Manufacturing Considerations in Sustainable Materials

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Sustainable Materials Course

Lecture 15- (some slight rearrangements)

Introduction
- Overview
- Historical Perspective

Challenges
- Human Health
- Environment

Solutions
- Old Polymers
- Next-gen materials for textiles (guest lecture)
- Sustainable food solutions
- Attempts w/ Impact
- Manufacturing techniques

Niche Applications
- Electronics and Optics
- Healthcare

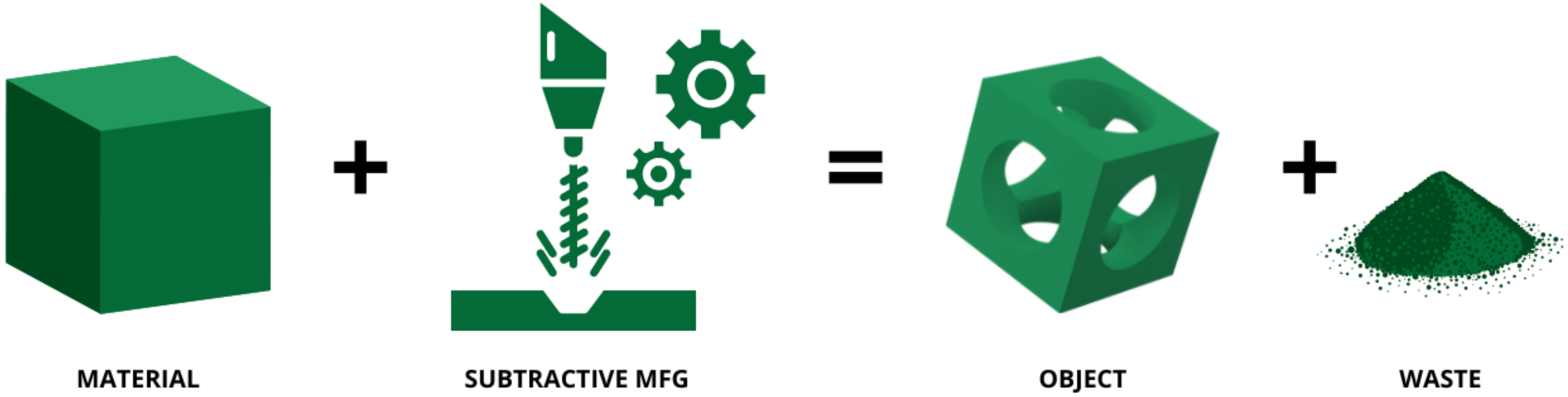
Future
- What do we need?
- How do we get there?

Learning outcomes

- Scientific principles behind manufacturing technologies
- Which manufacturing methods are used for what products (1D, 2D, 3D)
- How manufacturing processes can be improved overall

Sustainable manufacturing is about product creation that doesn’t deplete natural resources or harm the environment.

Subtractive manufacturing (machining) has been around for centuries



- Machining is the controlled removal or deformation to shape materials
- Early rudimentary machining tools: saws, chisels, knives
- Oldest industrial machining tool was the lathe invented in Egypt in 1300 BCE

Lathes, mills, drill presses are all used for machining metals, wood, composites, etc

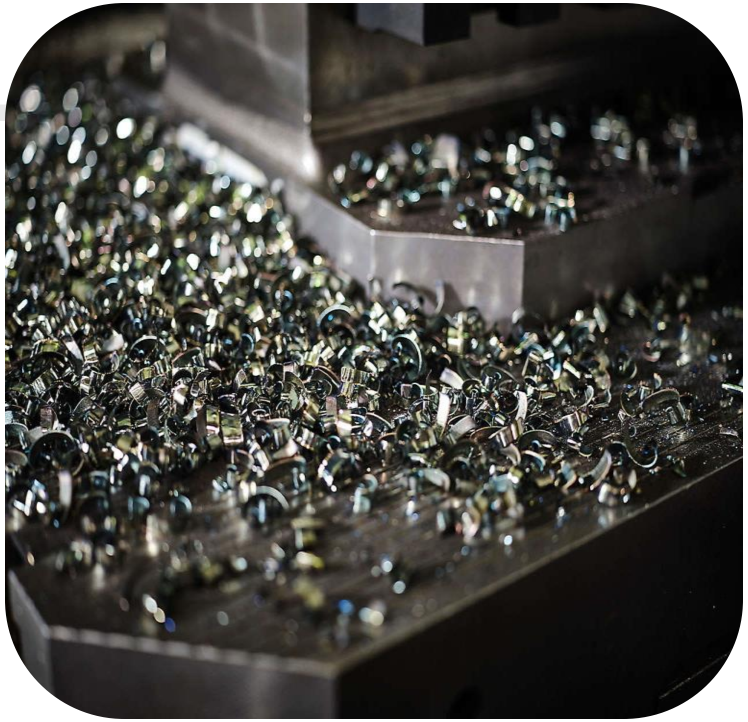
Lathes can shape round symmetrical pieces

Mills can cut fine, irregular shapes

Drill presses can insert holes into pieces

Downsides of machining techniques

- Lot's of waste- recycling not always possible
- Use of hazardous chemicals such as forging lubricants and cutting fluids
- Safety and health from dust, fumes,
- Computer Numerical Control (CNC) machining can reduce manual labor but is error-prone



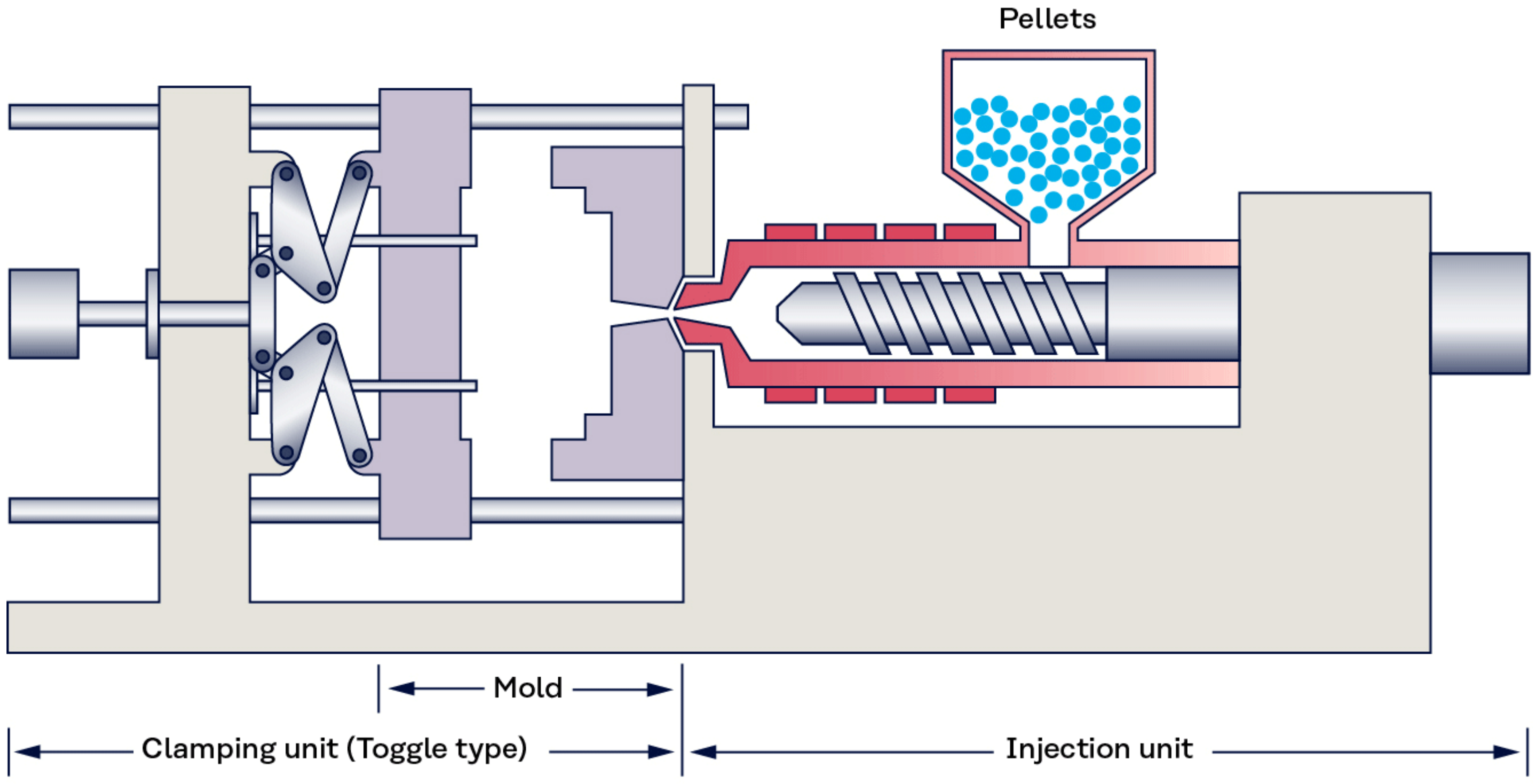
Discussion question: why use machining at all?

