3D Printing Technologies
6.S063 Engineering Interaction Technologies
Prof. Stefanie Mueller | MIT CSAIL | HCI Engineering Group
low-cost 3D printers, e.g. Ultimaker 3 ($3,500)
More than 278,000 desktop (under $5,000) 3D printers were sold worldwide last year.

3D Hubs: airbnb, lyft... for 3D printers

https://maps.3d hubs.com/
most common machines

https://www.3dhubs.com/trends
Fused Deposition Modeling (FDM)

learn today what this all means…

https://www.3dhubs.com/trends
HW6 until Oct 4
(ca. two weeks from now)
3D print your own keychain:
• due Oct 4
• shape and material up to you
• no taller than 2 inches each side
either download a model:
or create your own with a 3D editor! (recommended)

- Autodesk Fusion 360 (free for students)
- Solidworks (Windows only)
- SketchUp (free)
- TinkerCAD (super easy but doesn't get you very far)
3D printers in IDC:

- talk to Chris before using it

- Ultimaker 3

- Form2
Local 3D printing. Browse 30 3D printing services near Cambridge, United States.

1. Upload your parts

   1 file uploaded

   3dbenchy__-__multi-part__-__complete_17_shells__-__3dbenchy.com.stl

   60.0 x 31.0 x 48.0 mm

   Change units

   Printability: FDM - Review  SLA - Review  SLS - Review

2. Select a material

Search materials: e.g. SLS, Accura 25 or Polyjet

or

Get a recommendation

Popular materials

- **Prototyping Plastic** FDM
  - Fast and affordable parts
  - Dimensional accuracy: ±1% (lower limit: ~0.5mm)
  - Minimum feature detail: 1mm
  - Supports required: Yes

- **High Detail Resin** SLA
  - Smooth surface finish and fine detail
  - Dimensional accuracy: ±0.5% (lower limit: ~0.15mm)
  - Minimum feature detail: 0.5mm
  - Supports required: Yes

- **SLS Nylon** SLS
  - Strong and functional parts
  - Dimensional accuracy: ±0.3% (lower limit: ~0.3mm)
  - Minimum feature detail: ~0.8mm
  - Supports required: No
deliverables::

• upload a photo of your object to gradebook
• upload the 3D model file to gradebook (as .stl)
how can I 3D print something?
take your 3D model and **export as .stl format**

https://www.thingiverse.com/thing:763622
load into **slicing** software (generates infill and layers)

https://www.thingiverse.com/thing:763622
send design to 3D printer

https://www.thingiverse.com/thing:763622
remove support material
done!... but often **it’s not that easy**
different print quality...

https://www.thingiverse.com/thing:763622
let’s look at the **different technologies:**

how they work and what they can do
Fused Deposition Modeling (FDM)
most of today’s consumer printers use FDM

Ultimaker ($3,500)
PrintrBot ($300)
MakerBot ($2,500)
fused deposition modeling (FDM):

- **plastic** filament on spools
- pushed through a **hot extruder nozzle**
- melts when going through the nozzle
- and solidifies when placed on the build platform
how do I find out how much my printed object costs?

< 30s brainstorming >
example:

- 1kg plastic spool: $40
- so 1g costs: $40 / 1000g = 0.04 cents

- weigh your object: 110g
- total cost: 110g * 0.04 cents / gram = $4.40
can I recycle my printed object, and reuse the material as filament?

<30s brainstorming>
recycle and reuse?

yes, thermoplastic **melting and solidifying** is a reversible process, we already saw this here:
filament extruders:

- old crushed plastic parts in
- new filament out
- but: **only works a few times**, filament becomes brittle
is this really helping with sustainability?

<30s brainstorming>
is this really helping with **sustainability**?

**yes,** because you don’t trash the material.

**no,** because it requires energy to be recycled.

\[\text{there’s a whole science to calculating if recycling is worth it}\]
materials for FDM:
• many different thermoplastics
• 3mm or 1.75mm filaments
optical clear material
2012: Printed Optics
Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices

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Figure 1: Custom optical elements are fabricated with 3D printing and embedded in interactive devices, opening up new possibilities for interaction including: unique display surfaces made from 3D printed ‘light pipes’ (a), novel internal illumination techniques (b), custom optical sensors (c), and embedded optoelectronics (d).

