University of Southern California

ECE 105: Introduction to Electrical Engineering

Lecture 1

Introduction to EE, and ECE 105

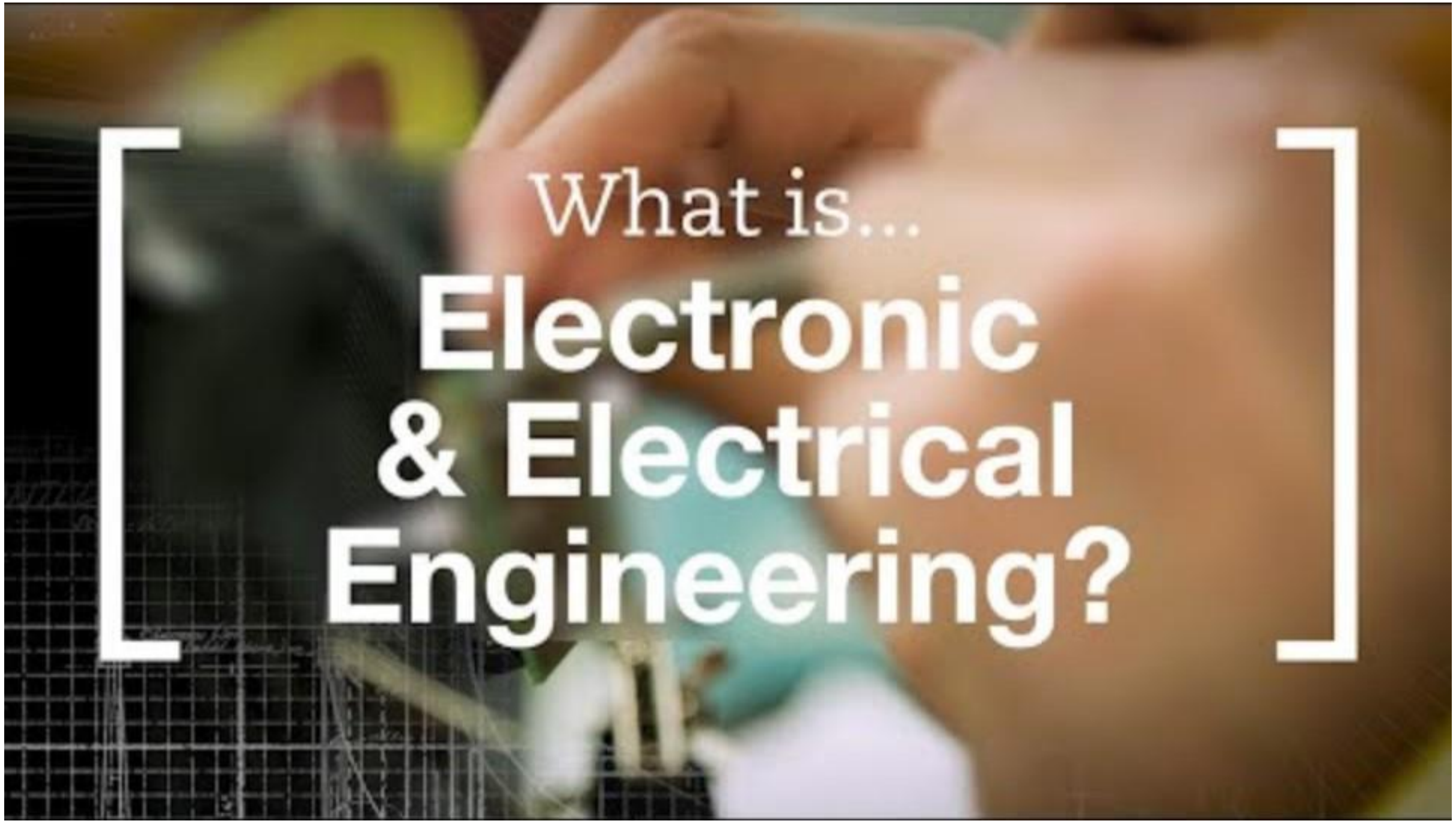
Yasser Khan

Rehan Kapadia

What is Electrical Engineering?

USC University of Southern California

- Electrical Engineering is an engineering discipline concerned with the study, design, and application of equipment, devices, and systems which use electricity, electronics, and electromagnetism.

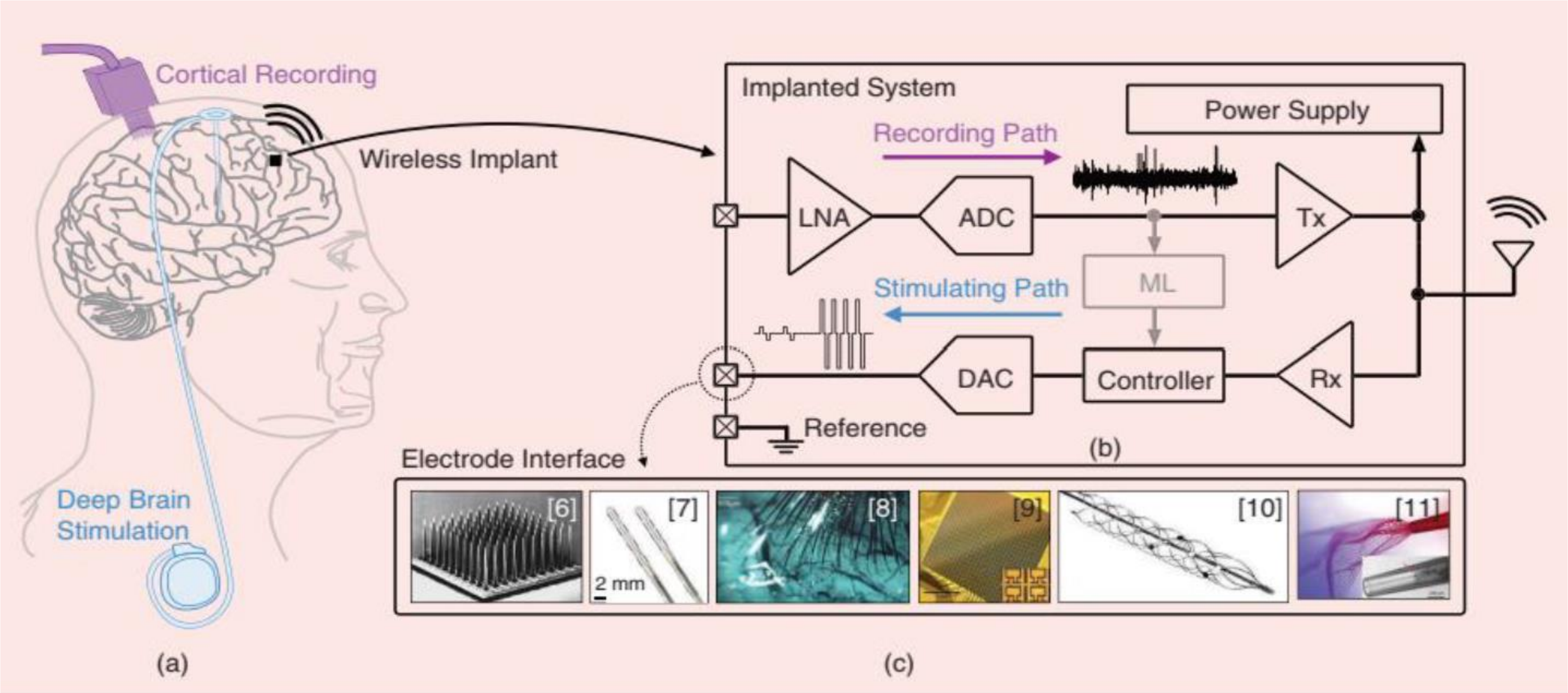


Let's look at EE at play: 3 little pigs demo by Neuralink

Neuralink – the neural implant

- Every step of the neural implant design and fabrication requires electrical engineering

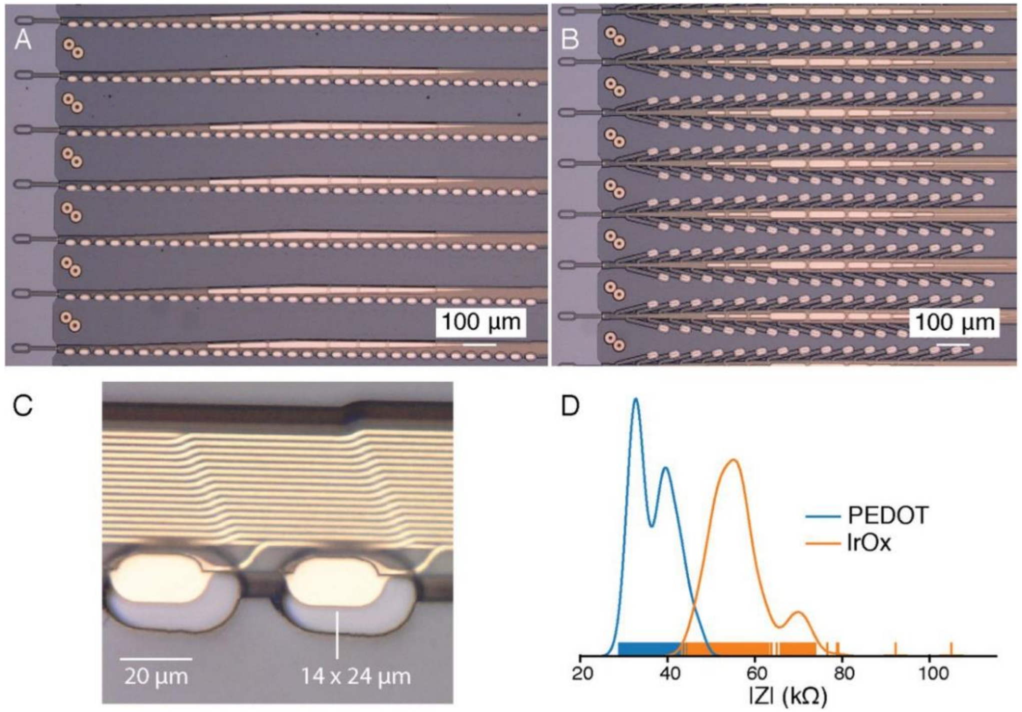
Neural interfaces – under the hood

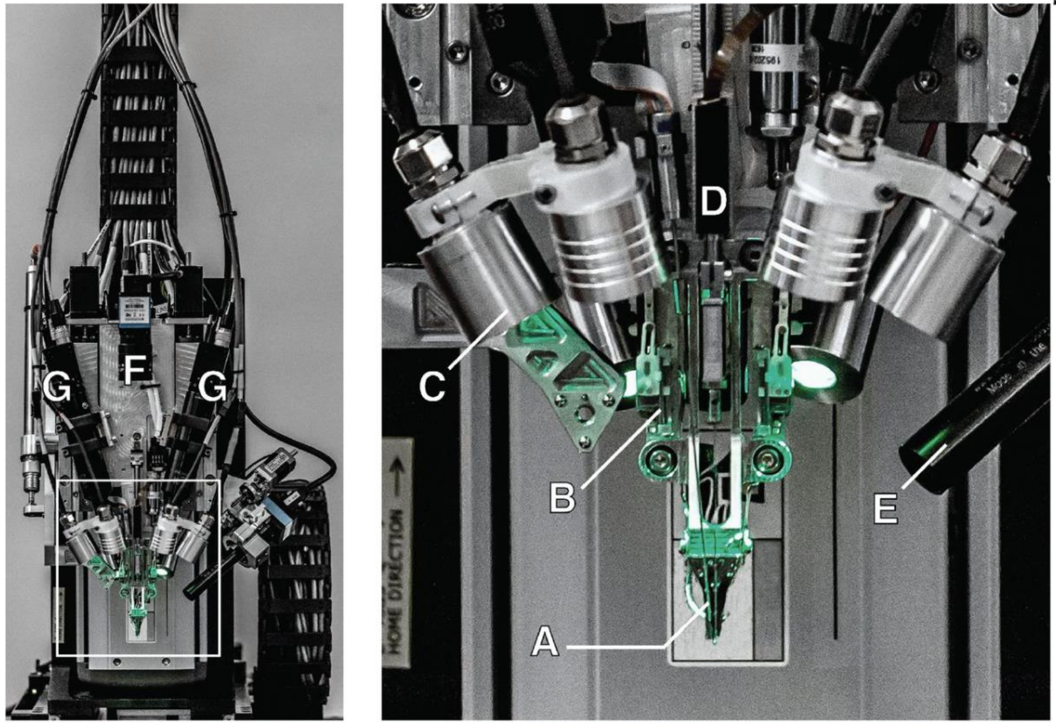


(a) Two clinical neural interfaces: a percutaneous neural recording implant similar to [1], and a deep brain stimulator. (b) Components for an implantable bidirectional (black) or closed-loop (black and gray) wireless neural interface. (c) Example neural interface electrodes. [From left to right (adapted from Utah microelectrode array [6], SENSIGHT by Medtronic [7], ultrathin polymer threads by Neuralink [8], high-density neural matrix [9], Stentrode by Synchron [10], and ultraflexible syringe-injectable mesh [11]).] LNA: low-noise amplifier; ADC: analog-to-digital converter; Tx: transmitter; ML: machine learning; DAC: digital-to-analog converter; Rx: receiver.