- Less limitations on material selection and characteristics (anything can be chiseled away at!)
- High geometrical dimension accuracy
- Controllable surface quality
- Highly repeatable
- Lower unit cost

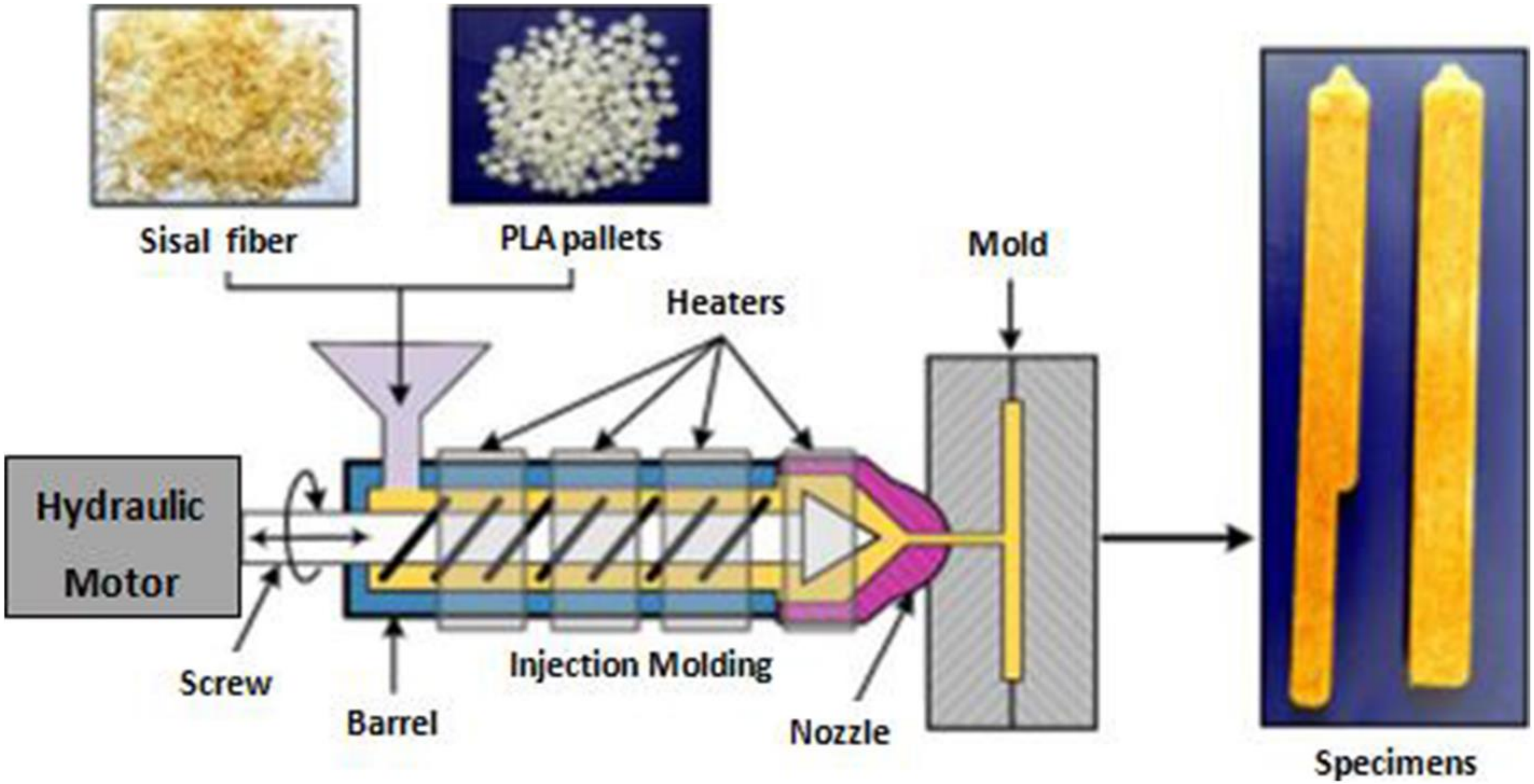
Injection molding is another method to make programmable shapes

- Step 1: Clamping
- Step 2: Injection
- Step 3: Cooling
- Step 4: Ejection of part

- Invented in 1872, a plunger was used to force celluloid through a heated cylinder and into a mold.
- First used to make small items like buttons and combs, and marked the beginning of the plastics manufacturing industry



Injection molded parts can be reinforced with biofibers to make fiber-reinforced biocomposites



Rabbi, M.S. et al. Injection-molded natural fiber-reinforced polymer composites–a review. *Int J Mech Mater Eng* 2021

