look into changing sequence of print
- outside shell
- raster print
- inside shell

} look into switching these up especially for large/long overhangs

→ if let print bed warm-up for a period of time to stabilize can help with
- adhesion issues
- warping

Assignment 2:
- look into our space and things that are manufactured and think about how easy it would be to CAD it up
- then look into how items grow organically
  i.e. plant → puts material where needed for maximum surface area to grow, absorb light/water
- model an organic shape that does not require supports
  → use lofting (look into blending)
* get head out of rectilinear design

*working with Katrina for A2

if want to learn other software – blender + rhino are great for making organic shapes

Discussion on articles (Kazmer + ??? from FDM unit):
- shorter article less differentiation on materials
- longer article was deep into fusion & wetting process while the other was more about how to get the best print
- longer article was more on the physics of the part

strength of part is a function of adhesion between layers, defects
- width of the bonds

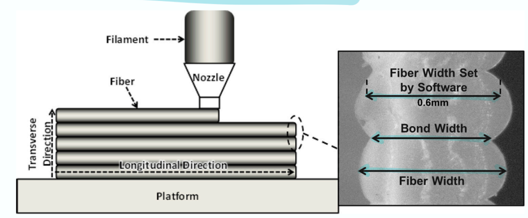
2nd article, 3 diff ways that that bonding may occur:
① wetting – process by which "water spreads and binds to surface, for example"
- as cools down, not getting wet anymore
- put pressure between layers to drive molecules to bind together
② polymerization
③

thicker and thicker roads → bond width decreases
what happens as make thinner + thinner layer?
→ pressure is less when thin
so then what happens to cooling w/ thin/thick?
→ thin will cool faster
→ but then layer adhesion will be worse
↳ if go too thin, won't get adhesion, might even get bubbling

Bond Part Strength in FDM (2017) — Coogan & Kazmer

- investigated the factors governing bond strength in FDM compared to strength in the fiber direction
- ABS boxes with thickness of single fiber made at different platform and nozzle temperatures, print speeds, fiber widths, and layer heights to produce multiple specimens for measuring strength
- study provides processing recommendations for producing the strongest FDM parts and the needs for higher nozzle temperatures and more robust feed motors are described
- compared to conventional plastic processing techniques such as injection-molding, FDM-made parts typically have lower mechanical properties because of the discontinuous nature of the process
- bond widths were consistently smaller than the fiber widths, indicating that the adjacent layers never achieved complete wetting
- following process parameters resulted in greater FDM bond strengths:
    - higher platform temperatures
    - higher nozzle temp
    - faster print speed
    - larger fiber widths
    - smaller layer heights —> more wetting and higher pressures exiting nozzle and pressure is believed to improve intimate contact between layers
    - the temperature trends explained by higher interface temperatures resulting in more polymer chain diffusion

Figure 1 Typical FDM process (left) and measured bond width and fiber width (right)



- majority of tensile specimens broke at cold locations furthest away from heated build platform
- deposited fiber widths increased further away from start of each layer
- variation in filament area correlated to variation in fiber area and bond strength
- less material deposited at fast print speeds
- if fibers all aligned in the same direction as tensile test, then bond strength is less of a concern with mechanical properties approaching that of constitutive filament

Prediction of Interlayer Strength in Material Extrusion Additive Manufacturing (2020) — Coogan & Kazmer

- interlayer strengths of parts produced through FFF suffer due to poor interlayer contact and insufficient diffusion
- model for predicting interlayer contact, based on pressure-driven flow, is combined with a model for polymer chain diffusion to predict the interlayer strength (aka bond strength) of material extrusion parts
- interlayer strength model is successfully validated against strength measurements of parts made with high impact polystyrene, indicating that the strength of all parts suffers due to incomplete interlayer contact while only some parts suffered from incomplete diffusive healing
- interlayer strength development in material extrusion can be considered as a combination of pressure-driven intimate contact followed by polymer diffusion
- while previous models have been described for predicting interlayer diffusion, this work presented the first experimentally validated model capable of predicting interlayer strength by accounting for both the contact area between layers as well as interlayer diffusion
- variations in strength and quality can now be monitored with in-line sensors by monitoring filament slip, analyzing variations in melt pressure that influence intimate contact, and observing changes in temperature and viscosity which affect intimate contact and diffusion
- a lack of interlayer contact is believed to be the primary cause for low mechanical properties in most extrusion parts
- the results show that in-line contact pressure measurements can be used to predict interlayer contact, which is useful for real-time analysis, but a model for predicting contact pressure (rather than measuring it) may be sufficient for broad adoption or a priori predictive models