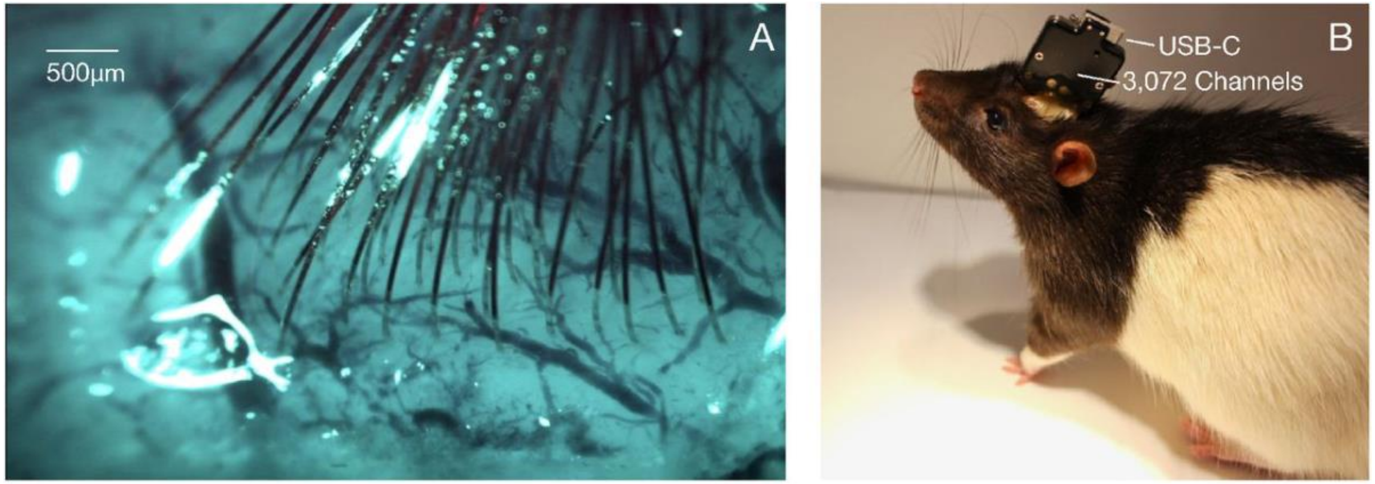
Link v0.9

Surgical robots need robotics, **electrical engineering**, mechanical engineering, control engineering



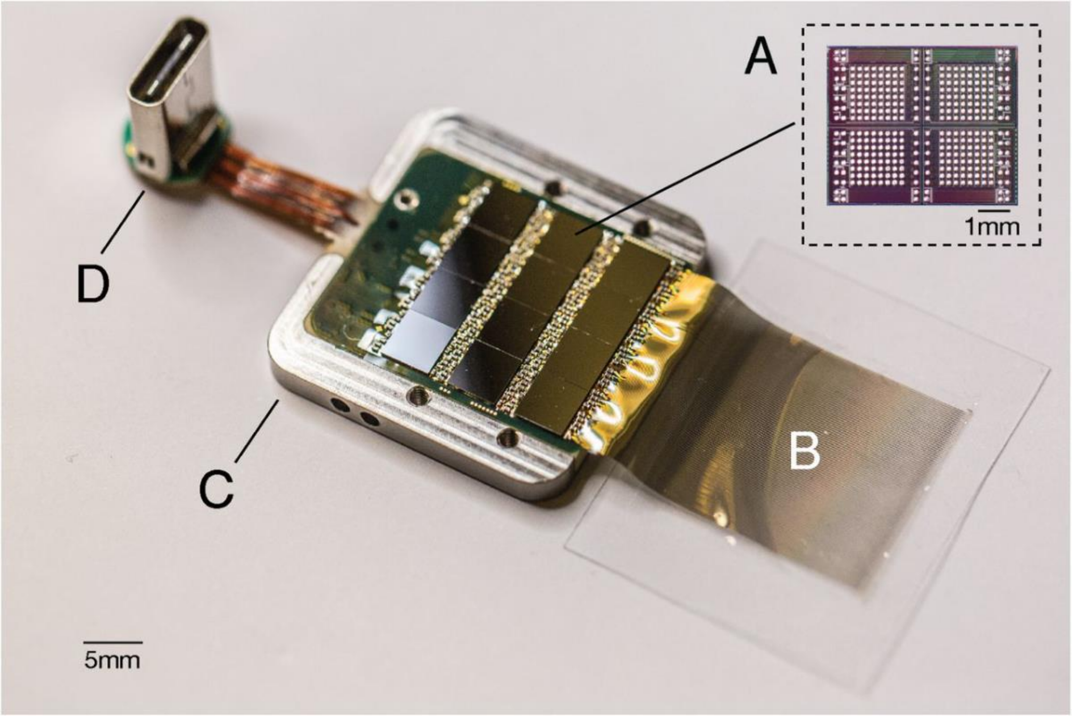


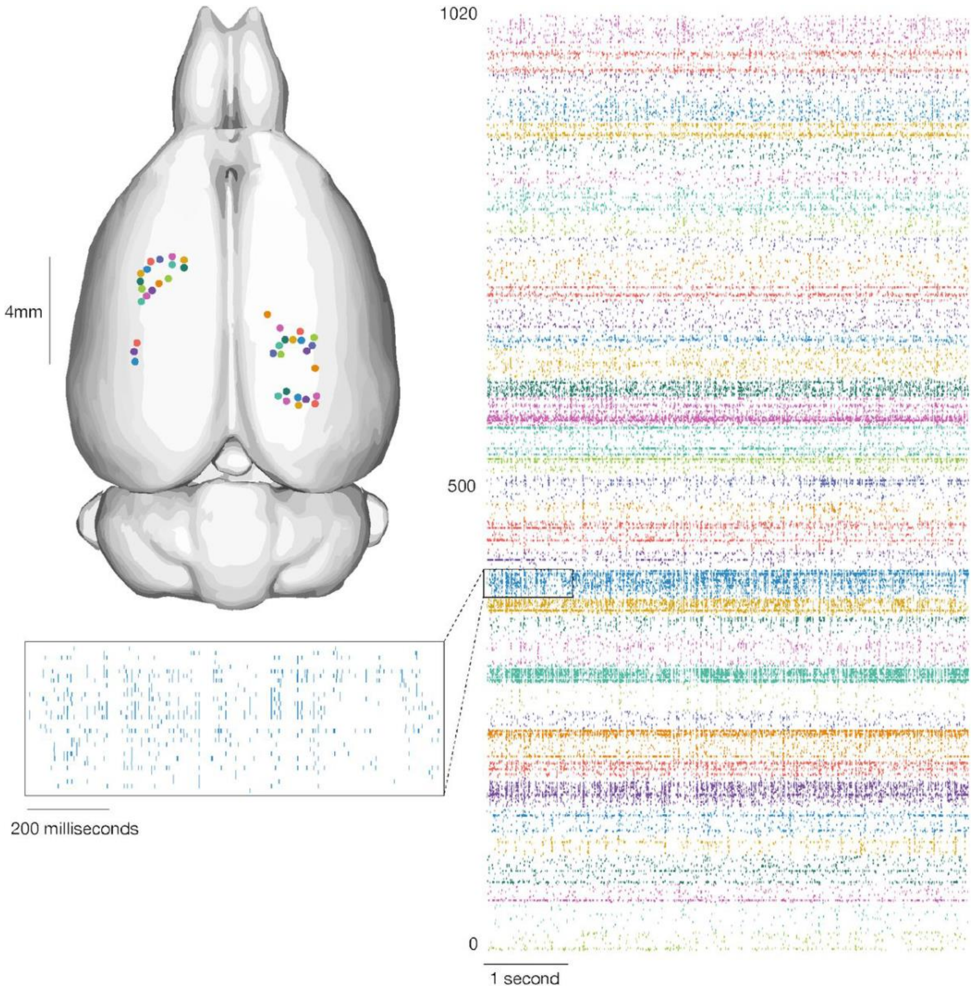
Sensors need **electrical engineering**, mechanical engineering, materials science, chemical engineering



Implants need **electrical engineering**, computer science

Brain recording from 1024 analog pixels



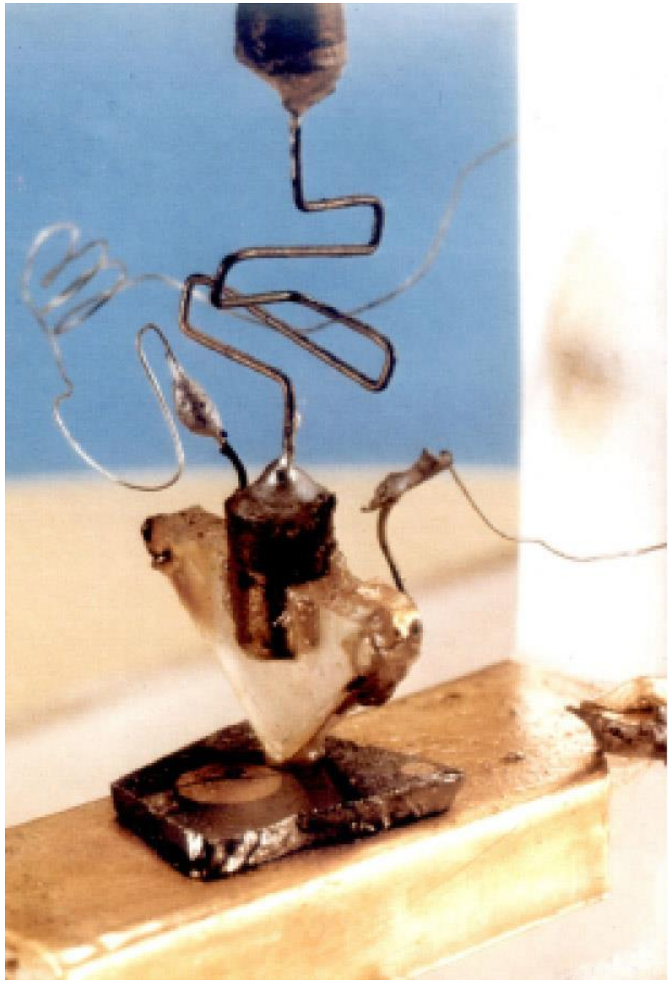


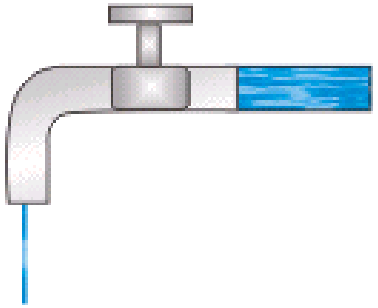
- Each neural recording unit requires sensors, integrated circuits, communications, and power

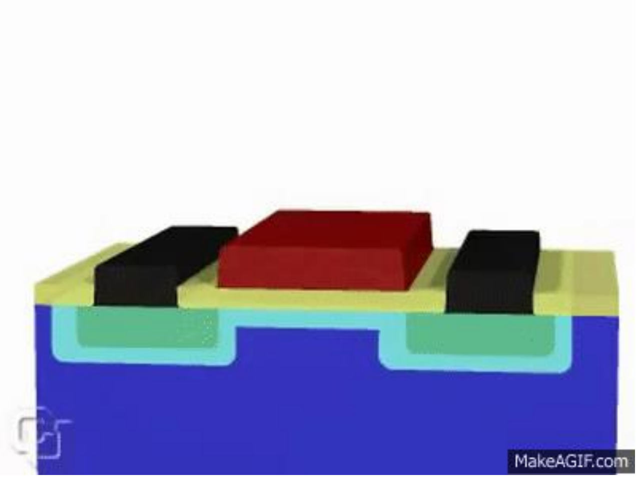
What is currently driving computing?

How do we carry out so much computing?

USC
University of
Southern California







We use transistors!

1956 Physics Nobel Prize

"for their researches on semiconductors and their discovery of the transistor effect"

William Bradford Shockley

1/3 of the prize

USA

Semiconductor Laboratory of Beckman Instruments, Inc.
Mountain View, CA, USA

John Bardeen

1/3 of the prize

USA

University of Illinois
Urbana, IL, USA

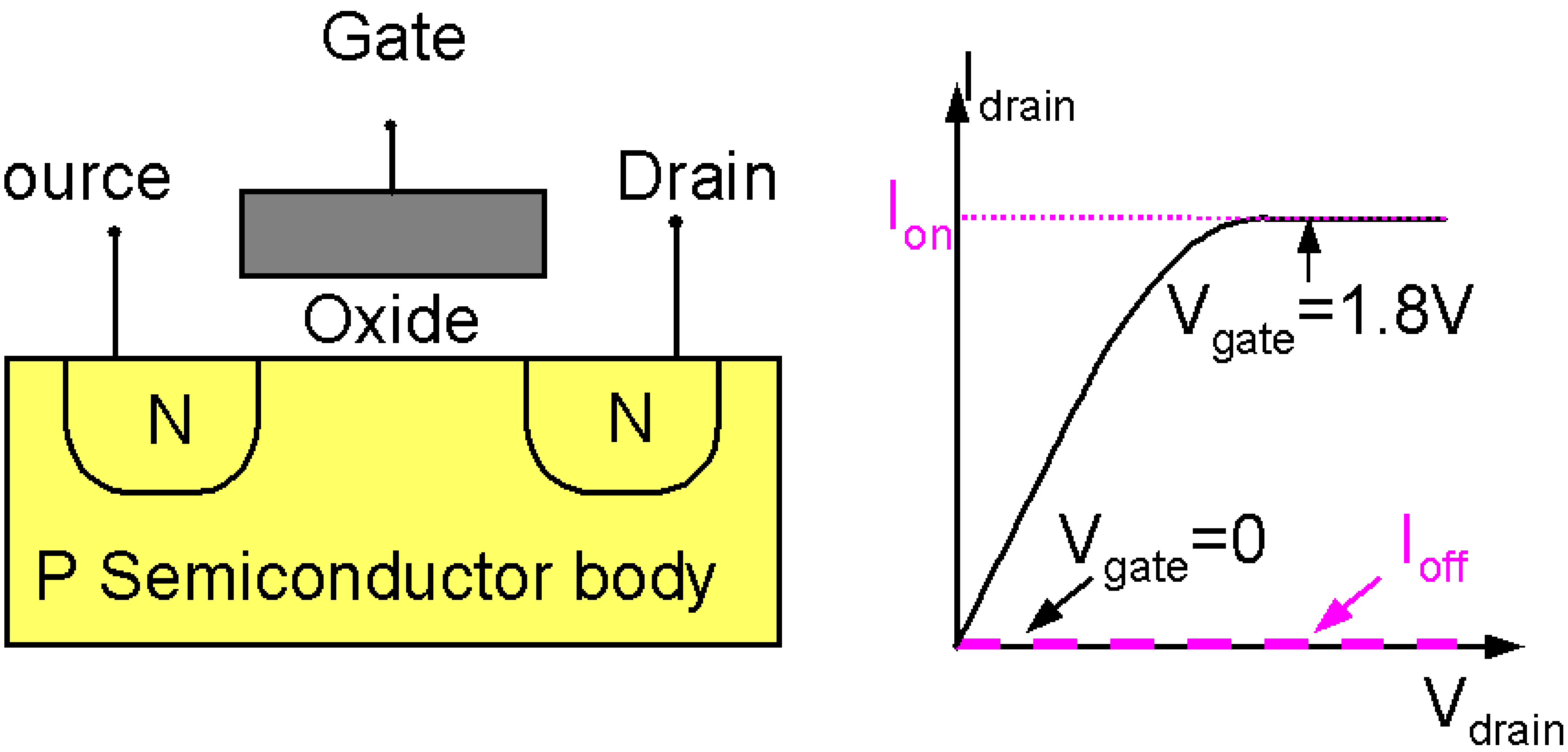
Walter Houser Brattain

1/3 of the prize

USA

Bell Telephone Laboratories
Murray Hill, NJ, USA

What is a transistor?