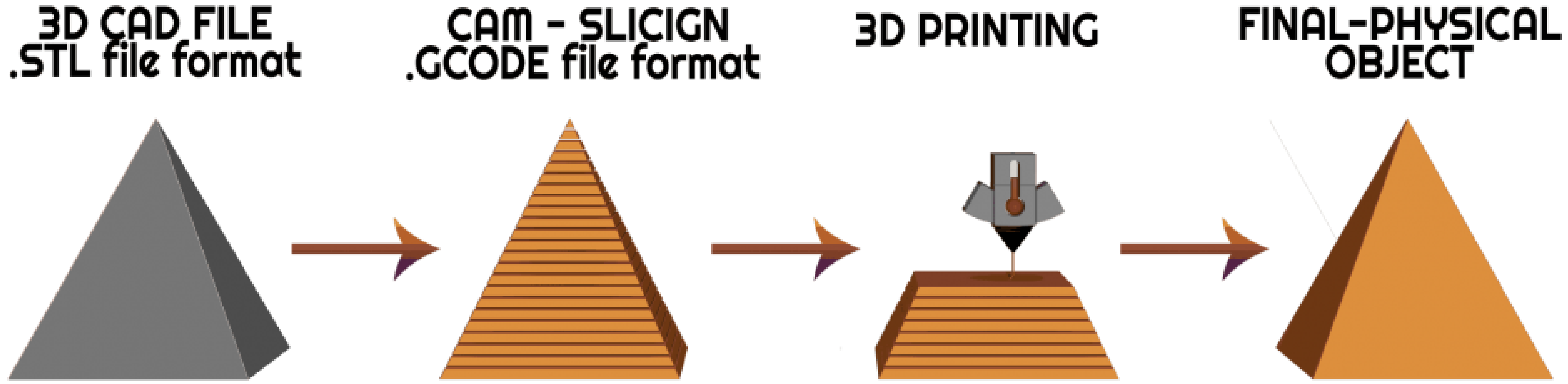
Downsides of injection molding

- Must make new mold every time you have a new part- high lead time
- Custom molds are expensive $1000-$100,000 + depending on size and complexity
- Only semi-programmable; design changes are costly
- High heat to melt plastic resins
- Limited materials can be injection molded- synthetic thermoplastics

Additive manufacturing (AM) can minimize waste material by up to 90%

- AM methods have the potential to minimize the life cycle material mass and energy spent relative to traditional subtractive processes by reducing scrap.
- Waste generated by additive manufacturing (AM) includes support structures created for overhanging pieces, material powders that are no longer recyclable, and trash produced by unanticipated flaws
- Can be **made to order!**

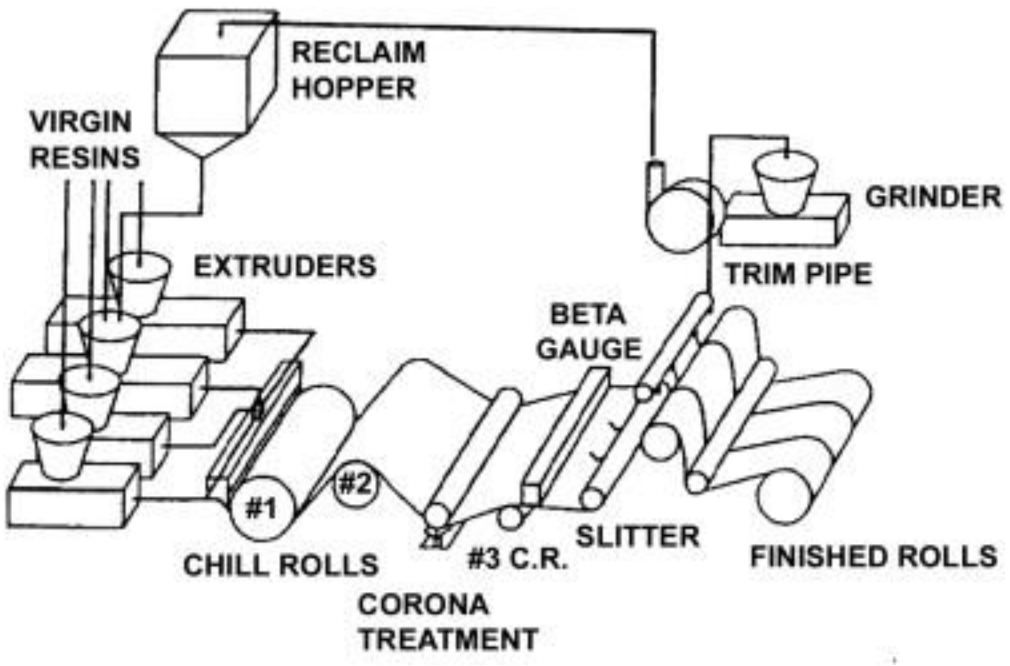
Additive manufactured products can be made directly from Computer-Aided Design (CAD) files via 3D printing

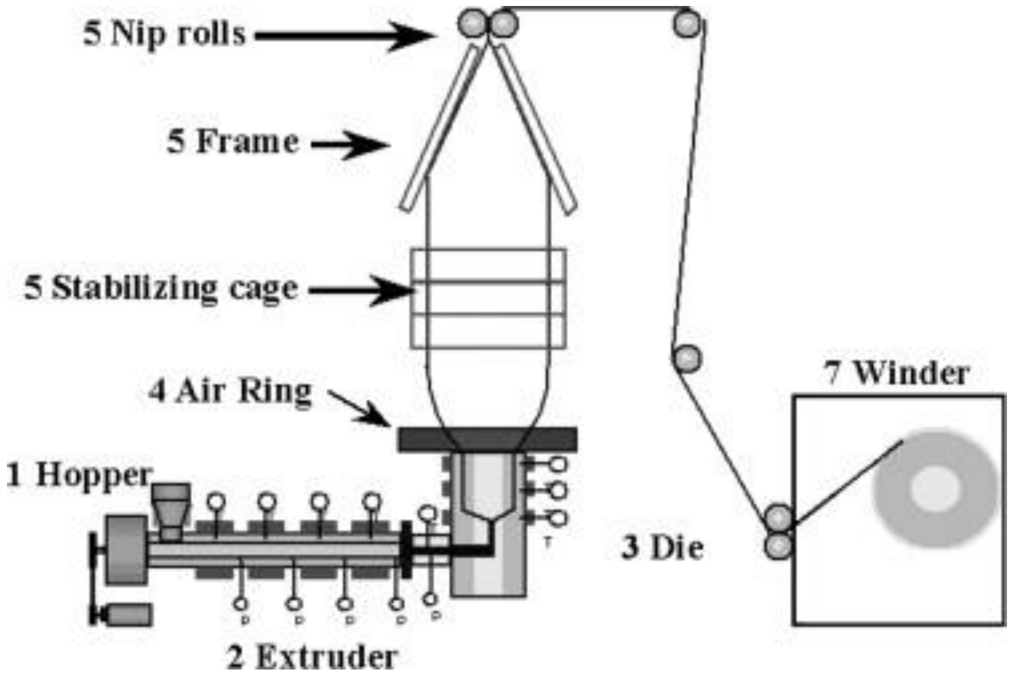


Discussion question: what are some remaining challenges with Additive Manufacturing?

- **Slower Production**: AM builds parts layer-by-layer, making it slower and less scalable for mass production.
- **Material Limitations**: Limited material options and inconsistent strength across layers; higher material costs.
- **Lower Precision & Finish**: Rougher surfaces, lower tolerances; often requires post-processing.
- **Structural Weaknesses**: Layer adhesion issues can cause weaker parts under stress.
- **Higher Energy Use**: Some AM processes consume more energy and have health risks due to fine particles.
- **Cost for High Volumes**: Less cost-effective than injection molding for large-scale production.