ABSTRACT
We present an approach to 3D printing custom optical elements for interactive devices labelled Printed Optics. Printed Optics enable sensing, display, and illumination elements to be directly embedded in the casing or mechanical structure of an interactive device. Using these elements, unique display surfaces, novel illumination techniques, custom optical sensors, and embedded optoelectronic components can be digitally fabricated for rapid, high fidelity, highly customized interactive devices. Printed Optics is part of our long term vision for interactive devices that are 3D printed in their entirety. In this paper we explore the possibilities for this vision afforded by fabrication of custom optical elements using traditional and new 3D printing processes.

INTRODUCTION
3D printing is becoming increasingly capable and affordable. We envision a future world where interactive devices can be printed rather than assembled; a world where a device with active components is created as a single object, rather than a case enclosing circuit boards and individually assembled parts (Figure 2). This capability has tremendous potential for rapid high fidelity prototyping, and eventually for production of customized devices tailored to individual needs and/or specific tasks. With these capabilities we envision it will be possible to design highly functional devices in a digital editor — importing components from a library of interactive elements, positioning and customizing them, then pushing to the 3D printer to fabricate the final device.
Personal Fabrication Research in HCI and Graphics: An Overview of Related Work

Webpage maintained by Stefanie Mueller, and Parinya Punpongsanon, HCI Engineering Group, MIT CSAIL.
For feedback and changes, please email: stefanie.mueller/at/mit.edu

The goal of this website is to provide a resource for newcomers in the field of computational fabrication so that they can quickly access recent contributions made in the field. This webpage serves as a related work directory - the creators of this webpage do not hold the rights for these works, please contact the authors directly.

Personal Fabrication
Patrick Baudisch and Stefanie Mueller.
In this journal paper, we survey the related work in HCI and Computer Graphics over the last five years and provide a roadmap for future research. The question we try to answer is whether the technology will further progress towards consumers, which would allow the technology to scale from hundreds of thousands of users to hundreds of millions of users. Our analysis reveals that a transition to consumers first requires a hardware + software system that embodies the skills and expert knowledge that consumers lack [...]
Direct Ink Writing (DIW)
direct ink writing:

- same as FDM but with cold extrusion
- allows to print pastes (ceramics, food etc.)
- typically uses a syringe and air pressure for extrusion
2011: printed kidney first versions
organovo: company dedicated to printing human organs
**IMPROVED PERFORMANCE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer thickness</td>
<td>50 microns</td>
</tr>
<tr>
<td>Resolution (XYZ)</td>
<td>1 microns</td>
</tr>
<tr>
<td>Printbed temperature</td>
<td>4-60 °C</td>
</tr>
<tr>
<td>Printhead temperature</td>
<td>4-250 °C</td>
</tr>
<tr>
<td>Integrated UV curing</td>
<td>365, 405 nm</td>
</tr>
<tr>
<td>Build volume</td>
<td>130×90×70 mm</td>
</tr>
<tr>
<td>Integrated germicidal UV-C</td>
<td>275 nm</td>
</tr>
</tbody>
</table>

**bio 3D printers:**
really just a ‘Makerbot’ with a syringe + a sterilize build chamber
Laminated Object Manufacturing (LOM)
what do you think these are made of?

<30s brainstorming>
they are made from paper!

how does this work?

<30s brainstorming>
- first sheet is **2D color printed**
- then **glued** onto the build plate
- then **cut** into shape

- second sheet is 2D color printer
- glued onto build plate
- cut into shape

[continue until done]
laminated object manufacturing (LOM)

- **glue** new sheet onto existing stack (e.g. with heater)
- **cut** into shape (e.g. with laser or knife)
- **lower platform** to make space for next layer
- **roll fresh material** into position
2015: printing soft objects
[Layered Fabric Printer, CHI 2015]
Stereolithography (SLA)
• Form2
stereolithography (SLA)

- liquid resin in a tank
- laser selectively hardens top layer of resin
- platform is lowered after each layer
- recoater blade equally distributes resin for new layer
stereolithography (SLA)

- you can also have it in a **flipped** configuration

so where would the laser, mirror, platform etc. go?
where would the material solidify in the tank?

<30s brainstorming>
stereolithography (SLA)

- you can also have it in a flipped configuration
what is a **benefit** of using a laser over an extruder?