What is desirable: large I_{on}, small I_{off}

What is a transistor?

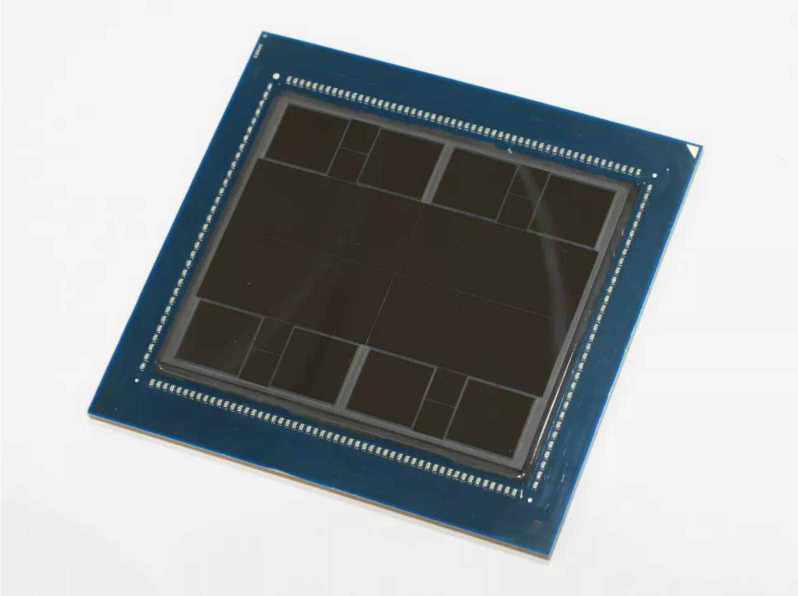
1. It acts as an on-off switch.

2. We want to switch it on and off as fast as possible.

3. We want to switch it on and off with as little power usage as possible.

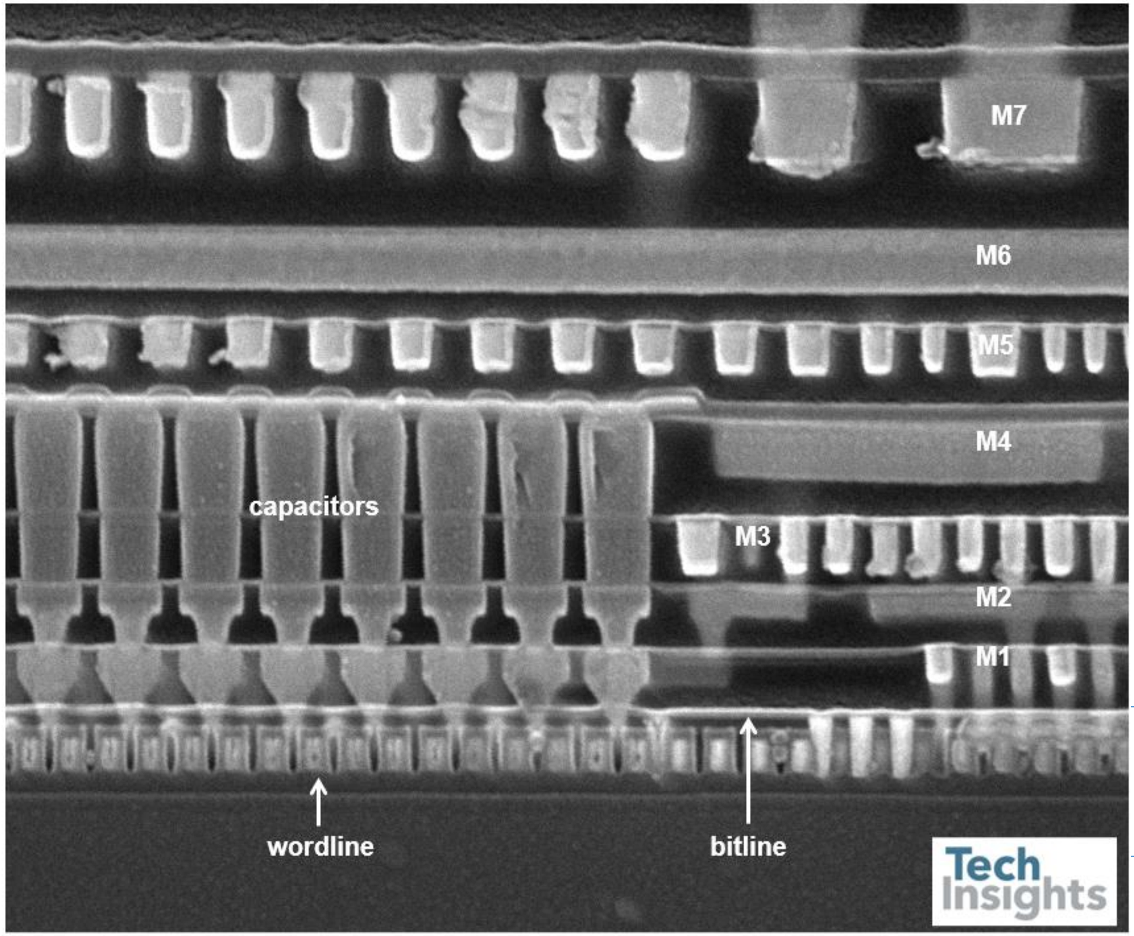
What do modern day integrated circuits look like?

AMD Instinct MI300 Accelerator



- Key points
  - Total of ~150 billion transistors
  - Uses 5 nm node technology
    - Density of transistors is ~130-230 million transistors/mm^2
    - In the area of a cell , we could fit ~100k - 1 million transistors
  - Multiple parts of this processor use 3-D stacked dies
    - Enables computing, memory, sensing, and stimulation to be integrated together
  - Performance ~8x improved over previous MI250 Accelerator
    - If they upgraded the fastest supercomputer to this part, they could train the largest AI/ML systems

What do these look like?

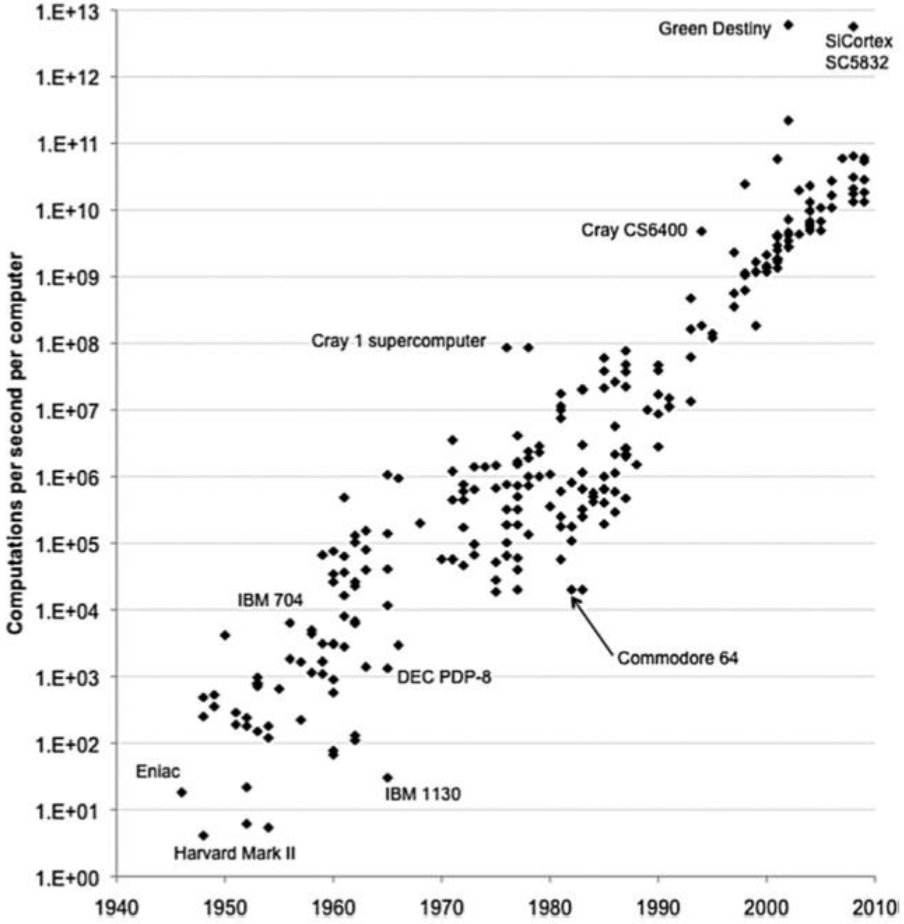


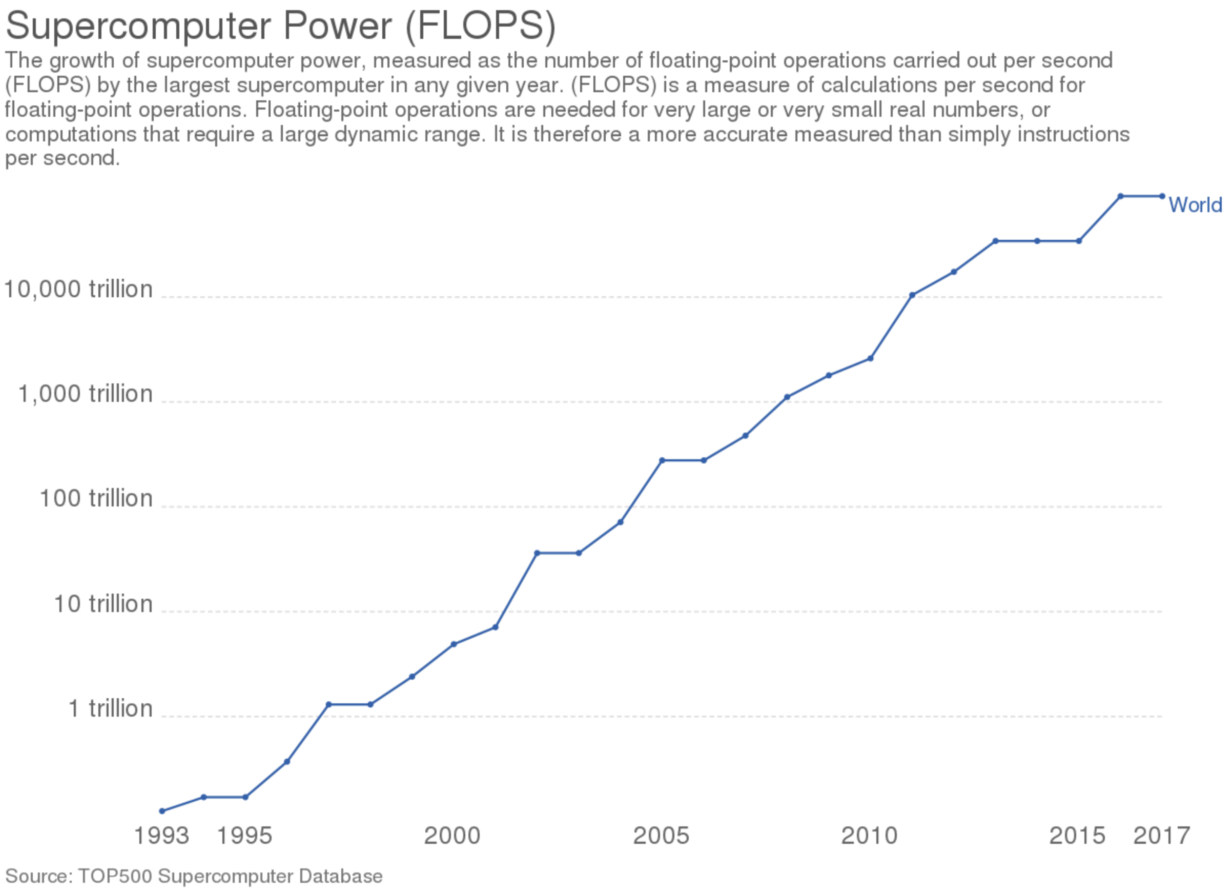
Wires to connect all the transistors together

Active devices (silicon transistors)

How did we get here?

How much has computing power increased?