Films can be cast or blown, mostly used for thermoplastics



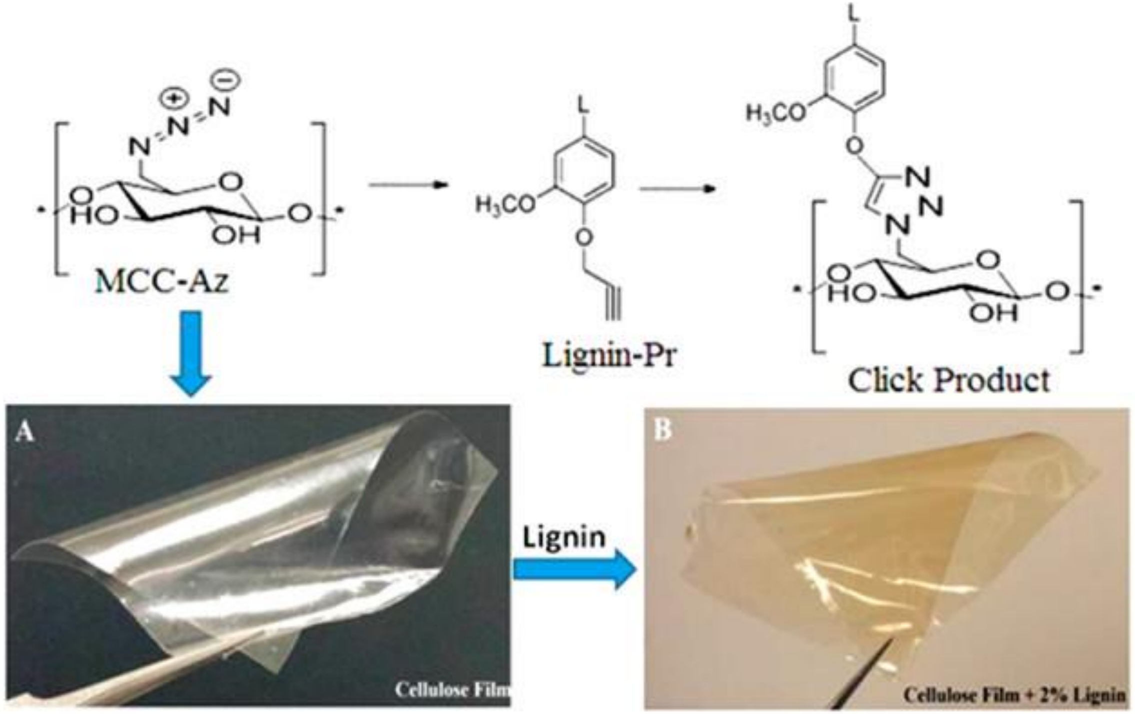


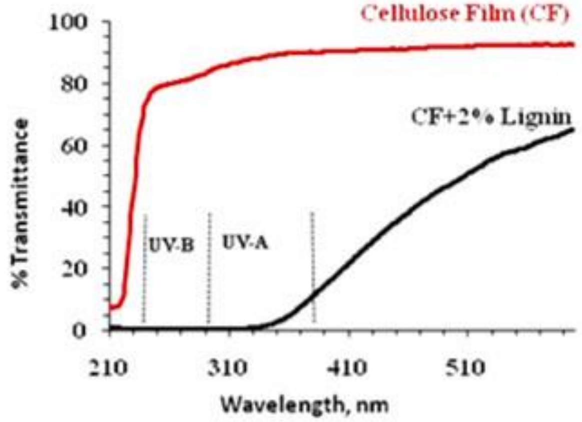
Cast Film Extrusion: Enables greater control over thickness and uniformity but may use more energy and produce more waste in startup or changeover phases.

Blown Film Extrusion: Requires precise control over temperature, extrusion rate, and cooling to achieve consistent film thickness.

Cellulose and lignin films can be made into UV-protective materials

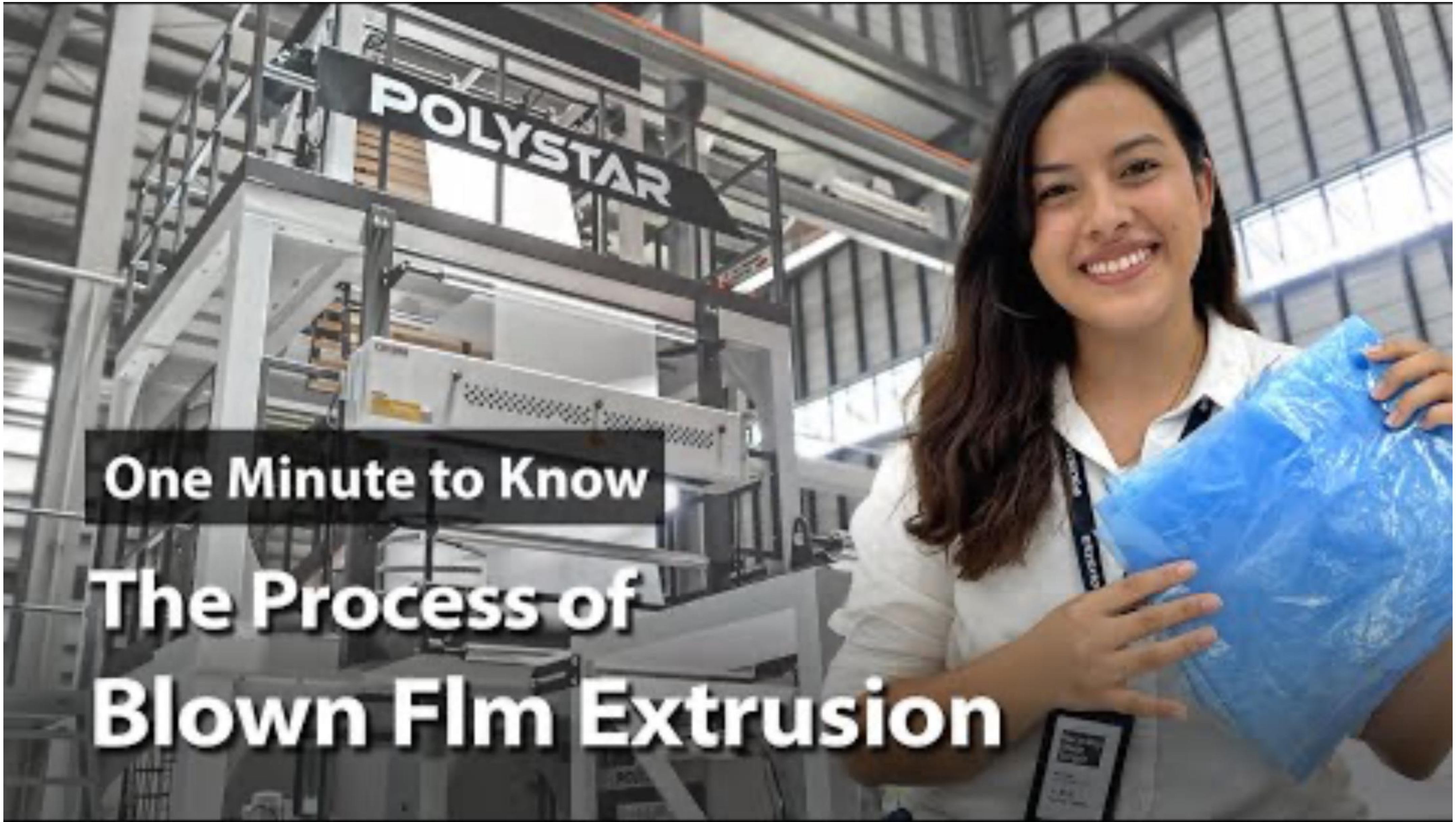
- Lignin can be added to cellulose chemically then cast into a film to provide UV protection which is ideal for packaging, window protection, possibly use in sunscreen, and transparent UV filters





