I only lectured until slide 153.

slides 153 - 170 are not part of the exam.
<hands up>

- a milling machine
- a laser cutter
- a 3D printer

how many of you have used:
Why talk about fabrication in an EECS program?
computing with digital information…

(aka: physical matter)

physical information…

computing with physical information…

next 10-50 years:

computing with digital information…

today:
Infor 2013, Tangible Media Group
this is actual reality! — physical

nope this is not augmented reality!
but 3D printing is slow... right?

14 hours

printing time
What if it was real-time?

Moore’s law for 3D printing?

new process: 100x faster
recent evolution:
desktop 3D printing & personal fabrication
30 sec brainstorming

Is everyone going to have a 3D printer at home?
There is no reason anyone would want a computer in their home.

Ken Olsen, 1977

founder of Digital Equipment Corporation

I think there is a world market for maybe five computers.

Thomas Watson, 1943

president of IBM
More than 278,000 desktop (under $5,000) 3D printers were sold worldwide last year.
3D Hubs: airbnb, lyft... for 3D printers

https://maps.3dhubs.com/
If personal fabrication follows the same trajectory as personal computing, how would our future look like?

30 sec brainstorming
Immediate feedback after input next morning
next morning
feedback

after
input
feedback

immediate
feedback

???

????
command line for physical matter
command line for physical matter

Mueller 2012
command line for physical matter

polyline
Abstract

Interactive Fabrication of Functional Mechanical Devices

Interactive Construction:

...
direct manipulation

Mueller 2017
mobile computing $\rightarrow$ mobile fabrication

[Roumen 2016]
Information transfer $\rightarrow$ Matter transfer [Mueller 2015]
Information transfer $\rightarrow$ matter transfer

Mueller 2015
is this how we will transfer objects in the future?
research:

speculating about the future.

then see who was right/wrong.

20 years later.
laser cutting
laser cutter
how can I laser cut something?
create a 2D vector drawing
define power, speed of laser (different for each material)
define power, speed of laser
Hit cut button

Laser cutter control panel:
If you haven’t used it, try it some time in: ‘Engineering Design Studio’ (EDS) (right next to our lab section space)
laser cut your own business card:::
Which materials to use?
• paper
• cardboard
• wood
• acrylic

most common materials:
food...

unconventional materials...
never cut materials that are flammable

• create toxic fumes
• that are flammable

If you are not sure, ask the shop manager!
where to buy materials?
Boston, MA 02127
116 B St
Altec Plastics

15 min on redline:
Buy materials here in Boston
Paper: $(10-20 per sheet)
Cardboard: $(10-20 per sheet)
Wood: depending on thickness
Acrylic: cheap

Low-fi prototyping costs:
Paper: 
Cardboard: 
Wood: 
Acrylic: cheap
how does a laser cutter work under the hood?
focused!

defocused
/too little power for cutting

distance of sheet to lens is important (focal length of lens)
some features...
how it works:

• use grayscale image

  darker areas get more deeply engraved

  relief effect

• how it works:
can we laser engrave 3D reliefs?
can we laser engrave 3D reliefs?

no, they are made with a different machine.

1. two lasers aim at the same spot.
2. where they interfere, the power is high enough to break the glass & create a 'dot'.

laser 1
laser 2
connecting 2D parts
<30 second brainstorming>

Will this fit?
no, it will not fit.

It will be very loose.

Material evaporates during cutting.

Make the joint larger than the gap.
http://boxdesigner.connectionlab.org/
replace 3D print with laser cut 2D plates:

living hinges::
To bend acrylic, use a heatgun or strip heater.
stacking:

connector

clamp

connector

stacking:
intersecting::

wood

::
surface folding::
gears & linkages:
what laser cutters exist?
industrial laser cutter

$20k - 50k
consumer laser cutters (e.g., GlowForge) $3,000 (e.g., GlowForge)
hacker laser cutters < $1,000
water pump under the desk!
MicroSlice is a low-power laser that cuts paper and makes light engravings. It is an Arduino-based device with a cost of about $200.
coding for laser cutters
LAOS board
(open source controller board)
Creating Value by Destroying Valuable Physical Objects
Gcode is the most widely used programming language for controlling industrial machines such as mills, lathes and cutters as well as 3D-printers. It is used in the field of industrial programming for controlling industrial machines. The code G1 X0 Y0 Z3 F500 indicates a move command with focus on speed and move coordinates. The code can be found in the article: https://www.norwegiancreations.com/2015/08/an-intro-to-g-code-and-how-to-generate-it-using-inkscape/
advanced tricks for laser cutting
focused laser

defocused laser

Mueller, Kruck, Baudisch, LaserOrigami CHI 2013
Mueller, Kruck, Baudisch, LaserOrigami CHI 2013

Our idea: bending

Laser cutting:
[Mueller LaserOrigami CHI 2013]
Figure 1: LaserOrigami: Rapid Prototyping Laser Cutting, Interfacing by Laser and Paper