Extrusion-Based Systems

- material extrusion tech can be visualized as similar to cake icing in that material contained in a reservoir is forced out through a nozzle when pressure is applied
- is pressure remains constant, resulting extruded material (referred to as "roads") will flow at a constant rate and will remain a constant cross-sectional diameter
- material that is extruded must be in a semisolid state when it comes out of the nozzle and this material must fully solidify while remaining in that shape
- material must bond to material that has already been extruded so that a solid structure can result
- AM machine must be capable of scanning in a horizontal plane as well as starting and stopping the flow of material while scanning —> once a layer is completed, machine must index upwards, or move part downwards, to that a further layer can be produced

Key Features in Extrusion-Based Systems

- loading of material
- liquification of material
- application of pressure to move the material through the nozzle
- extrusion
- plotting according to a predefined path and in a controlled manner
- bonding of material to itself or secondary build materials to form a coherent solid structure
- inclusion of support structures to enable complex geometrical features

Material Loading

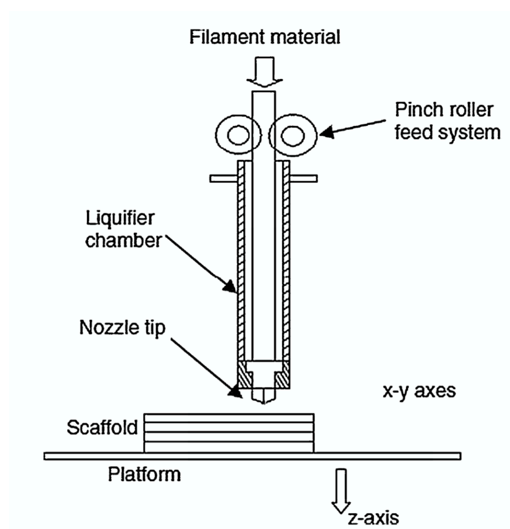
- chamber is main location for the liquification process
- materials fed through system under gravity require a plunger or compressed gas to force through narrow nozzle
- continuous filament can be pushed into the reservoir chamber, thus providing a mechanism for generating an input pressure for the nozzle

Liquification

- works on principle that what is held in the chamber will become a liquid that can eventually be pushed through the nozzle
- material inside chamber should be kept in molten state by case should be taken to maintain it at as low a temperature as possible since some polymers degrade quickly at higher temperatures

Extrusion

- extrusion nozzle determines shape and size of extruded filament
- larger nozzle diameter will enable material to flow more rapidly but would result in a part with lower precision compared with the original CAD drawing
- diameter of nozzle also determines the minimum feature size that can be created
- no feature can be smaller than nozzle diameter and in practice features should normally be large relative to the nozzle diameter to faithfully reproduce them with satisfactory strength
- extrusion-based processes more suitable for larger parts that have features and wall thicknesses that are at least twice the nominal diameter of the extrusion nozzle used
- material flow through nozzle is controlled but he pressure drop between the chamber and the surrounding atmosphere



Solidification

- once material extruded, should ideally remain same shape and size
- gravity & surface tension however may cause the material to change shape while size may vary according to cooling and drying effects
- if material is extruded in a molten state, may also shrink when cooling
- possible that cooling is nonlinear, resulting part will distort —> can be minimized by ensuring the temperature differential between the chamber and the surrounding atmosphere is kept to a minimum

Positional Control

- extrusion head is typically carried on a plotting system that allows movement in the horizontal plane
- plotting must be coordinated with the extrusion rate to ensure smooth and consistent deposition
- since rapid changes in direction can make it difficult to control material flow, common strategy would be draw the outline of the part to be built using a slower plotting speed to ensure that material flow is maintained at a constant rate
- internal fill pattern can be built more rapidly since the outline represents the external features of the part that corresponds to geometric precision

Bonding

- for heat-based systems there must be sufficient residual heat energy to activate the surfaces of the adjacent regions causing bonding
- if there is insufficient energy, regions may adhere but there would be a distinct boundary between new and previously deposited material
  - this can represent a fracture surface where the materials can be easily separated
  - too much energy may cause the previously deposited material to flow which in turn may result in a poorly defined part