UV Protection

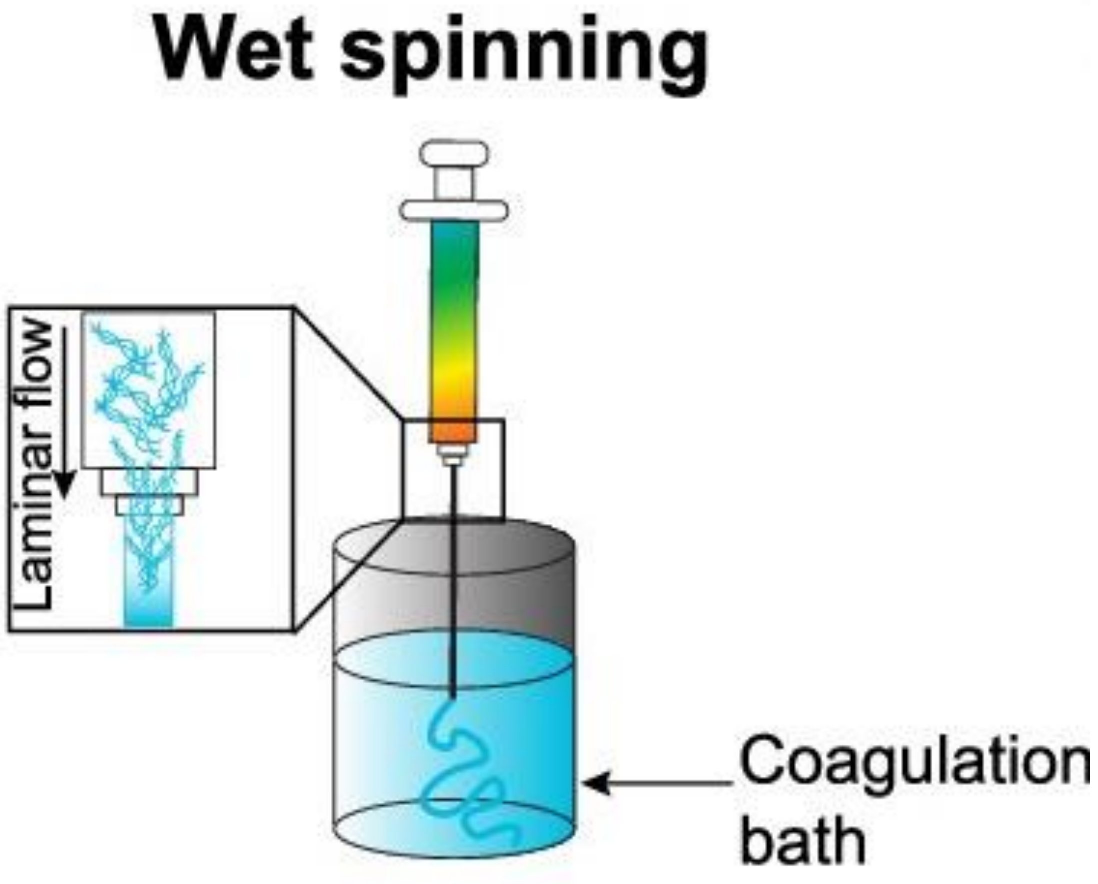
Cellulose-Lignin Biodegradable and Flexible UV Protection Film. *ACS Sustainable Chemistry & Engineering*. 2017


POLYSTAR
One Minute to Know
The Process of
Blown Flm Extrusion

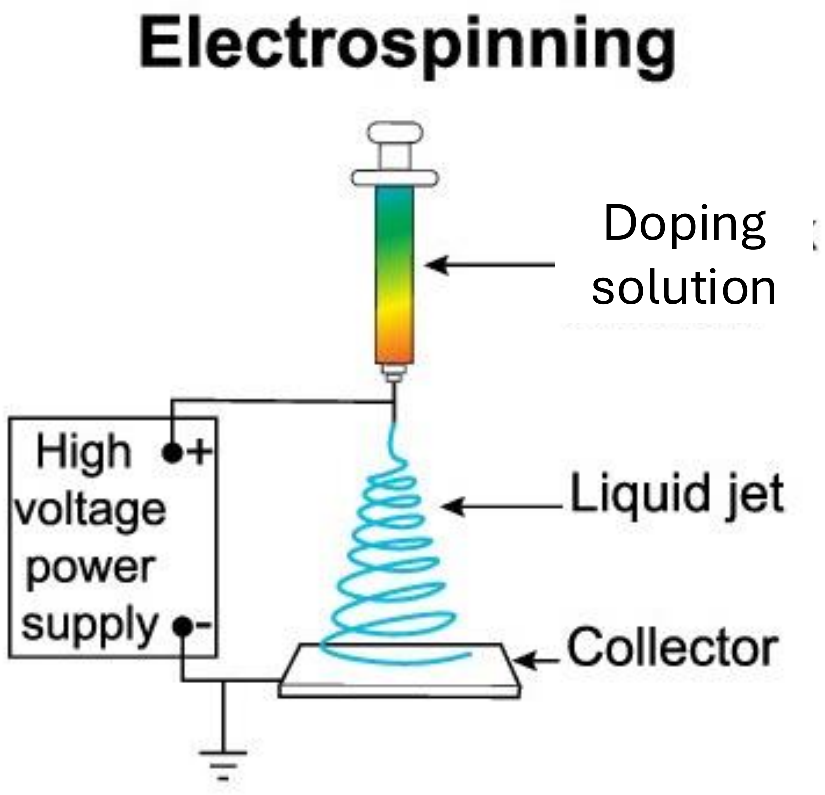
Regenerated fibers (e.g. viscose or Tencel) are made from spinning processes

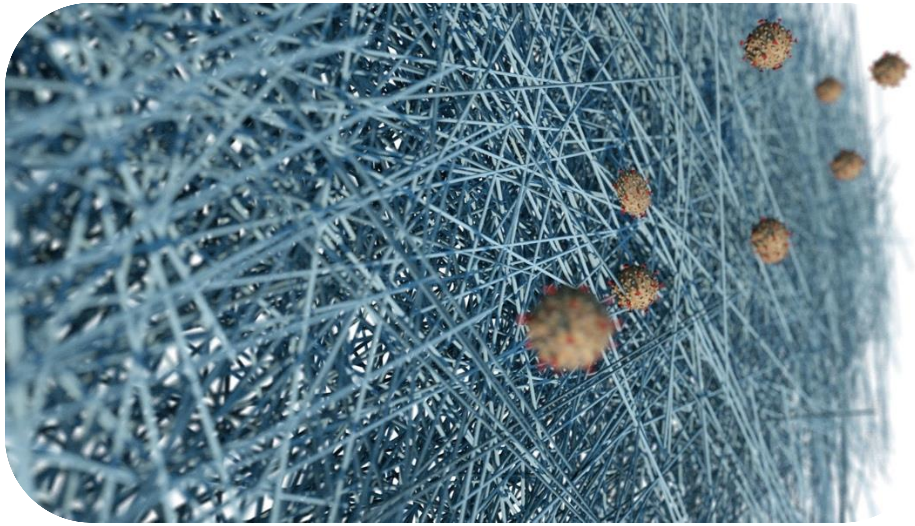
Wet-spinning is most used for textile fibers

- Wet-spinning is a method that involves solubilizing a polymer in a doping solution, then extruding it through a nozzle into a coagulation bath.
- This method is typically chosen when there is risk of thermal degradation of the polymer or to enable specific surface characteristics.