Step-by-step process in which laser interaction and origami anatomy transform a simple interactive origami version of LaserOrigami into a tangible piece of physical objects. Finally, we demonstrate how to use them in a simple integrated process by automatically moving the single integrated process of laser cutting and bending into a single integrated process by automatic cutting and bending in a surface LaserOrigami implements cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single 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cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and bending in a single integrated process by automatic cutting and b
LaserStacker

locally welding
multiple sheets
together

UIST 2015
Seufert, Wall, Baudisch,
Umepathi, Chen, Mueller,
Laserstacker: Fabricating 3D Objects by Laser Cutting and Welding

Hasso Plattner Institute, Potsdam, Germany
Udyan Umapathi, Hsing-Ting Chen, Stefan Müller, Ludwige Wall
lens array: locally melting with defocused laser
haptic features, e.g. a mini keyboard

[Mike Sinclair]
haven't 3D printed yet?
3D print your own keychain:
e.g. download a model from Thingiverse
let's talk about the underlying tech...
3D Hubs: airbnb, lyft... for 3D printers

https://maps.3dhubs.com/
most common machines
Learn today what this all means...

Fused Deposition Modeling (FDM)
Local 3D Printing. Browse 3D Printing services near Cambridge, United States.
how can I 3D print something?
take your 3D model & export as .stl format

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

https://www.thingiverse.com/thing:763622

Infill artifacts against shell
Send design to 3D printer

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

https://www.thingiverse.com/thing:763622
different print quality...
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

- MakerBot ($2,500)
- PrintrBot ($300)
- Ultimaker ($3,500)
• plastic filament on spools
• pushed through a hot extruder nozzle
• fused deposition modeling (FDM)
  platform
how do I find out how much my printed object costs?
• 1kg plastic spool: $40

Example:

- Weigh your object: 110g
- So 1g costs: $40 / 1000g = 0.04 cents
- 110g costs: 110g * 0.04 cents / gram = $4.40
- Total cost: $4.40

Weigh your object: 10g
- 10g plastic spool: $40
many different thermoplastics for FDM:
optical clear material
Introduction

In this paper we explore the possibilities for this vision for interactive devices that are printed in their entirety and embedded in interactive surfaces. Novel "optical tattoos" combine printed optics, QoE-optimised display, and embedded projection components to create interactive devices. Unlike current flat displays, interactive tattoo displays can be designed, prototyped, and embedded in interactive surfaces. These displays are capable of being directly embedded in the casing of interactive devices, opening up new possibilities for interaction design.

Abstract

Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices
Furthermore, shape deformation and extra weights are also utilized to optimize the shape for design goals. "...

Further advances in fabrication technology have led to new opportunities for manufacturing customized objects with a wide range of properties and capabilities. These advances enable the creation of complex and highly functional structures. The goal of our research is to explore these novel fabrication techniques and their implications for the design of everyday objects. In this paper, we present our findings and discuss their potential applications.

Personal Fabrication

We believe that the rapid development of fabrication technologies enables designers and engineers to create new products and services more efficiently. The goal of this work is to provide a detailed analysis of the recent advances in the field of personalized fabrication and demonstrate how they can be used to create custom products.

For feedback and inquiries, please email: [email: csail.mit.edu/fabpub]
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 & air pressure

• same as FDM but with cold extrusion
• allows to print pastes (ceramics, food etc.)
• typically uses a syringe & air pressure
2011: printed kidney first versions
organovo: company dedicated to printing human organs
bio 3D printers: really just a 'Makerbot' with a syringe + a sterilize build chamber
Laminated Object Manufacturing (LOM)
30s brainstorming

What do you think these are made of?
how does this work?

how are they made from paper?
repeat:

• then cut into shape

• glued onto the build plate

• sheet is 2D color printed

continue until done
Laminated Object Manufacturing (LOM)

1. Roll fresh material into position
2. Lower platform to make space for next layer
3. Cut into shape (e.g., with laser or knife)
4. Glue sheet onto existing stack (e.g., with heater)

Glue sheet onto existing stack (e.g., with heater)
2015: printing soft objects

[Layered Fabric Printer, CHI 2015]
Layered Fabric Printer, CHI 2015
Stereolithography (SLA)
e.g. Form2

3D printer
Stereolithography (SLA)

- Laser selectively hardens top layer of resin
- Platform is lowered after each layer
- Recoater blade distributes resin for new layer
- Liquid resin in a tank
What is a benefit of using a laser over an extruder?
What is a benefit of using a laser over an extruder?