- From 1990 to today, the worlds largest super computers have increased computing power by 100,000x
  - That's a lot!

By Our World In Data - https://ourworldindata.org/grapher/supercomputer-power-flops

The First Moon Landing Was Achieved With Less Computing Power Than a Cell Phone or a Calculator

On board Apollo 11 was a computer called the Apollo Guidance Computer. It had 2,048 words of memory that could be used to store "temporary results"—data that is lost when there is no power. This type of memory is referred to as RAM (random access memory). Each word comprised 16 binary digits (bits), with a bit being a zero or a one. This means that the Apollo computer had **32,768 bits of RAM memory**.

My computer has 64,000,000,000 bits of RAM memory

That is 2,000,000 times more than what was needed in Apollo 11.

How do we make transistors faster?

Scaling – How much have we scaled devices?

USC University of Southern California

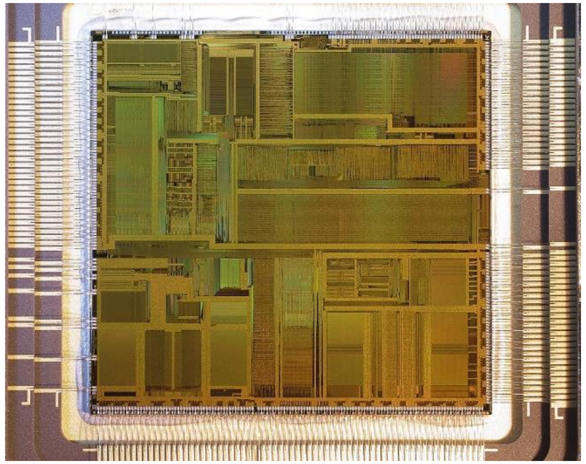
- 1971: The first commercial microprocessor…Intel 4004
  - 4-bits
  - Less than 1 square inch in area
  - Transistors that were 10 micrometers long
  - ~750 kilohertz speed
  - …but more powerful than the computers from earlier that weighed 30 tons

Let’s say that this is a scaled version of how long a transistor was in 1971

Scaling – How much have we scaled devices?

USC University of Southern California

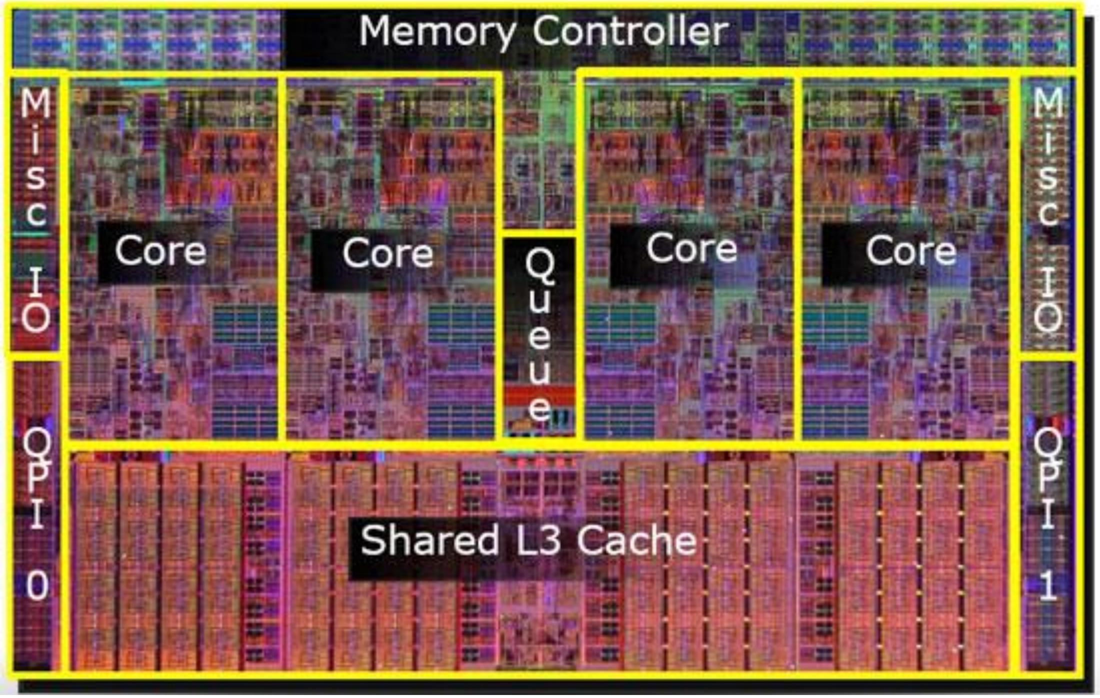
- 1990s: The first Pentium processor
- 66 MHz. That's 100 times faster than in 1970.
  - Can you think of anything else that has improved by 100x in 20 years?



Scaling – How much have we scaled devices?

USC University of Southern California

- 2012:
  - 1-3 GhZ
  - Multi-core
  - Super-fast
  - Each transistor is almost 1000 times smaller!

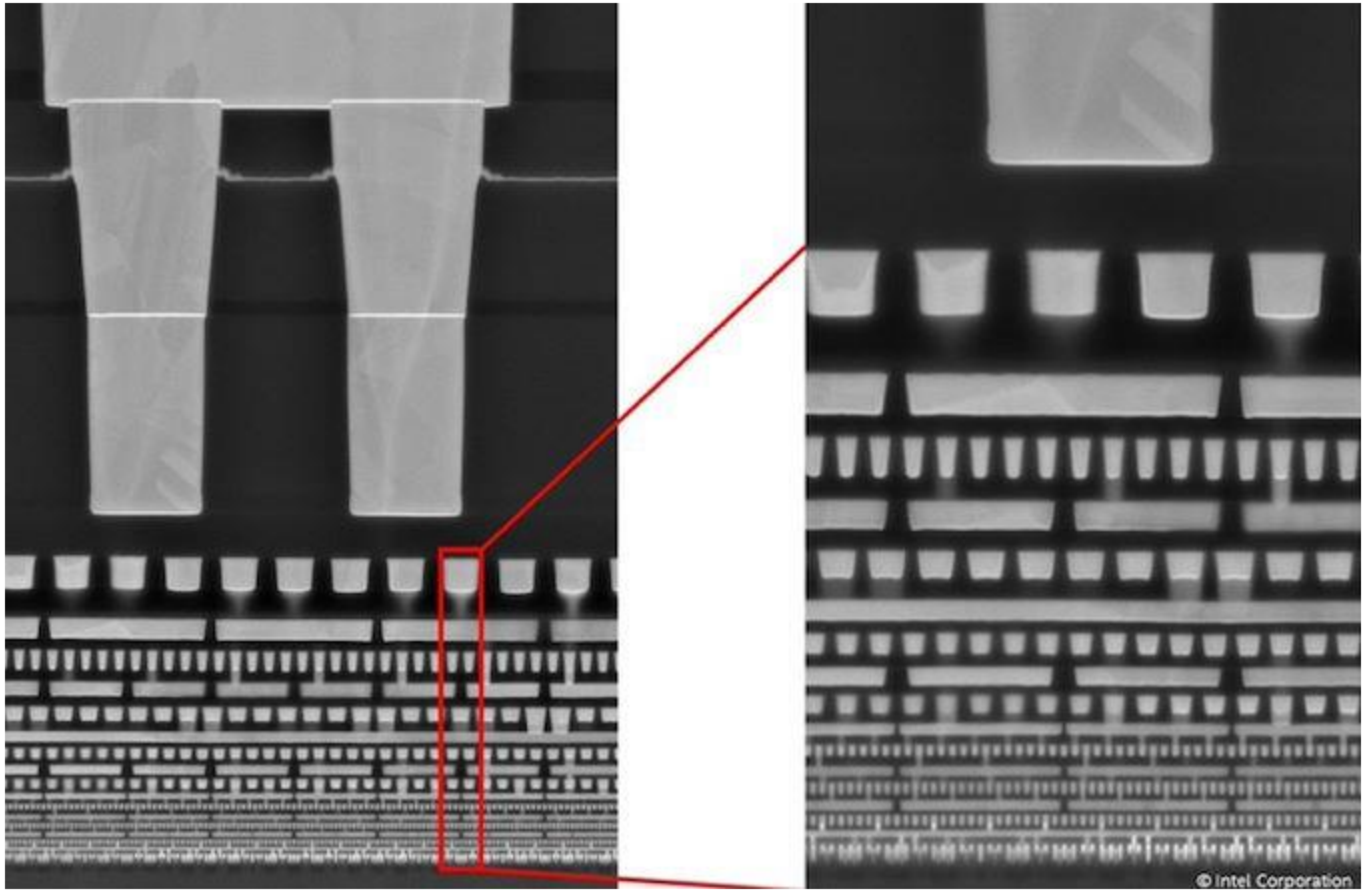


1971

1993

Can’t even see the size on the screen…not enough pixels

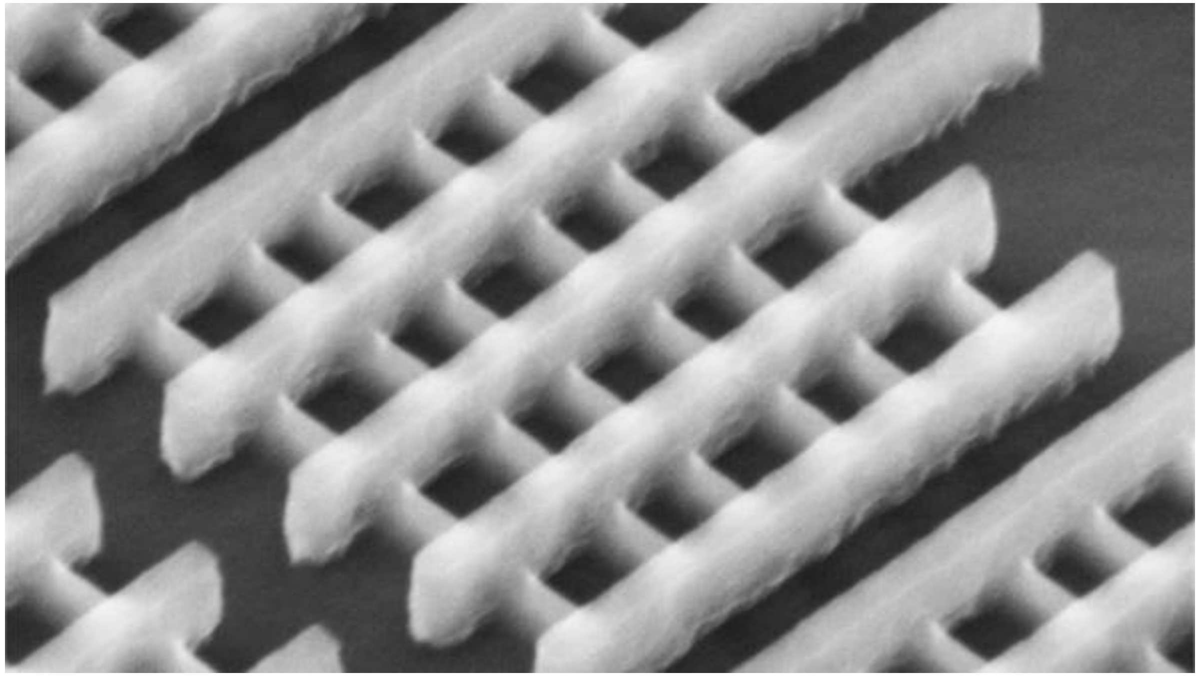
Scaling – How much have we scaled devices?

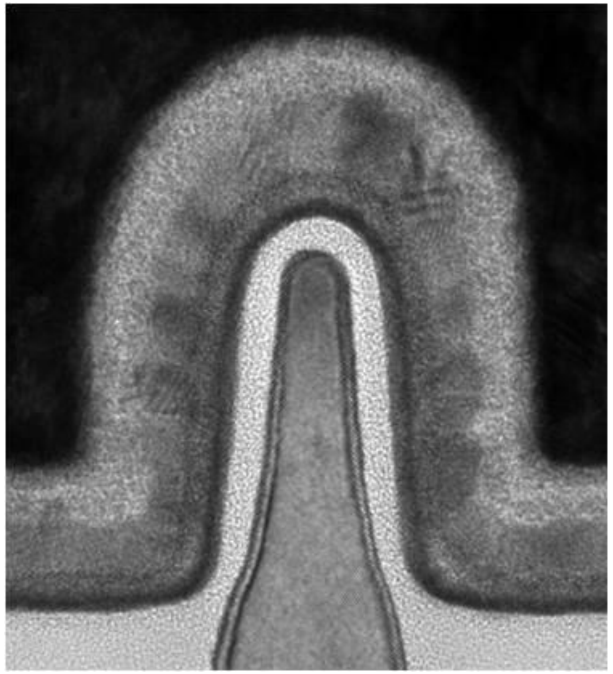


Intel 4 cross section:
to be released 2023

- What does a modern CPU cross section look like?
  - Where are the transistors?
  - What are we looking at?