Electrospinning can spin organic polymers such as proteins, starches, and plastics by aligning them on an electric current

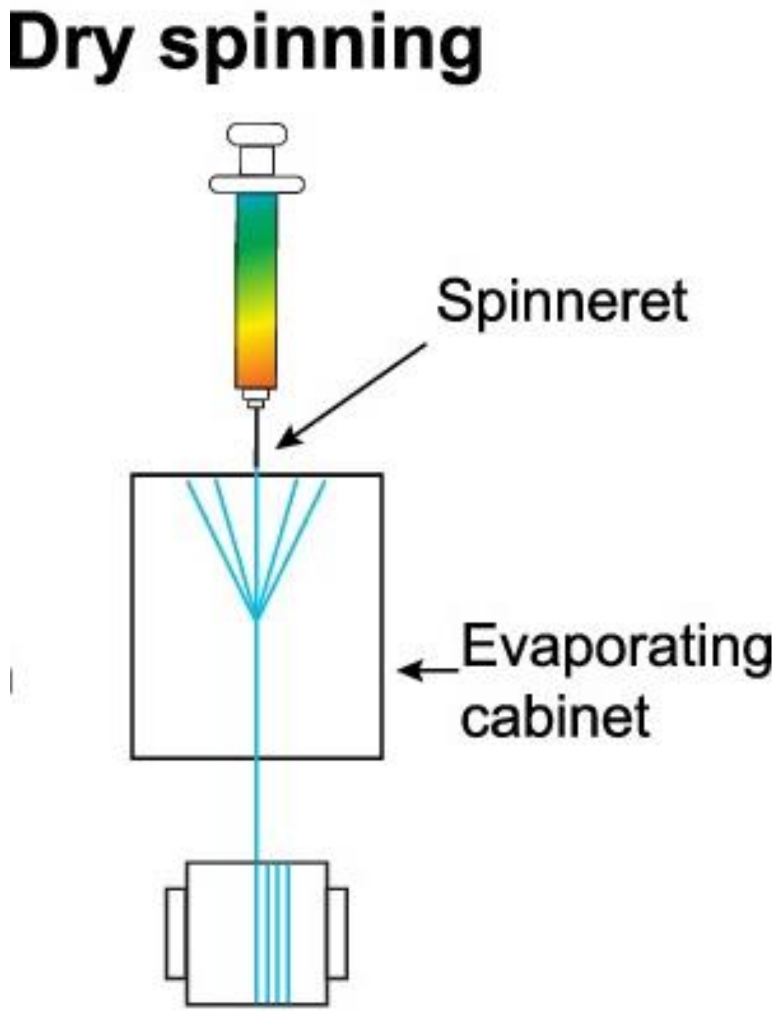




- Electrospinning involves aligning charged particles along an electric current to form fibers, which results in **nanometer scale** strands which have weaker tensile properties compared to natural silk and other spinning methods.
- Electrospinning is an efficient way of producing nonwoven materials and mats.

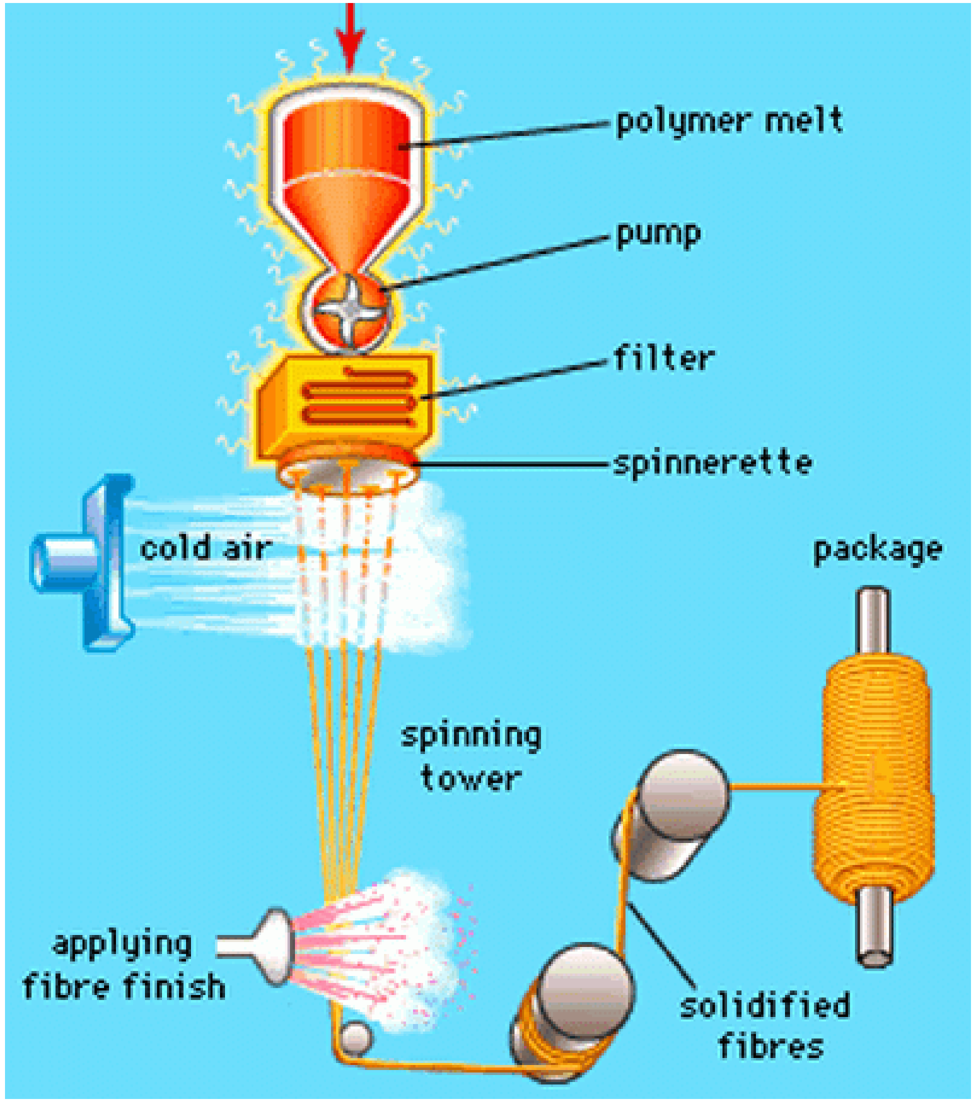
Dry spinning uses heat and air to spin fibers in a dry state