- Laser is more precise!
- But only works with materials that solidify under light
and not a laser and not a laser and not a laser, just uses a projector. Same as SLA, just uses a projector.
What are some benefits / drawbacks of using a projector vs laser?
using a projector:

- Faster since entire layer is solidified at once
- Square pixels
- Resolution and surface finish suffer due to square pixels
<30s brainstorming>

(Think: handheld)

How can you make this a mobile 3D printer?
2015: mobile 3D printer

[ONO 3D printer, $99]
ONO 3D printer, $99

2015: Mobile 3D Printer
Almost the same process as used in Carbon3D
selective laser sintering (SLS)
Selective laser sintering (SLS) is a process very similar to SLA, but just with powder and not with fluids (resins). It uses a laser to selectively fuse powder together after each layer is lowered, moving new powder into place. The recoater blade moves new powder into place. Just with powder and not with fluids (resins). Very similar to SLA.
(temperatures with high powder that fuses glass, ceramics great for metal,
Machines are industry only so far... use a printing service such as Shapeways...
<table>
<thead>
<tr>
<th>Material Test 1.4mm</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>E2.0278.70</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>E1.895.80</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>E1.356.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>E6.23</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>E8.79</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
This Cambridge-based company tries to make metal desktop-ready from prototyping to mass production.

Introducing two metal 3D printing systems for the full product life cycle –
binder jetting (BJ)
(powder-bed printing, inkjet-head 3D printing)
• uses 2D inkjet heads
• heads deposit inks onto powder
• the inks act as binder that fuses the powder

binder jetting (BJ)

• platform is lowered after each layer
• rocoater blade moves new powder into place
• similar to SLS but inkjetting not laser
• full color spectrum possible
• it’s just 2D printing onto powder
material jetting (PolyJet 3D printing)
• similar to plastic extrusion but with inkjet heads
• inkjet heads deposit droplets of fluid onto platform
• Platform is lowered for next layer
• Material cures (on its own, UV light, thermally)
• Similar to plastic extrusion but with inkjet heads (polyjet 3D printing)
Abstract

We present ColorFab, a method for changing the color of a 3D-printed object. ColorFab works based on photochromic inks that can switch their appearance when exposed to light of a certain wavelength. The color remains even when the object is moved from a transparent to a colored condition. The process is fully reversible, allowing users to recolor the object as many times as they want. We describe ColorFab’s projector-camera setup and the user interface that comes with a conversion tool for 3D-printing.

We also contribute a printable photochromic ink, our own material formula for a 3D-printable photochromatic ink that allows for the desired appearance. We also contribute an ink that allows us to print in two ways as well as a printing interface that makes physical user interface that comes with a conversion tool for 3D-printing.

We describe ColorFab’s projector-camera setup and the user interface that comes with a conversion tool for 3D-printing. We also contribute a printable photochromic ink, our own material formula for a 3D-printable photochromatic ink that allows for the desired appearance. We also contribute a project-based approach to photochromic inks that can switch their appearance when exposed to light of a certain wavelength. The color remains even when the object is moved from a transparent to a colored condition. The process is fully reversible, allowing users to recolor the object as many times as they want. We describe ColorFab’s projector-camera setup and the user interface that comes with a conversion tool for 3D-printing.
Photochromatic materials are typically activated by UV light.
summary 3D printing
most common processes

Fused Deposition Modeling (FDM)

https://www.3dhubs.com/trends
<table>
<thead>
<tr>
<th>Material</th>
<th>Supports Required</th>
<th>Dimensions Required</th>
<th>Minimum Feature Detail</th>
<th>Dimensional Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLS Nylon</td>
<td>No</td>
<td>~0.8mm</td>
<td>~0.5% (lower limit ~0.3mm)</td>
<td>0.5% (lower limit ~0.5mm)</td>
</tr>
<tr>
<td>SLA Resin</td>
<td>Yes</td>
<td>~0.5mm</td>
<td>~1% (lower limit ~0.5mm)</td>
<td>0.5% (lower limit ~0.5mm)</td>
</tr>
<tr>
<td>FDM Plastic</td>
<td>Yes</td>
<td>~1.0mm</td>
<td>~2% (lower limit ~1.0mm)</td>
<td>1% (lower limit ~1.0mm)</td>
</tr>
</tbody>
</table>

Popular materials:
- SLS Nylon
- SLA Resin
- FDM Plastic

Select a material:
- SLS Nylon - ~0.8mm - ~0.5% (lower limit ~0.3mm)
- SLA Resin - ~0.5mm - ~1% (lower limit ~0.5mm)
- FDM Plastic - ~1.0mm - ~2% (lower limit ~1.0mm)

Upload your parts:
- How it works:

Local 3D Printing: Browse 3D Printing services near Cambridge, United States.
is everyone going to have a 3D printer at home?

maybe... maybe not.

What's your best guess for the future?
More than 278,000 desktop (under $5,000) 3D printers were sold worldwide last year.

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

https://maps.3dhubs.com/
new process: 100x faster

Moore’s law for 3D printing? What if it was real-time?
computing with digital information...

(aka: physical matter)

Physical Information

Computing with physical information...

next 10-50 years:

today:

Computing with digital information...