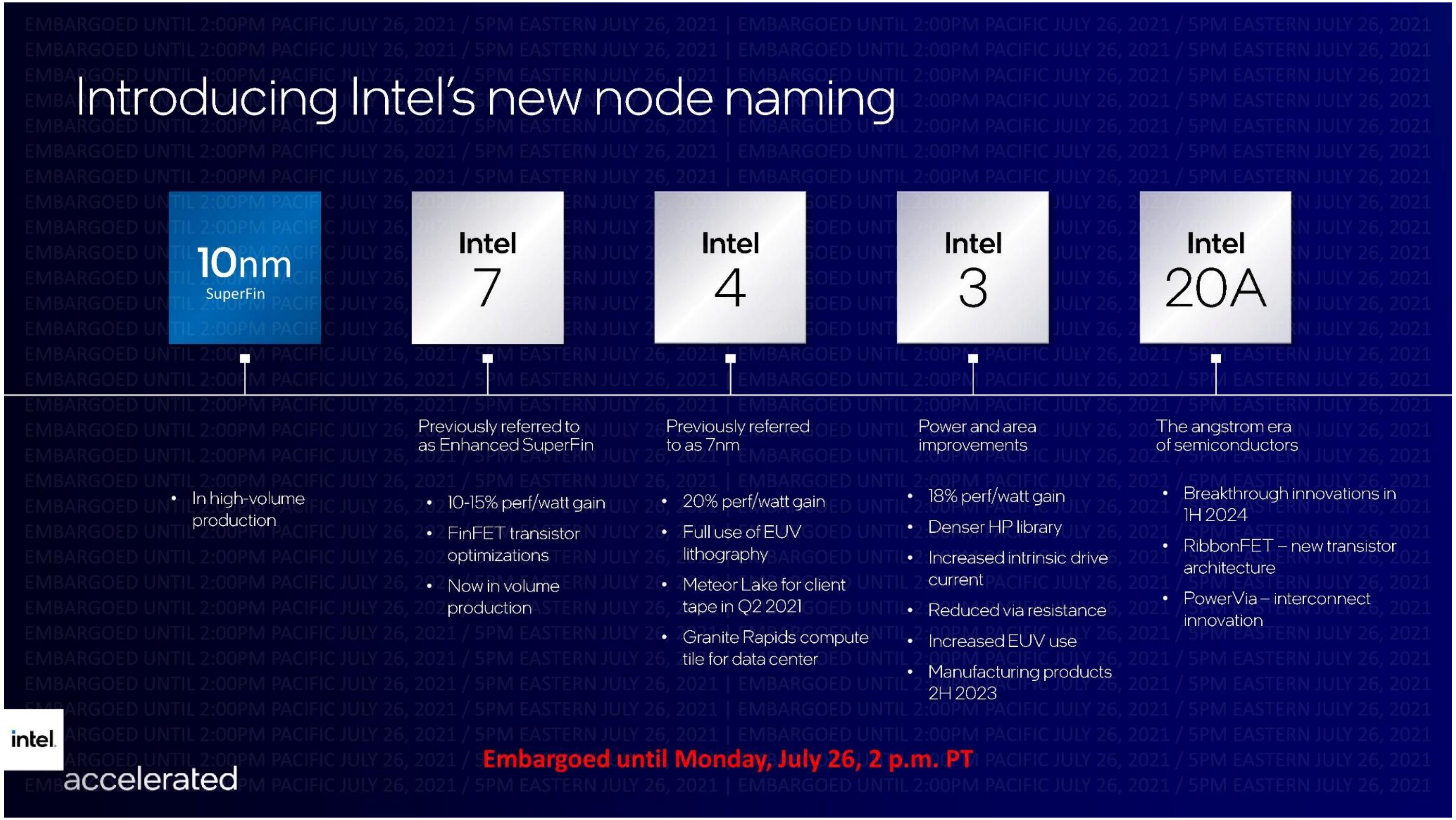
FinFET Transistors (May 2011 and After)





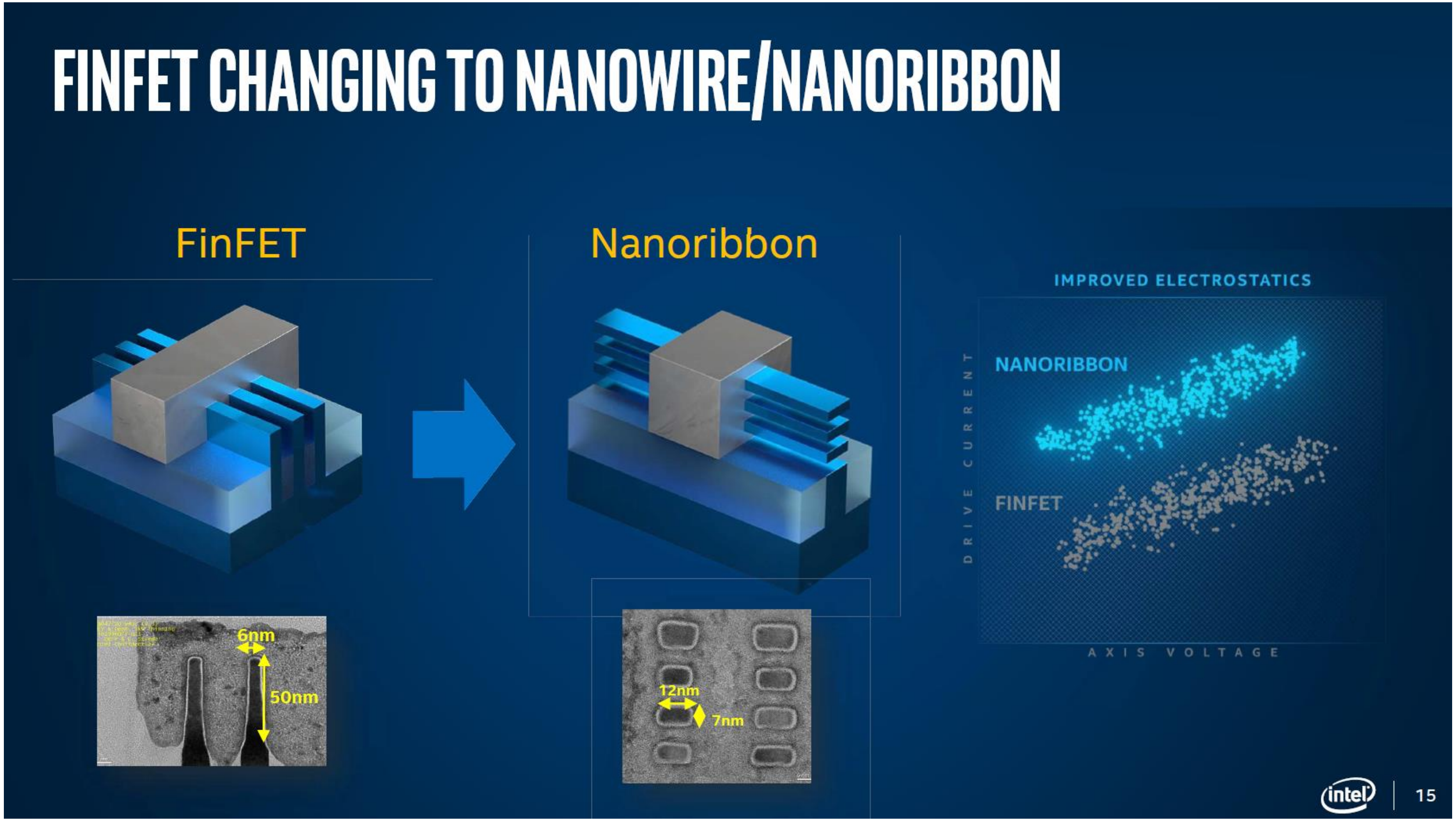
- FinFETs
  - Why is it called that?
  - What do you think the advantage is?

Scaling – How much have we scaled devices?



- This is a recent roadmap for Intel's transistor scaling plans

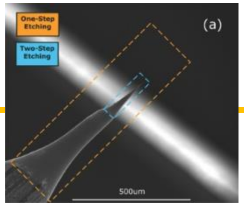
Scaling – How much have we scaled devices?



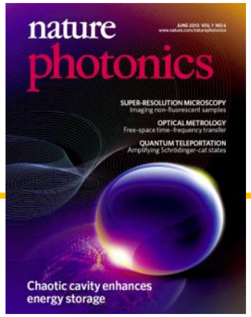
- What is a Nanoribbon FET?
  - Why does it give better performance?

My background and research

BS, EE, 2010



Electrical Engineering and Materials Science

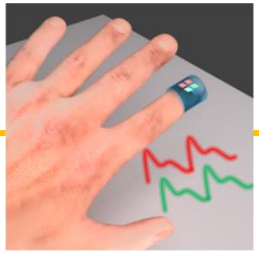


MS, EE, 2012

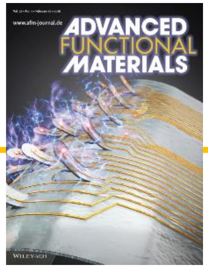
Started PhD, 2013

Bioelectronic and Biophotonic Systems

2014

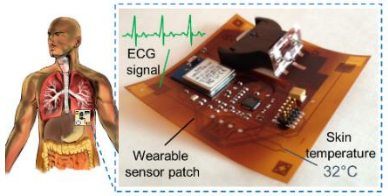


2015



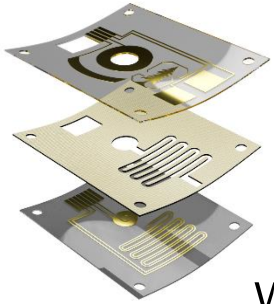
2016

Flexible Hybrid Electronics

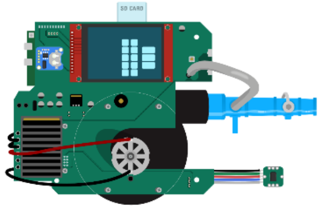


PhD, EECS, 2018

Started postdoc, 2019



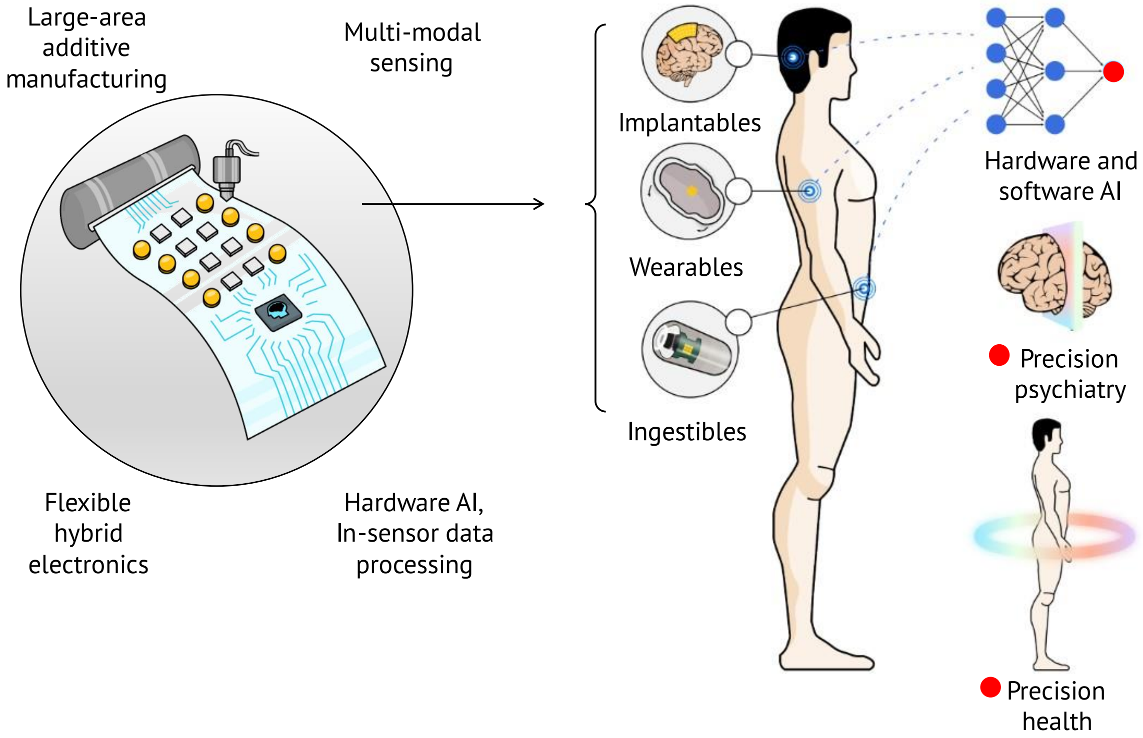
Wearables for precision health and psychiatry