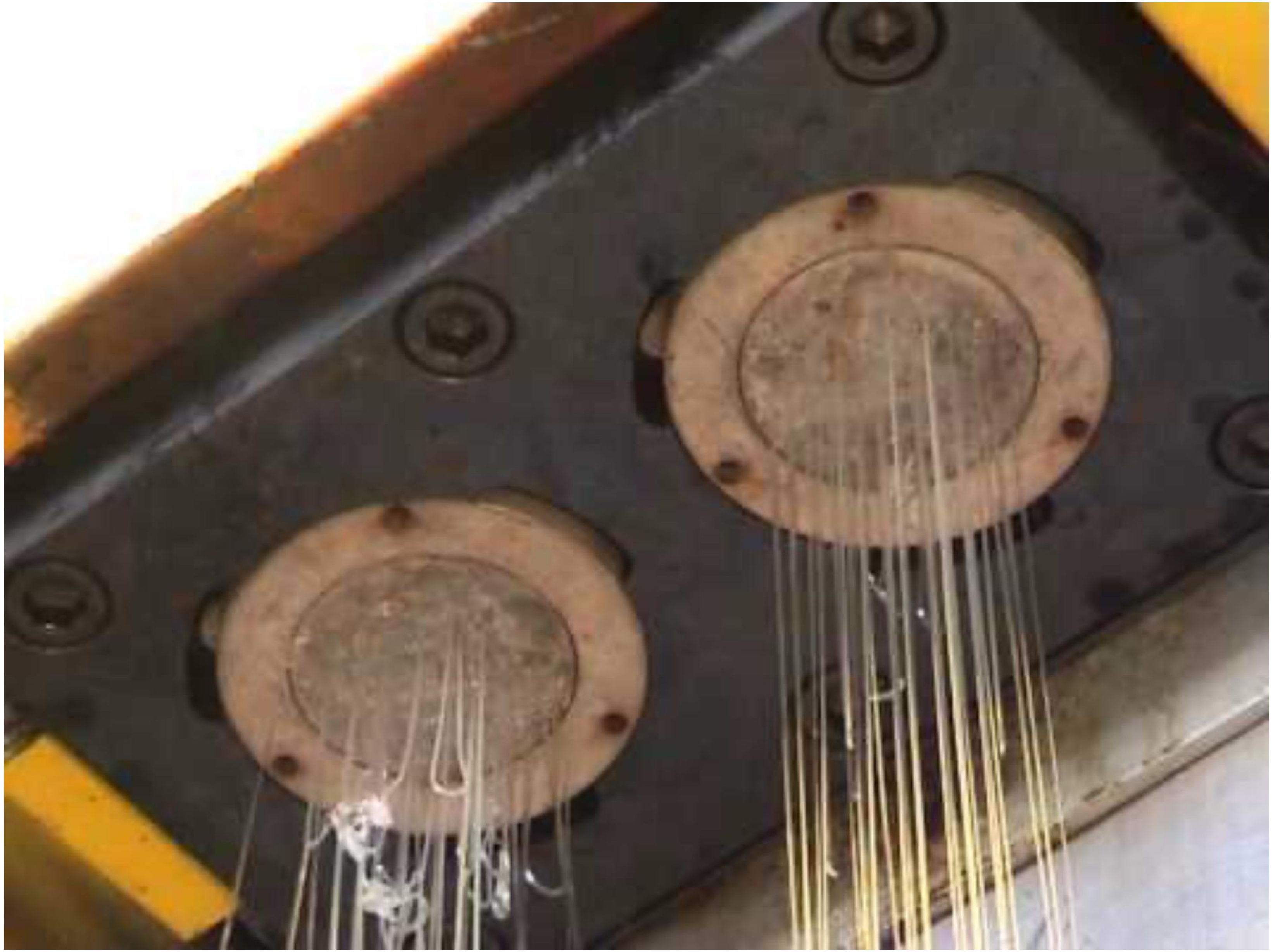
- Used for synthetics like acrylic, nylon, polyester as well as bio-based fibers like linen
- Often combined with wet-spinning after dry-spinning
- Dry spinning can produce long fibers that can be minimally processed after spinning.
- Uses volatile organic solvents that evaporate quickly



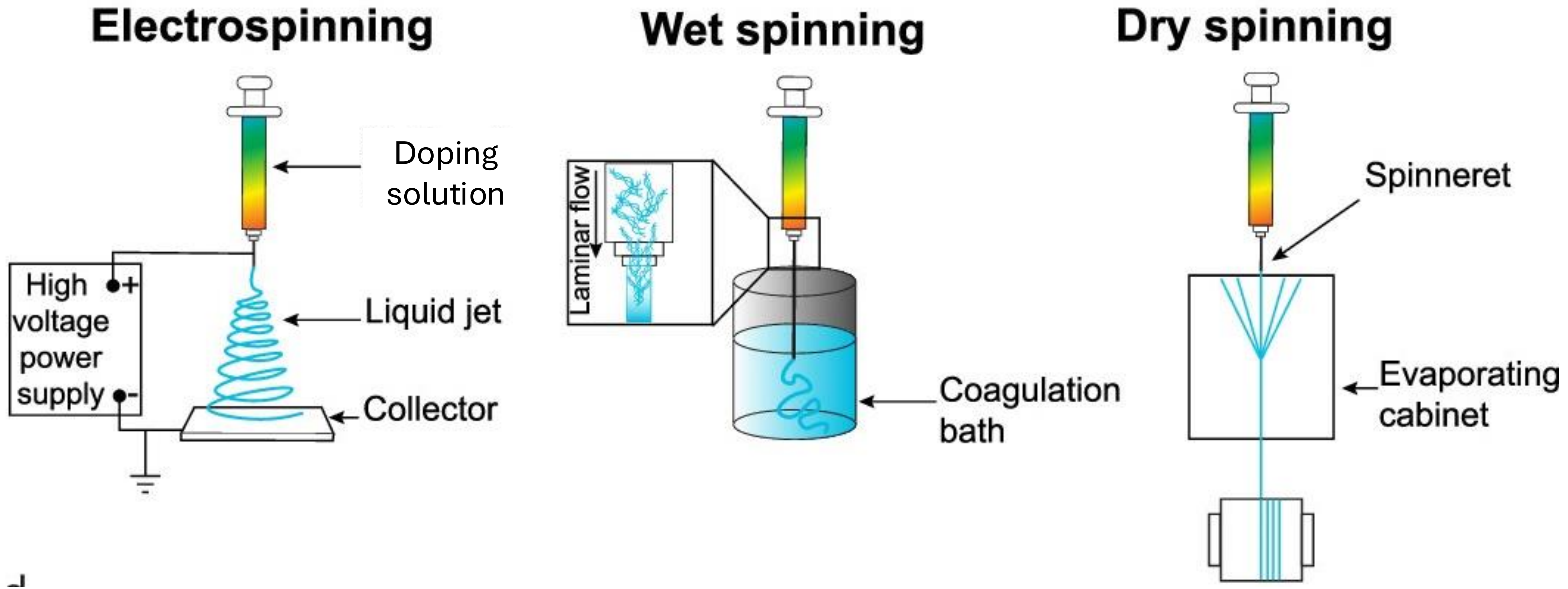
Melt spinning is used for thermoplastics and metal fibers

- **Cold air is used to solidify melted polymers** rather than evaporate as in dry spinning
- Melt spinning is widely used in the textile industry to produce synthetic fibers such as polyester, nylon, polypropylene, and metals
- Applications include clothing, carpets, upholstery, metal fibers and filaments, filters, conductive materials, and reinforcement in composites.
- Plastics and metals generally exhibit true melting points, meaning they **transition from solid to liquid** under heat **without decomposing**. For plastics, this is because their structure allows for thermal motion of the polymer chains at high temperatures.
- Biopolymers degrade and denature at lower temperatures



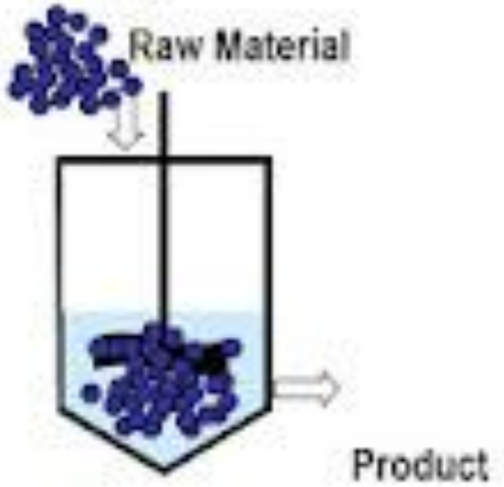


Discussion question- which spinning technique is most “sustainable” to you and why? No right answers!!