Support Generation

Supports take two forms in extrusion-based systems

1. similar material supports
2. secondary material supports

Most effective way to remove supports from the part is to fabricate them in a different material
Variations in material properties can be exploited so that supports are easily distinguishable

- visually (different color material)
- mechanically (weaker material for the support)
- chemically (using material that can be removed using a solvent without affecting the part material

Plotting and Path Control

- part accuracy is maintained by plotting the outline material first which will act as a constraining region for the fill material
- outline would generally be plotting with a lower speed to ensure consistent material flow
- outline is determined by extracting intersections between a plane (representing the current cross section of the build) and the triangles in the STL file

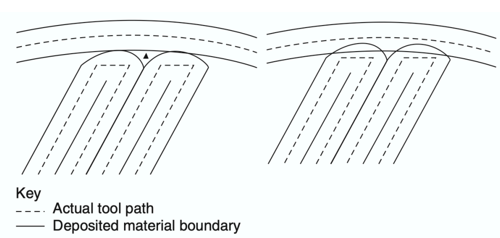


Fig. 6.5 Extrusion of materials to maximize precision (*left*) or material strength (*right*) by controlling voids

- intersections then ordered so that they form a complete, continuous curve for each outline (there may be any number of these curves, either separate or nested inside of each other, depending upon the geometry of that cross section
- remaining thing for software to do at this stage is to determine the start location for each outline —> start location defined by the center of the nozzle, stop location will be final point on this trajectory, located approximately one nozzle diameter from the start location
- if all start/stop regions are stacked on top of each other, then there will be a seam running down the part

<u>Fused Deposition Modeling from Stratasys</u>
- FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament and the filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure
- FDM requires material to be plotted in a point-wise, vector fashion that involves many changes in direction

<u>Materials</u>
- FDM works best with polymers that amorphous in nature rather than the highly crystalline polymers that are more suitable for PBF processes
- polymers work best are those that are extruded in a viscous paste rather than in a lower viscosity form
- as amorphous polymers, there is no distinct melting point and the material increasingly softens and the viscosity lowers with increasing temperature
- viscosity at which these amorphous polymers can be extruded under pressure is high enough that their shape will be largely maintained after extrusion, maintaining extrusion shape and enabling them to solidify quickly and easily
- when material added in an adjacent road or as a new layer, previously extruded material can easily bond with it —> this is different from Selective Laser Sintering which relies on high crystallinity int he powdered material to ensure that there is a distinct material change from the powder state to a liquid state within a well-defined temperature region

<u>Limitations of FDM</u>
- speed of an FDM system is reliant on the feed rate and the plotting speed
- feed rate is also dependent on the ability to supply the material and the rate at which the liquefier can melt the material and feed it through the nozzle
- an important design consideration when using FDM is to account for the anisotropic nature of the part's properties
- different layering strategies result in different strengths (for instance, right-hand scanning strategy stronger parts than left-hand (see Figure 6.5)

<u>Bioextrusion</u>
- process of creating biocompatible and/or biodegradable components that are used to generate frameworks, commonly referred to as "scaffolds" that play host to animal cells for the formation of tissue (tissue engineering)

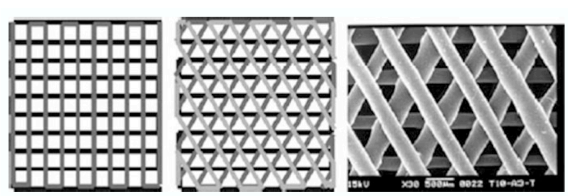


Fig. 6.8 Different scaffold designs showing a porous structure, with an actual image of a scaffold created using a bioextrusion system [10]

<u>Contour Crafting</u>
- in normal AM layers are considered as 2D shapes extruded linearly in the third dimension
- thicker layers result in lower part precision, particularly where there are slopes or curves in the vertical direction

— **FDM Printing - 3D Hubs** —

FDM aka Fused Filament Fabrication (FFF)

- object built by selectively depositing melted material in a pre-determined path layer-by-layer
- materials used are thermoplastic polymers and come in filament form

How Does FDM Work?

