stationary or slow-moving.

MarkForged

MarkForged kinematic has dedicated short Y drive belts moving the X axis, and a T-shaped X belt path moving along one side and the X axis. Moving the Y axis motor(s) alone will move the toolhead diagonally, but moving the X motor will move the toolhead only in X.

This allows the print to move slowly or not at all (depending on Z kinematics).

The Y belts, which carry a heavier load, are short belt paths. The X belt is longer but the toolhead is comparatively light.

The X axis has a lot of idlers on the belt path, causing higher friction particularly with higher belt tensions.

All motors are stationary or slow-moving.

Delta

Delta printers have three columns, each with a straight belt run along a linear guide. Each carriage carries a spherical-jointed parallelogram linkage to a triangular plate that carries the toolhead, providing parallel 3-degree-of-freedom control of the toolhead.

The print is stationary.

All belts have short belt paths and minimal idlers.

All motors are stationary.

The motion system rigidity is limited by the preload of the spherical joints and the arm stiffness.

Delta kinematics require calibration that compensates for manufacturing variance (tower spacing and arm length) to achieve dimensional accuracy.

Bed Tramming

Bed tramming is the alignment of the bed plane with the XY gantry to minimize the need for mesh compensation (which is when Z adjusts continuously as X and Y move). This can be done manually as a part of machine setup, or automatically using a bed probe and independent Z actuators.

Manual Tramming

When a machine doesn't provide (fully) independent Z tilt control, the bed must be trammed manually. Some machines have no native support for this at all, relying on their construction to be "close enough" and compensating the rest of the way using a bed probe and mesh compensation.

Manual tramming enables the use of more robust Z linear motion systems compared to automatic tramming systems, but they should be checked and adjusted periodically, and the ideal alignment may vary with bed or chamber temperature.

Manually-trammed beds are supported by a number of compliant supports such as silicone columns and held down by screws. The stiffer the support the more rigidly the bed will be coupled to the printer structure (good).

Non-adjustable machines may use rigid columns that can be swapped for something slightly compliant if desired, such as the "silicone tube mod" for i3-style machines such as Prusas and Sovol SV06. However, on bedslingers, a rigid connection is better.

Three-point

On rigid, well-made beds that are trusted to be relatively flat, tramming manually only needs three points of support to control tilt in all axes. This cannot correct for any deformations in the bed, though.

Four-point

Cheaper machines with simple aluminum PCB beds may use four screws to adjust for a potato-chip-shaped bed. This has the disadvantage of possibly letting the user *induce* a potato-chip shape in the bed by adjusting one screw at a time.

Multi-point

Many machines with no adjustability mount the bed in 8, 9, or more locations. Modding them with silicone tubes as springs offers much finer control over the bed shape prior to mesh compensation.

Automatic Tramming

When the Z mechanism provides control over either the gantry or the bed tilt, tramming can be an automatic process performed as part of homing the machine, using the bed probe near the edges of the bed.

Gantry Tilt

Bedslinger

Bedslingers with independent Z motion for the two sides of the X gantry can tram automatically, but in only one direction. Fore/aft tilt of the bed must still be trammed manually, and the other axis of the bed is ideally trammed for perpendicularity to minimize skew of the print that must be calibrated out.

This requires that the gantry have some degree of articulation where it attaches to the Z linear guides.

Triple Z Flying Gantry

This isn't very common, but when the entire XY gantry is rigid and hoisted on three independent Z actuators, the gantry can be trammed to be level relative to the bed.

This requires that the gantry have some degree of articulation where it attaches to the Z linear guides.

Quadruple Z Flying Gantry

When the XY gantry has some flex and is hoisted on four independent Z actuators on the corners, the gantry can be trammed to be level and de-skewed relative to the bed.

This requires that the gantry have some give to handle the skew adjustment.

Bed Tilt

Two Point

Why do they do this? This is dumb. Some printers have only two independent Z actuators moving the bed so they can control one axis of bed tilt, but not the other. So you get some automatic tramming but you still need to manually tram, and it's often not even stiffly-enough constrained in the other tilt axis...

Three-Point

When the bed is hoisted on three independent Z actuators, the bed can be trammed relative to the gantry.

This is good.