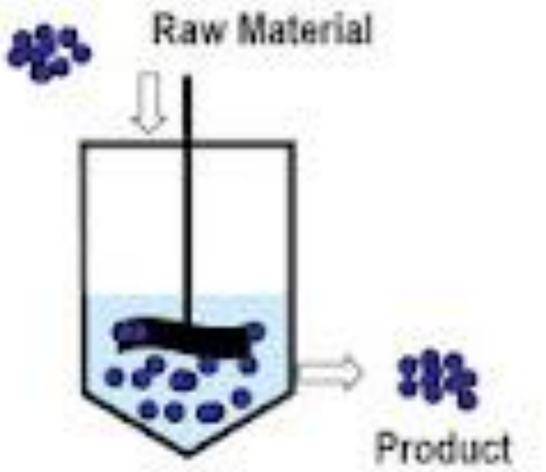
Polymers or materials can be processed in batch or continuously

Batch Manufacturing
All materials are charged before the start of processing and discharged at the end of processing



Examples: Bin blending, lyophilization, some reactions

Continuous Manufacturing
Material is simultaneously charged and discharged from the process



Examples: Petroleum refining, much of food processing

What do you think is more efficient- continuous or batch processing, and why?

- Although reliable, **Batch Processing** is viewed a **slower manufacturing method** for materials
- Less safe because of **higher risk for contamination and errors** between steps
- Requires larger tanks to meet production goals, which are not always space efficient or available

- **Continuous manufacturing** is faster, more efficient, and inherently safer.
- Improved safety is derived from **rigid quality control requirements** in continuous manufacturing.
- High capital investment!!
- Many experts maintain that continuous manufacturing is ultimately a far less costly production process (considering efficiency and safety), **once the initial plant, equipment, and training costs are paid off**

The digital transformation is heavily influencing manufacturing

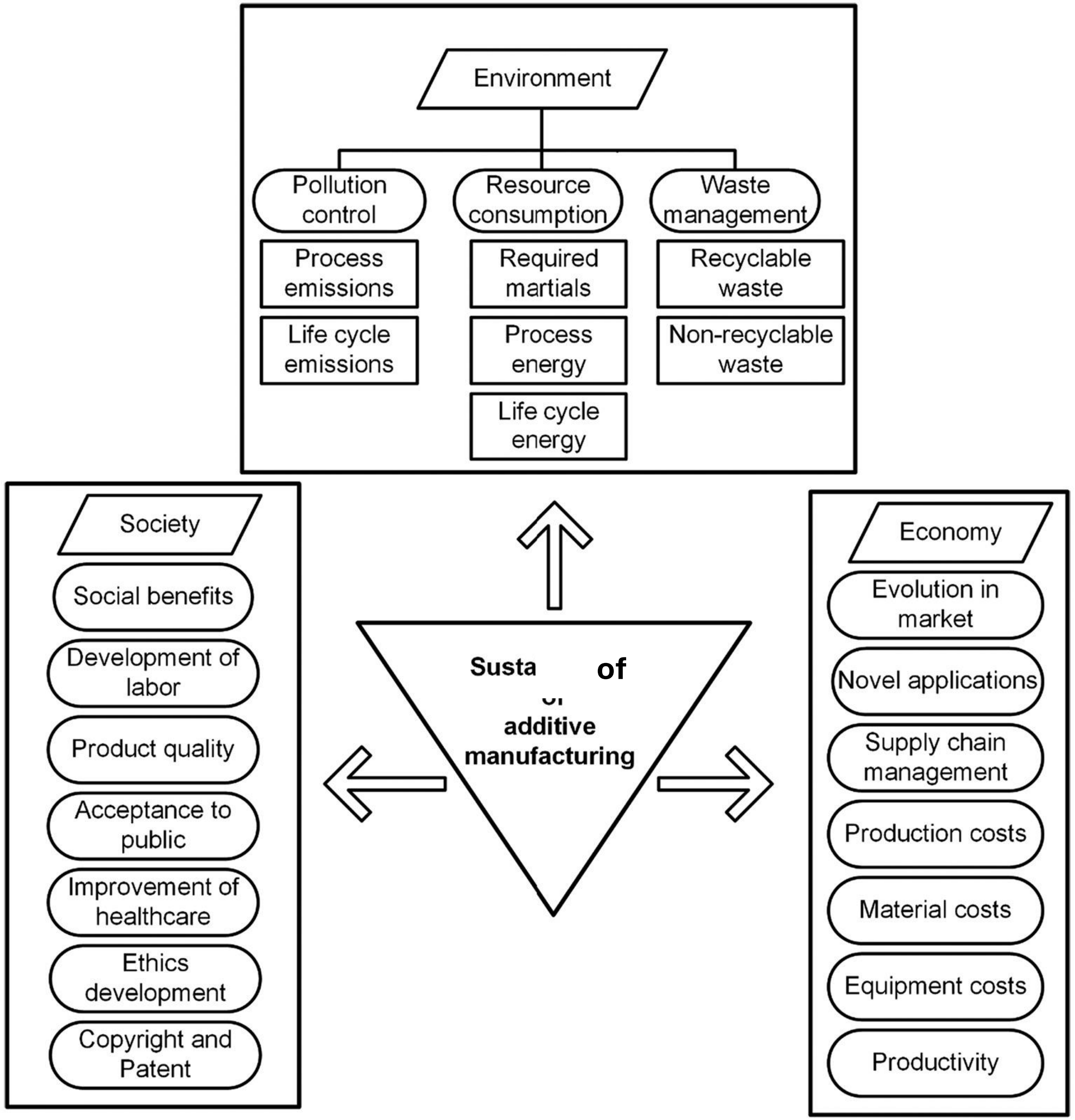
IoT = Internet of Things

Low Impact coatings and finishings are a big opportunity areas for post-manufacturing processing

Low-Impact Coatings and Finishes: Many traditional coatings, like paints, varnishes, and protective finishes, contain volatile organic compounds (VOCs) and solvents that can release hazardous air pollutants. Sustainable alternatives include:

- **Water-Based Coatings**: These use water as a solvent, reducing VOC emissions and allowing for safer handling and disposal.
- **Powder Coating**: This solvent-free, dry finishing process applies powder to the surface, which is then heated to form a durable layer.
- **UV and EB (Electron Beam) Curing**: UV and electron beam curing use less energy and reduce emissions by instantly curing coatings without the need for prolonged drying times.
- **Natural oils, waxes, or plant-based coatings** provides a biodegradable option that minimizes toxicity and environmental impact. These finishes work well in applications like furniture and consumer goods but require regular reapplication.

Broad opportunities for improving sustainability across the manufacturing process



Q&A Time

Don’t forget SCOBY show and tell on Wednesday!
Upload slide before Slack and prepare for 1 min per person.