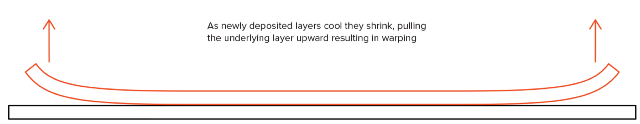
1. spool of thermoplastic is first loaded into the printer; once nozzle reached desired temp, filament is fed to the extrusion head and in the nozzle is where it melts
2. extrusion head is attached to a 3-axis system that allows it to move in the X, Y, and Z-directions; the melted material is extruded in this strands and is deposited layer-by-layer in predetermined locations where it cools and solidifies
3. to fill an area, multiple passes are required (similar to coloring a rectangle with marker); when layer finished, build platform moves down (or extrusion head moves up), and new layer is deposited
4. process is repeated until part is complete

Printer Parameters

- adjustment of temp of nozzle and build platform, build speed, layer height, speed of cooling fan
- available build size of a desktop 3D printer is commonly 200x200x200 mm
- typical layer height varies between 50 and 400 microns and can be determined upon placing an order
- smaller height produces smoother parts and captures curved geometries more accurately, while larger height produces parts faster and at a lower cost
- layer height of 200 microns is most commonly used

Warping

- common defect, when extruded material cools during solidification, its dimensions decrease
- as different sections of the print cool at different rates, their dimensions also change at different speeds
- differential cooling causes the buildup of internal stressed that pull the underlying layer upwards, causing it to warp
- warping can be prevented by closer monitoring of the temp of the FDM system and by increasing the adhesion between the part and build platform
- choices the designer can make to reduce the probability of warping
  - large flat areas are prone to warping and should be avoided
  - thin protruding features (like fork prongs) also prone and should be avoided
  - sharp corners warp more often than rounded shapes so adding fillets is good practice
  - different materials more susceptible to warping, ABS more susceptible than PLA or PETG because has higher coefficient of thermal expansion



Schematic showing edge warping of an FDM part

Layer Adhesion

- when molten thermoplastic is extruded through the nozzle, it is pressed against the previous layer
- the high temp and the pressure re-melts the surface of the previous layer and enables the bonding go the new layer with the previously printed part

- the bond strength between different layers is always lower than the base strength of the material
  - therefore FDM parts are inherently anisotropic: their strength in the Z-direction is always smaller than their strength in the X,Y-plane
- since molten material is pressure against previous layer, shape is deformed to an oval, meaning that FDM parts will always have a wavy surface even for low layer height and that small features such as small holes or threads may need to be post processed after printing

Support Structure
- printing on dissolvable supports improves significantly the surface quality of the part, but increases the overall cost of a print

Infill & Shell Thickness
- FDM parts are not usually printed solid to reduce print time and save material
- outer perimeter is traced using several passes, called the shell, and the interior is filled with an internal, low-density structure, called the infill
- greatly affect the strength of a part

Benefits & Limitations of FDM
+ FDM is most cost-effective way of producing custom thermoplastic parts and prototypes
+ lead times of FDM are short (as fast as next-day delivery), due to high availability of technology
+ wide range of thermoplastic materials is available, suitable for both prototyping and some non-commercial functional applications
- FDM has the lowest dimensional accuracy and resolution compared to other 3D printing technologies it's not suitable for parts with intricate details
- FDM parts are likely to have visible layer lines so post processing is required for a smooth finish
- layer adhesion mechanism makes FDM parts inherently anisotropic

Rules of Thumb
- FDM can produce prototypes and functional parts fast and at a lost cost from a wide range of thermoplastic materials
- typical build size of a desktop FDM 3D printer is 200x200x200 mm (industrial machines have larger build size)
- to prevent warping avoid large flat areas and add fillets in sharp corners
- FDM is inherently anisotropic, therefore not recommended for mechanically critical components

	Fused Deposition Modeling (FDM)
Materials	Thermoplastics (PLA, ABS, PETG, PC, PEI etc)
Dimensional accuracy	± 0.5% (lower limit ± 0.5 mm) - desktop ± 0.15% (lower limit ± 0.2 mm) - industrial
Typical build size	200 x 200 x 200 mm - desktop 1000 x 1000 x 1000 mm - industrial
Common layer height	50 to 400 microns
Support	Not always required (dissolvable available)