Ventilator for COVID-19

Khan Lab @ USC

USC University of Southern California

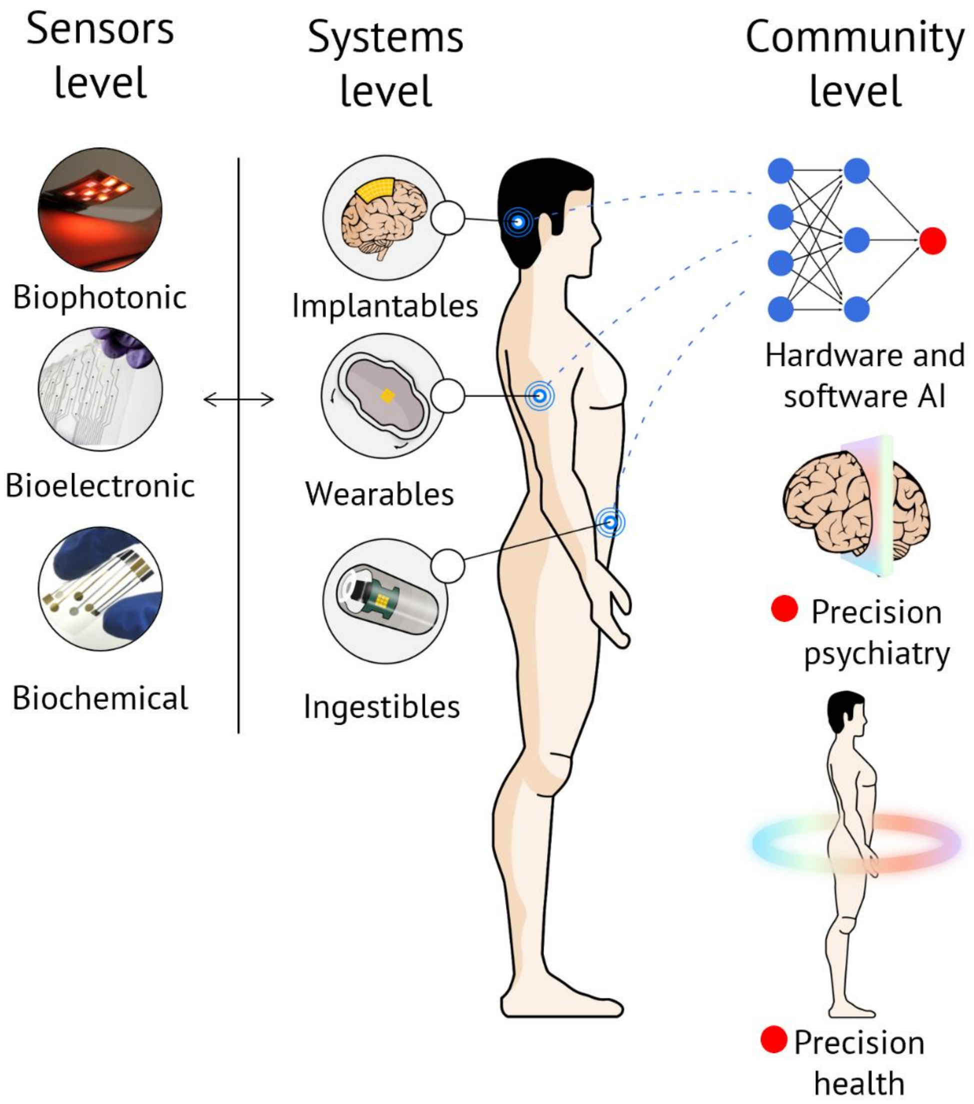


USC Viterbi School of Engineering

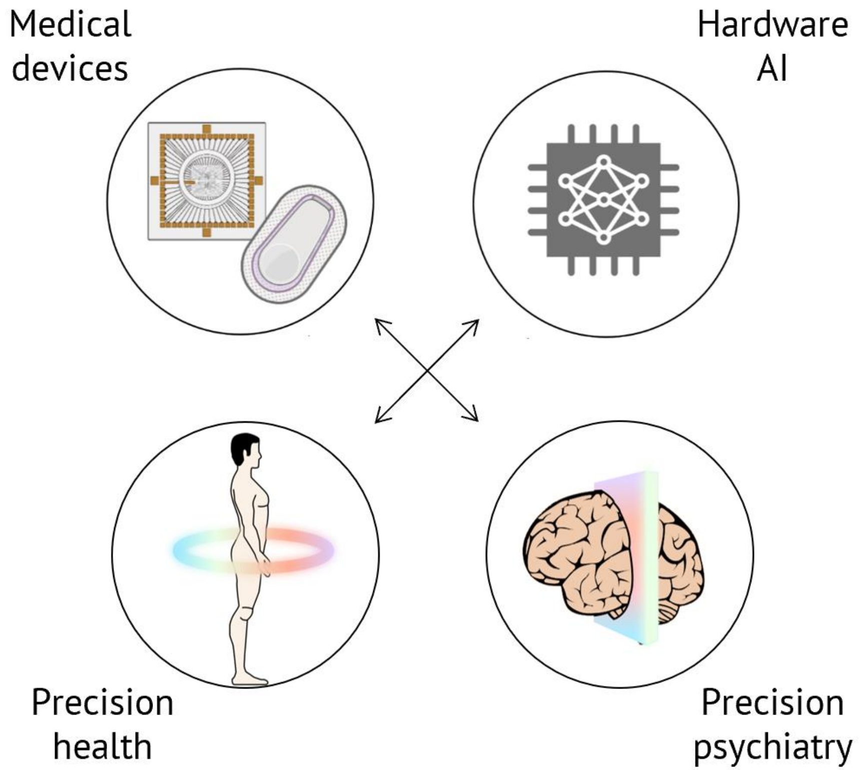
Keck School of Medicine of USC

USC Institute for Technology And Medical Systems Innovation

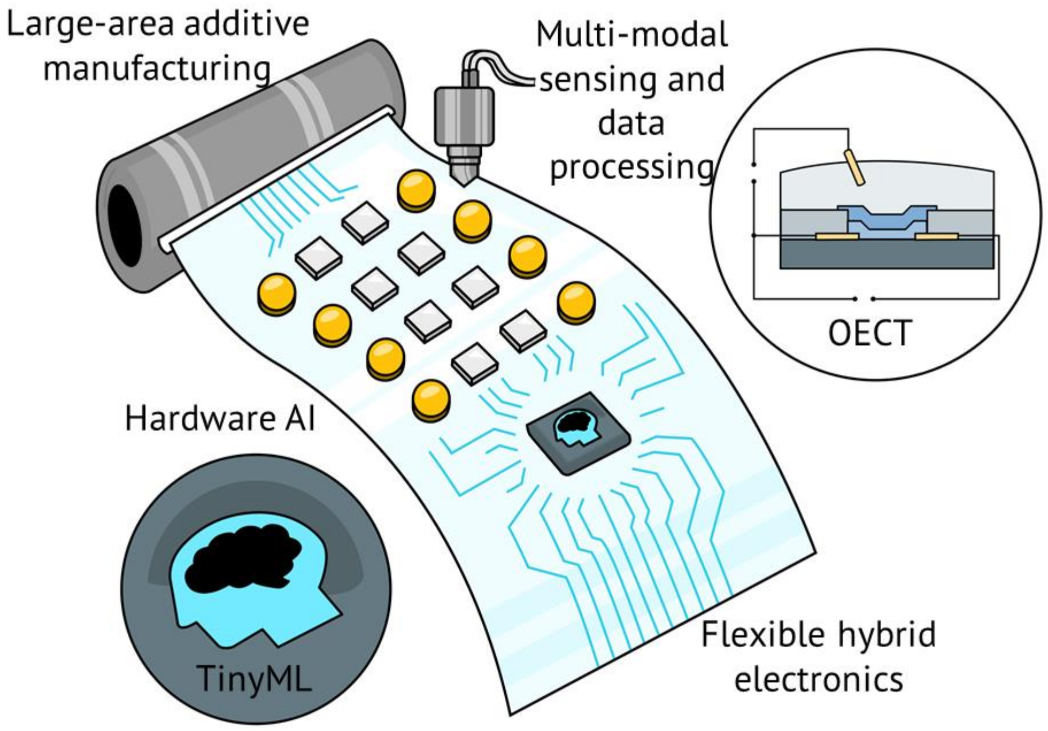
Khan Lab @ USC



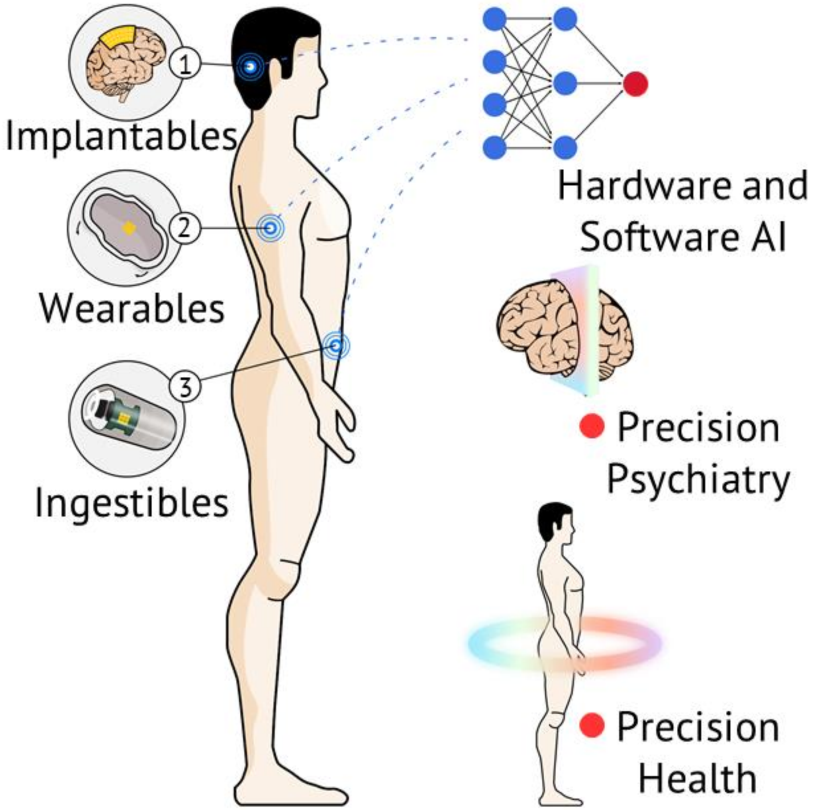
Research Focus



Soft sensor systems for precision health and psychiatry



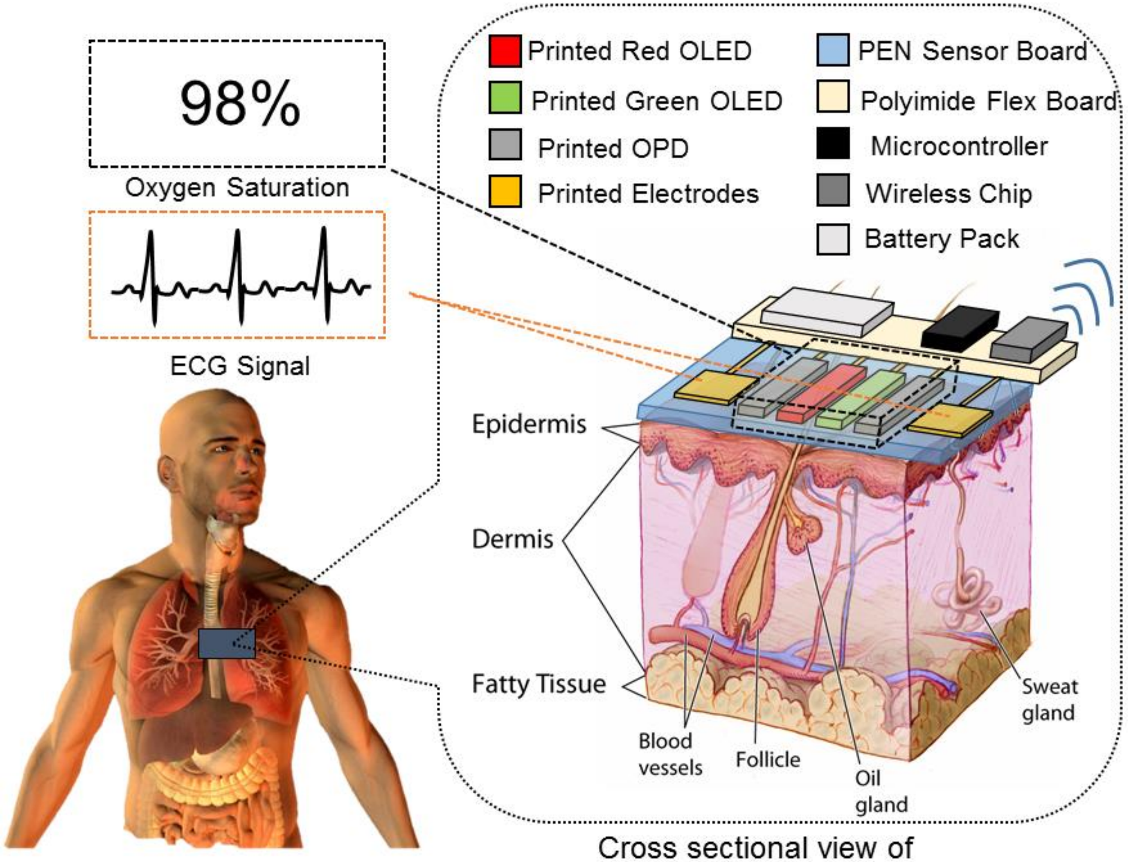
Materials, Manufacturing, Design, Devices, and Circuits



Systems and Applications

Sensors for precision health and psychiatry

Current state:
Big machines with a lot of wired rigid sensors that limits the comfort of the patient