<30s brainstorming>
what is a **benefit** of using a laser over an extruder?

- laser is more **precise**!
- but only works with materials that solidify under light
Digital Light Processing (DLP)
digital light processing (DLP)

• same as SLA, just uses a projector not a laser
what are some benefits / drawbacks of using a projector vs laser?
using a projector:

- is **faster** since entire layered is solidified at once
- **resolution** and **surface finish** due to square pixels
how can you make this a mobile 3D printer? (think: handheld)

<30s brainstorming>
2015: mobile 3D printer

[ONO 3D printer, $99]
2015: mobile 3D printer

[ONO 3D printer, $99]
2015: adding speed… 100x faster (7 min to print this, wow)
selective laser sintering (SLS)
selective laser sintering (SLS)

- very similar to SLA
- just with **powder** and not with fluids (resins)

- **laser selectively fuses** powder together
- **platform is lowered** after each layer
- **recoater blade** moves new powder into place
great for **metal, glass, ceramics**
(powder that fuses with high temperatures)
machines are industry only so far.. use a **printing service** such as shapeways...
### Material Test 1.4mm

- **File**: material_test_1.4mm.stl
- **Name**: Material Test 1.4mm
- **Category**: Select Category
- **Size**:
  - Cm: 3.12 x 2.542 y / 2.542 z
  - In: 1.228 x 1.001 y / 1.001 z
- **Part Count**: 1
- **Material Volume**: 3.3308cm³
- **Machine Space**: 21.5390cm³
- **Surface Area**: 86.4196cm²

#### Material Choices

<table>
<thead>
<tr>
<th>Material</th>
<th>View 3D tools</th>
<th>View Issues</th>
<th>Passed</th>
<th>Price (€)</th>
<th>Quantity</th>
<th>Add To Cart</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished Brass (Interlocking)</td>
<td>View 3D tools</td>
<td>X</td>
<td>View Issues</td>
<td>135.02</td>
<td>1</td>
<td>ADD TO CART</td>
</tr>
<tr>
<td>Raw Bronze</td>
<td>View 3D tools</td>
<td>✓</td>
<td>Passed</td>
<td>86.79</td>
<td>64.23</td>
<td>ADD TO CART</td>
</tr>
<tr>
<td>Raw Bronze (Interlocking)</td>
<td>View 3D tools</td>
<td>X</td>
<td>View Issues</td>
<td>135.02</td>
<td>1</td>
<td>ADD TO CART</td>
</tr>
<tr>
<td>Polished Bronze</td>
<td>View 3D tools</td>
<td>✓</td>
<td>Passed</td>
<td>135.02</td>
<td>81.13</td>
<td>ADD TO CART</td>
</tr>
<tr>
<td>Polished Bronze (Interlocking)</td>
<td>View 3D tools</td>
<td>X</td>
<td>View Issues</td>
<td>135.02</td>
<td>1</td>
<td>ADD TO CART</td>
</tr>
<tr>
<td>14K Gold</td>
<td>View 3D tools</td>
<td>✓</td>
<td>Passed</td>
<td>1,895.80</td>
<td>2,078.70</td>
<td>ADD TO CART</td>
</tr>
</tbody>
</table>

**Total Price**: €1,895.80
**Subtotal**: €2,078.70
Introducing two metal 3D printing systems for the full product life cycle – from prototyping to mass production.

desktop ready
binder jetting (BJ)
(powder-bed printing, inkjet-head 3D printing)
binder jetting (BJ)

- uses 2D inkjet heads to deposit inks onto powder
- the inks act as **binder that fuses the powder**

- **platform is lowered** after each layer
- **rocoater blade** moves new powder into place
- similar to SLS but inkjetting not laser
binder jetting (BJ)

- full color spectrum possible (it’s just 2D printing on powder)
material jetting (Polyjet 3D Printing)
material jetting (polyjet 3D printing)

- similar to plastic extrusion but with inkjet heads
- **inkjet heads deposit droplets** of fluid onto platform
- material either **cures** on its own or with UV light
- **platform is lowered** for next layer
Abstract