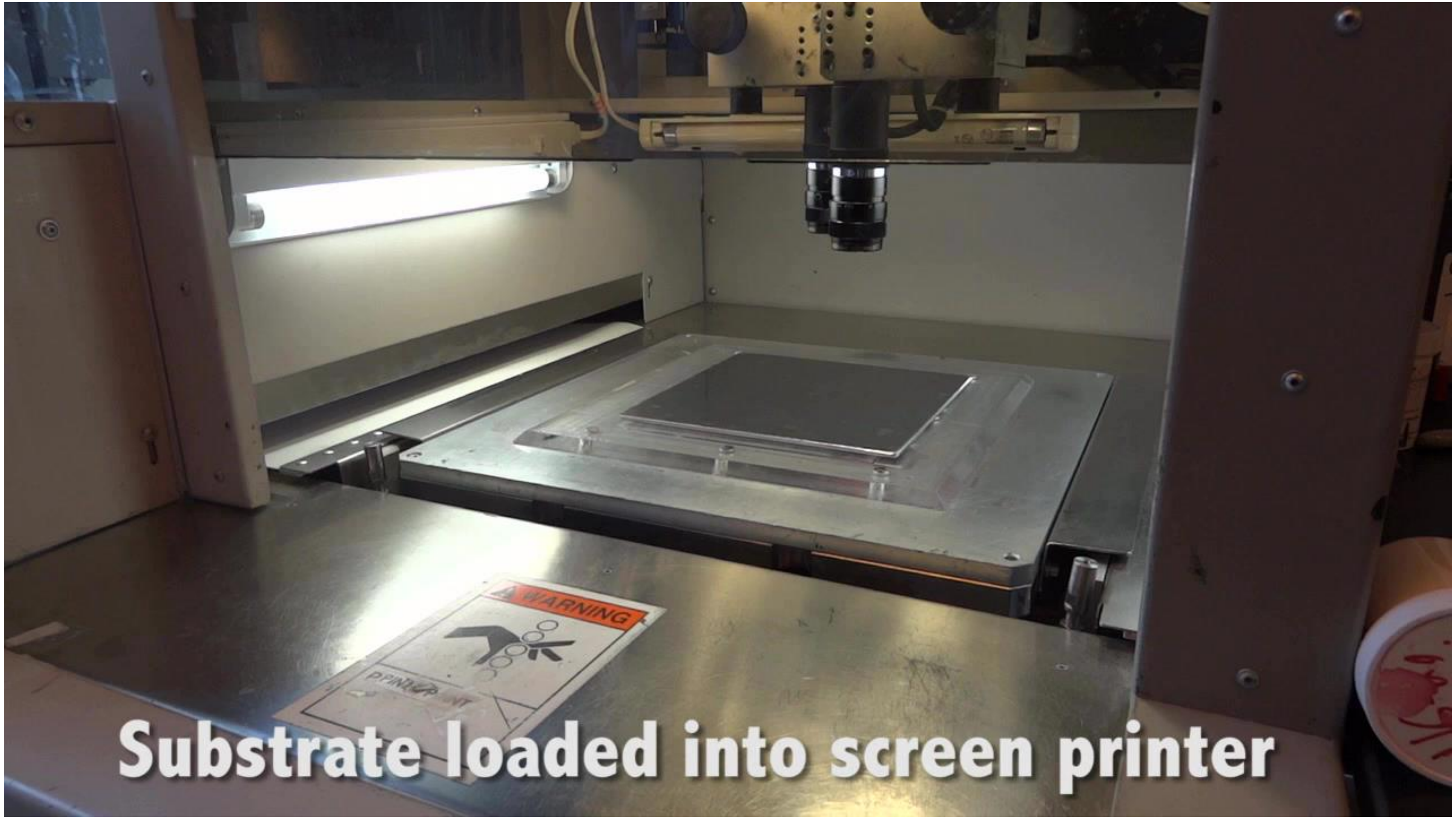
Cross sectional view of flexible sensor patch placed on chest

Vision:
A flexible sensor patch that seamlessly measure vital signs - measurements of the body's most basic functions

AI-powered biosensor for detecting hand gestures

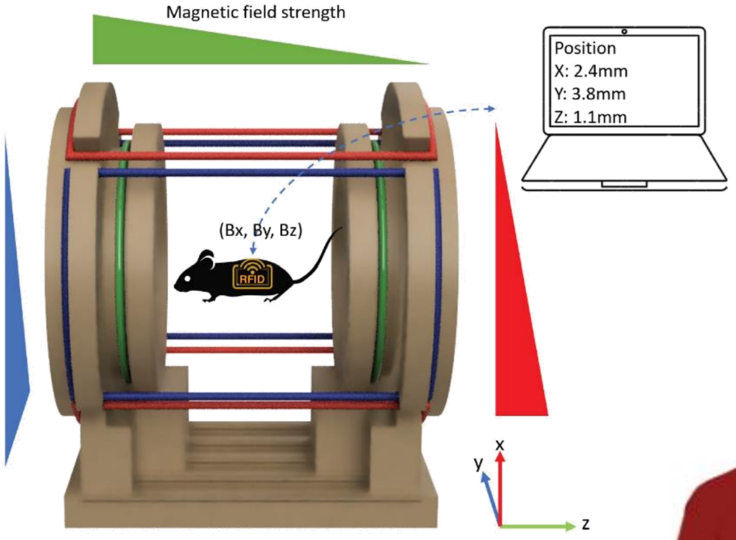
- Biopotential sensing for gesture recognition

Screen-printed MRI receive coils



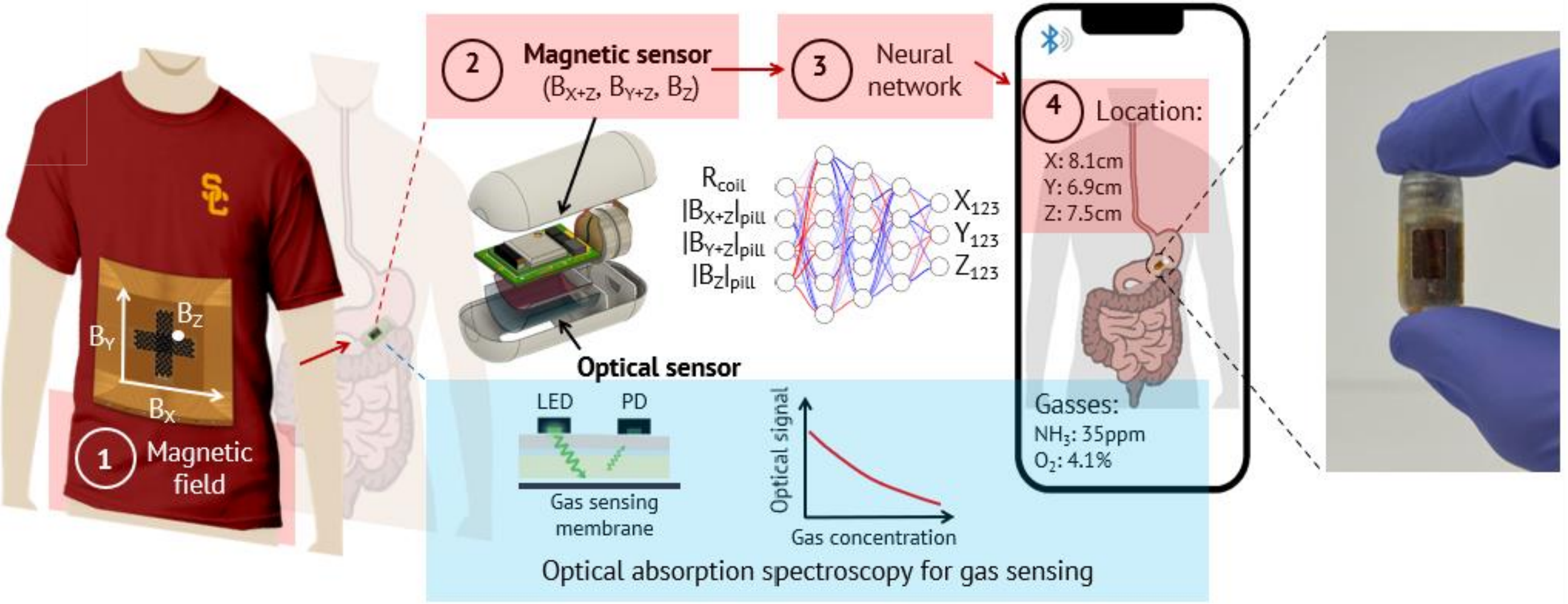
- High-throughput.
- Scalable.
- Fast.
- Significantly less process steps compared to photolithography.

3D gas mapping in the gut with AI-enabled ingestible and wearable electronics



Existing approach: Helmholtz coil for producing a region of nearly uniform magnetic field and localizing ingestible inside the coil.

Our approach: Wearable multi-layer coil for 3D field gradient, and use a bend sensor for accounting for movement.



3D gas mapping in the gut with AI-enabled ingestible and wearable electronics

USC Viterbi School of Engineering

About Academics Admission Research Innovation

From Wearables to Swallowables: USC Engineering Researchers Create GPS-like Smart Pills with AI

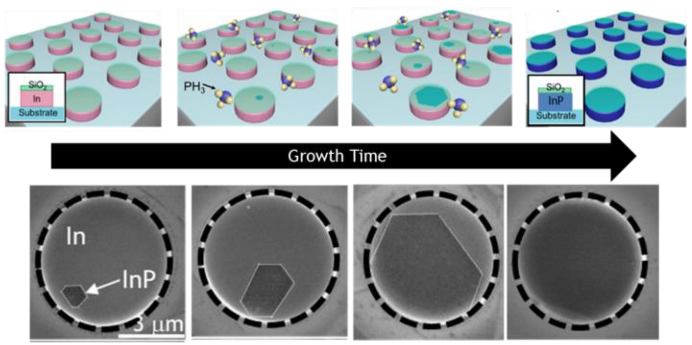
Amy Blumenthal | June 12, 2024

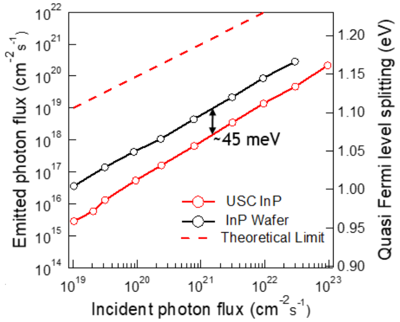
Utilizing wearable electronics and AI, new ingestible sensors provide real-time 3D monitoring of gastrointestinal health

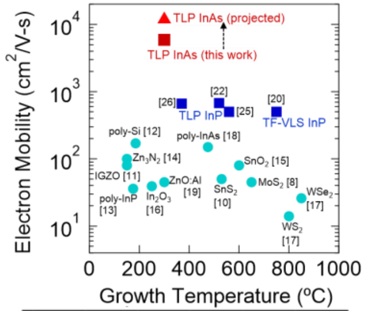
AN INGESTIBLE SMART SENSOR COULD DETECT CANCERS. IMAGE CREDIT: THE KHAN LAB

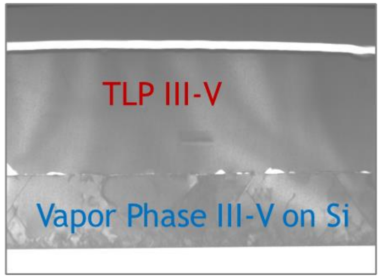
Kapadia Lab Research Portfolio

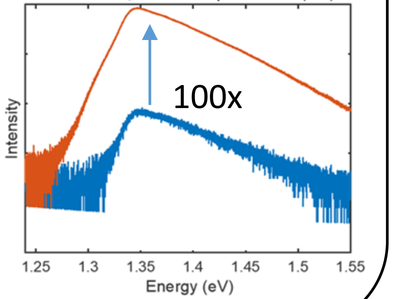
Back-End Materials Growth and Heterogeneous Integration



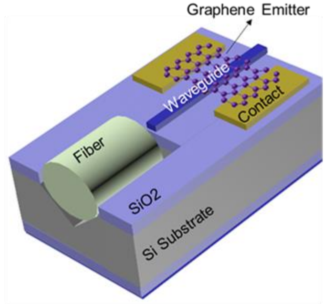


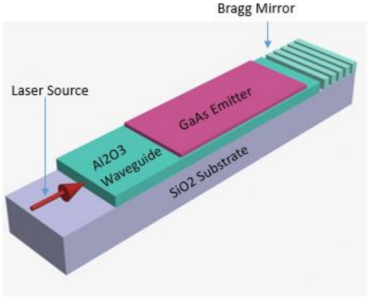


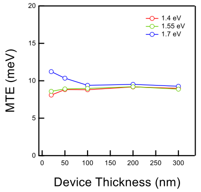


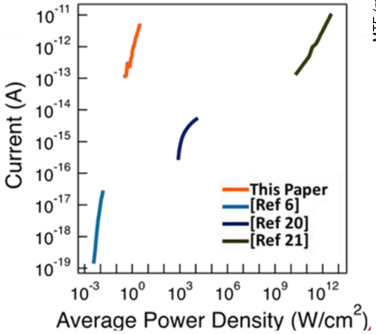


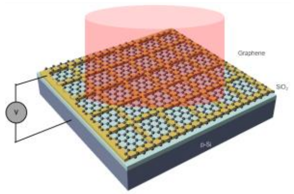
Electron Emission Devices for GHz to THz Applications

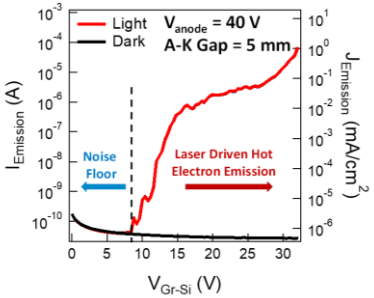




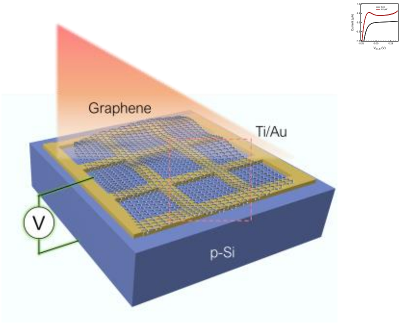


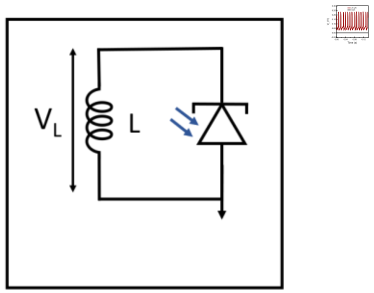


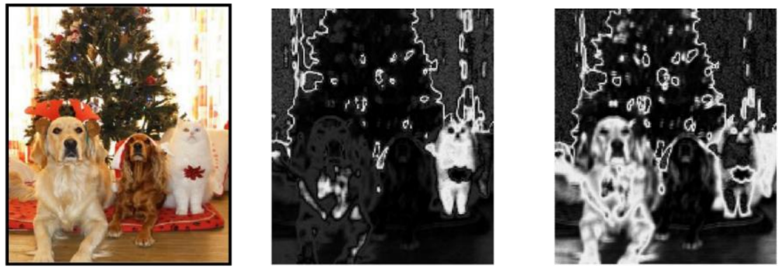




Ultra-Low Power Computing







Original image

3.5 KHz (B-channel) Cat

4.0 KHz (B-channel) Dog-1

John O’Brien Nanofabrication Laboratory

USC
University of
Southern California

Etch | Deposition | Lithography | Wet Processing | Packaging | Infrastructure

---

- $50M 12,000 Sq. ft. facility
- +24,000 sq. ft. automated facility for facilities, gases, and support systems
- 35+ state-of-the-art cleanroom tools including e-beam and direct write tools, Si and compound semiconductor processing
- Sample size from pieces to 100mm (min) and 150mm (subset – but all III-V)