We have developed a multi-material 3D printing platform that is high-resolution, low-cost, and extensible. The key part of our platform is an integrated machine vision system. This system allows for self-calibration of printheads, 3D scanning, and a closed-feedback loop to enable print corrections. The integration of machine vision with 3D printing simplifies the overall platform design and enables new applications such as 3D printing over auxiliary parts. Furthermore, our platform dramatically expands the range of parts that can be 3D printed by simultaneously supporting up to 10 different materials. 2015: polyjet + camera tracking for precision
ColorFab: Recoloring 3D Printed Objects using Photochromic Inks

SUBMISSION ID: 2335

ABSTRACT
We present ColorFab, a method for changing the color of a 3D-printed object even after fabrication. ColorFab works based on photochromic inks that can switch their appearance from transparent to colored when exposed to light of a certain wavelength. The color remains even when the object is removed from the light source. The process is fully reversible allowing users to recolor the object as many times as they want.

To switch between different colors (e.g. red to yellow), we use a multi-color pattern with one color per voxel across the surface of the object. When recoloring the object, our system locally turns on only those voxels with the desired color and turns all other voxels off.

We describe ColorFab’s projector-camera setup and the user interface that comes with a conversion tool for 3D-printing as well as a painting interface that matches physical voxels with the desired appearance. We also contribute our own material formula for a 3D-printable photochromic ink.

Author Keywords
Personal fabrication; multi-color 3D printing.

ACM Classification Keywords
H.5.2. [Information interfaces and presentation]: User Interfaces, Input devices and strategies.

INTRODUCTION
With recent advances in 3D printing, objects can now be fabricated in a fraction of the time it used to take to create the same object in a factory. One of the limitations in the rapid advances in the field is that objects tend to be monochromatic, i.e. they are usually of one color. This is because most 3D printers fabricate objects in layers of one material. ColorFab is a method that allows users to recolor objects even after fabrication. (a) To accomplish this, ColorFab uses 3D printing of photochromic dyes in a dense multi-color pattern. (b) When users apply a specific color texture using ColorFab’s user interface, only the voxels with the matching color are turned on. (c) The same object re-colored.

2017: research from my group, under submission
photochromic materials are typically activated by a UV light

2017: research from my group, under submission
2017: research from my group, under submission
support material
how does the support material for each of these work? how do you get it off?

<30s brainstorming>

fused deposition modeling (FDM)

digital light processing (DLP)

laminated object manufacturing (LOM)

selective laser sintering (SLS)

stereolithography (SLA)

binder jetting (BJ)

material jetting (polyjet)
FDM, Polyjet:

- break it off or use special acid bath for dissolving
BJ, SLS (anything powder)

- dig out from powder
LOM

- dig out from stack of sheets
DLP, SLA:
- take it out from the liquid bath
summary
most common processes

https://www.3dhubs.com/trends
Local 3D printing. Browse 30 3D printing services near Cambridge, United States.

1. **Upload your parts**

   ![View in 3D]
   **3dbenchy__multi-part__complete_17_shells__3dbenchy.com.stl**
   60.0 × 31.0 × 48.0 mm
   Change units
   Printability: ▲ FDM - Review ▲ SLA - Review ▲ SLS - Review
   Quantity: 1

2. **Select a material**

   Search materials: e.g. SLS, Accura 25 or Polyjet
   or
   Get a recommendation

**Popular materials**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Method</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prototyping Plastic</td>
<td>FDM</td>
<td>Fast and affordable parts</td>
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<tr>
<td>High Detail Resin</td>
<td>SLA</td>
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<tr>
<td>SLS Nylon</td>
<td>SLS</td>
<td>Strong and functional parts</td>
</tr>
</tbody>
</table>

- **Prototyping Plastic**
  - Dimensional accuracy: ±1% (lower limit: ~0.5mm)
  - Minimum feature detail: 1mm
  - Supports required: Yes

- **High Detail Resin**
  - Dimensional accuracy: ±0.5% (lower limit: ~0.15mm)
  - Minimum feature detail: ~0.5mm
  - Supports required: Yes

- **SLS Nylon**
  - Dimensional accuracy: ±0.3% (lower limit: ~0.3mm)
  - Minimum feature detail: ~0.8mm
  - Supports required: No
HW4 until next Wednesday:
team partner and project website

—> just the name of your team members + the template website
(do not upload project ideas yet)
if you do not yet have team partner, 
**come to the front and we match you up!**

let’s take a 5 min break
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end.