Scalability:

- +200 users (2024) with expansion to +500 users planned. The lab can handle 100 active users.
- Space available within current facility for additional capacity and capability

The MOSIS Service: Background and History

- The MOSIS Service was founded in 1981 at Information Sciences Institute, Viterbi School of Engineering of University of Southern California
- DARPA provided the contract for The MOSIS Service to facilitate the first manufacturing projects for fabless organizations
- The MOSIS Service pioneered the Multi-Project Wafer (MPW) model
- The MOSIS Service has processed over 60,000 designs at more than a dozen foundries
- Customers of The MOSIS Service have included US Government Laboratories, foreign and domestic corporations, and foreign and domestic universities
- MOSIS has enabled IC designers to prototype innovative semiconductor designs in CMOS FinFET, FD-SOI, Bulk, III-V Compound, high-voltage BCD, and other specialty processes

Overview of MOSIS 2.0

USC University of Southern California

Academic Customers

National Lab Customers

Commercial Customers

M2 Engineering Team

MPWs

MPWs & Custom Processes

Commercial Fabs/OSATS

- intel
- Tower Semiconductor
- GlobalFoundries
- skywater
- tsmc
- SAMSUNG SEMICONDUCTORS

Nanofabs/Low-volume Fabs

- TELEDYNE TECHNOLOGIES INCORPORATED
- NORTHROP GRUMMAN
- HRL LABORATORIES
- USC University of Southern California
- Caltech
- UCI University of California, Irvine
- UC SANTA BARBARA
- UCLA
- UC RIVERSIDE
- UC San Diego

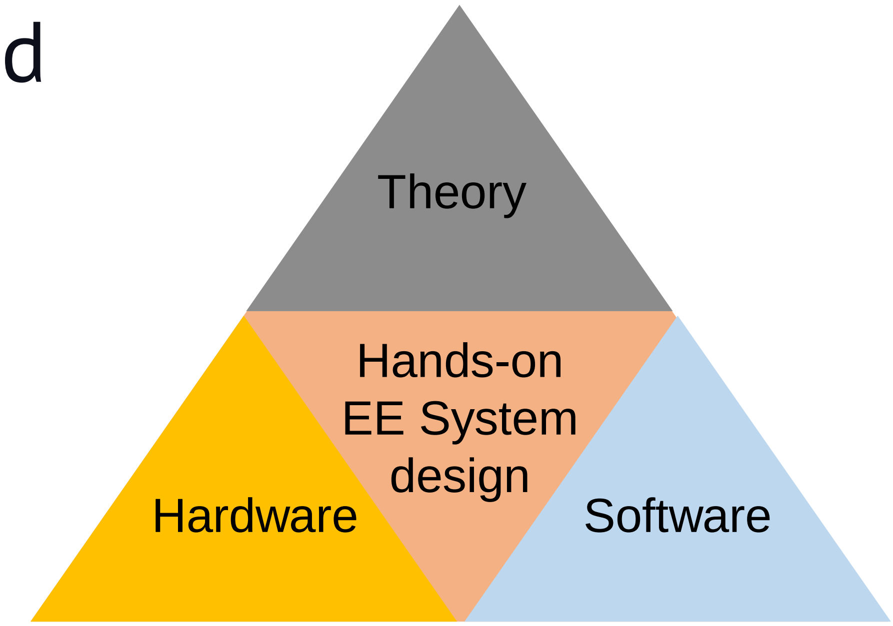
Overview of MOSIS 2.0 – MPW Offerings

USC
University of Southern California

Foundry	Technology	Nodes (nm)
Intel	Si CMOS	16, 22
Skywater	Si CMOS	90, 130
TSMC	Si CMOS	12, 16, 22, 28, 40, 45, 55, 65, 90, 130, 180, 250, 350
Samsung	Si CMOS	28, 65, 130
WIN Semi	GaAs pHEMT	100, 150, 180, 250, 450, 500
WIN Semi	GaN HEMT	120, 150, 250, 450
WIN Semi	GaAs HBT	7th Gen, 5th Gen, 4th Gen
Northrop Grumman	Under Development	GaN GaN20_PWR; InP N60; GaAs P3H; GaAs P3K; GaAs P3D;
Teledyne	Under Development	InP N60
Global Foundries	Under Development	Si CMOS ; RF SOI; RF SiGe; SiPh SOI
Tower Semi	Under Development	SiGe
HRL	Under Development	GaN T3

EE 105 Course objectives

- Understand theoretical and practical concepts in electrical engineering.
- Overview of devices, circuits, systems, and AI/ML tools.
- Design simple biosensor systems from end to end.
- Design imager systems with embedded ML.
- Design and implement electronic systems for given specifications.



Full-stack electronic system development

Syllabus

- Dynamic syllabus: https://drive.google.com/file/d/1HjTI33m4UouCzfoHWDAxYqaWjobf419k/view?usp=sharing

Prof. Yasser Khan
Emails: yasser.khan@usc.edu
Offices: MCB 270D

Prof. Rehan Kapadia
Emails: rkapadia@usc.edu
Offices: PHE 626

Atiyeh Abbasi Jalal
(Teaching Assistant)
Emails: abbasija@usc.edu

Vikas Addepalli (Course Mentor)
Emails: daddepal@usc.edu

Walter Unglaub
(Research Engineer)
Emails: unglaub@usc.edu

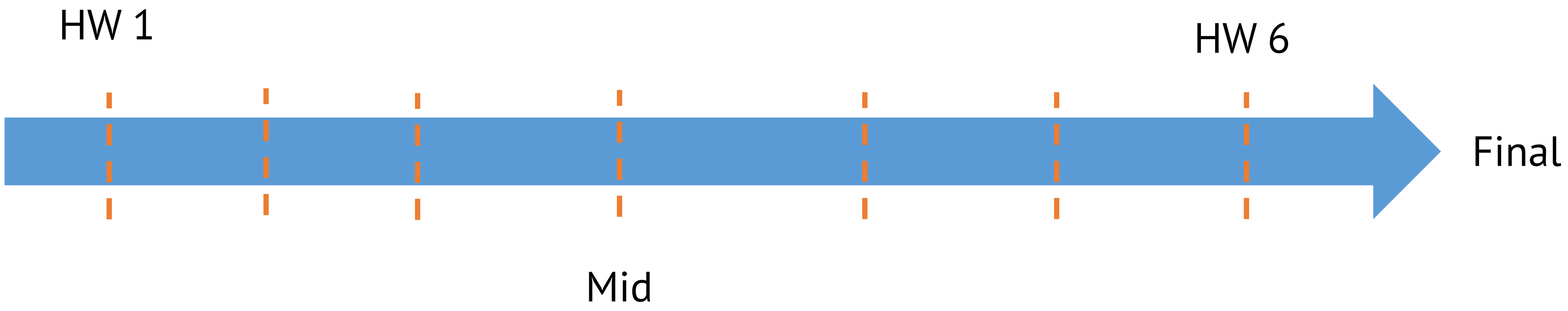
Course structure

- Lectures and discussions are sufficient for homework and final exam
- Emphasis on *practical learning*
- Homework to review major concepts

Homework	**30% (6)**
Mid	**30% (October 17, Thursday)**
Final	**40% (December 12, 2-4pm, cumulative)**

Approximate schedule

- Course homepage: https://brightspace.usc.edu/d2l/home/114204
- 6 homework assignments
- Final in finals week
- Mid October 17 in class



Course content

ECE 105: WEEKLY COURSE SCHEDULE

Week	Day	Dates	Topic	Deliverables
Week 1	Tuesday	8/27	Introduction to EE, ECE 105	
	Thursday	8/29	Electronic system design	
Week 2	Tuesday	9/3	Electronic system design	
	Thursday	9/5	Circuit analysis	
Week 3	Tuesday	9/10	Circuit analysis	HW1 on circuits released
	Thursday	9/12	Devices: semiconductors	
Week 4	Tuesday	9/17	Devices: semiconductors	**HW1 on circuits due**
	Thursday	9/19	Devices: optoelectronics	
Week 5	Tuesday	9/24	Devices: optoelectronics	HW2 on devices released
	Thursday	9/26	Sensors	
Week 6	Tuesday	10/1	Biosensing system	**HW2 on devices due**
	Thursday	10/3	Biosensing system	
Week 7	Tuesday	10/8	Biosensing system	
	Thursday	10/10	Fall break	
Week 8	Tuesday	10/15	Biosensing system	HW3 on system released
	Thursday	10/17	**Midterm**	
Week 9	Tuesday	10/22	Introduction to AI/ML	**HW3 on system due**
	Thursday	10/24	Linear algebra	
Week 10	Tuesday	10/29	No Class	
	Thursday	10/31	Linear algebra	HW4 on linear algebra released
Week 11	Tuesday	11/5	Neural networks	
	Thursday	11/7	Neural networks	**HW4 on linear algebra due**
Week 12	Tuesday	11/12	Neural networks	HW5 on neural network released
	Thursday	11/14	Imager	
Week 13	Tuesday	11/19	Introduction to communication systems	**HW5 on neural network due**
	Thursday	11/21	Optical communications	
Week 14	Tuesday	11/26	Optical communications	HW6 on optical comm released
	Thursday	11/28	Thanksgiving	
Week 15	Tuesday	12/3	Optical communications	**HW6 on optical comm due**
	Thursday	12/5	Quantum computing	
	Tuesday	12/12	**Final (2pm – 4pm)**	

USC University of Southern California

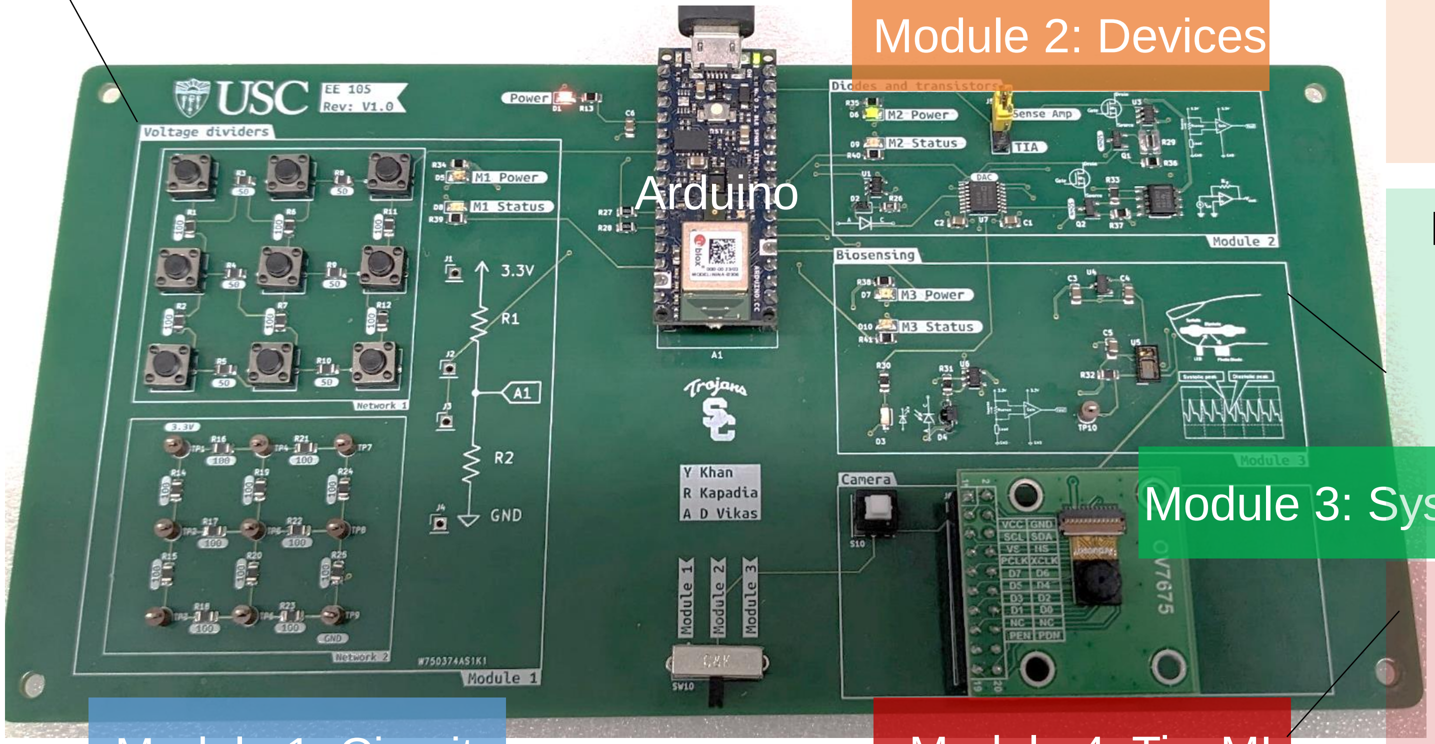
- **6 homeworks are on 6 modules**
  - **Circuits**
  - **Devices**
  - **Systems**
  - **Linear algebra**
  - **Neural network**
  - **Communication systems**
- **Midterm will cover circuits, devices, and biosensing systems**
- **Final will cover everything.**

Custom demonstration board for EE 105

Circuits

Voltage dividers

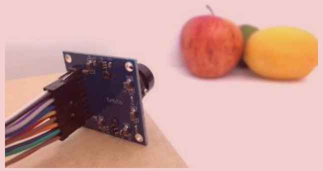
Arduino Nano 33
BLE



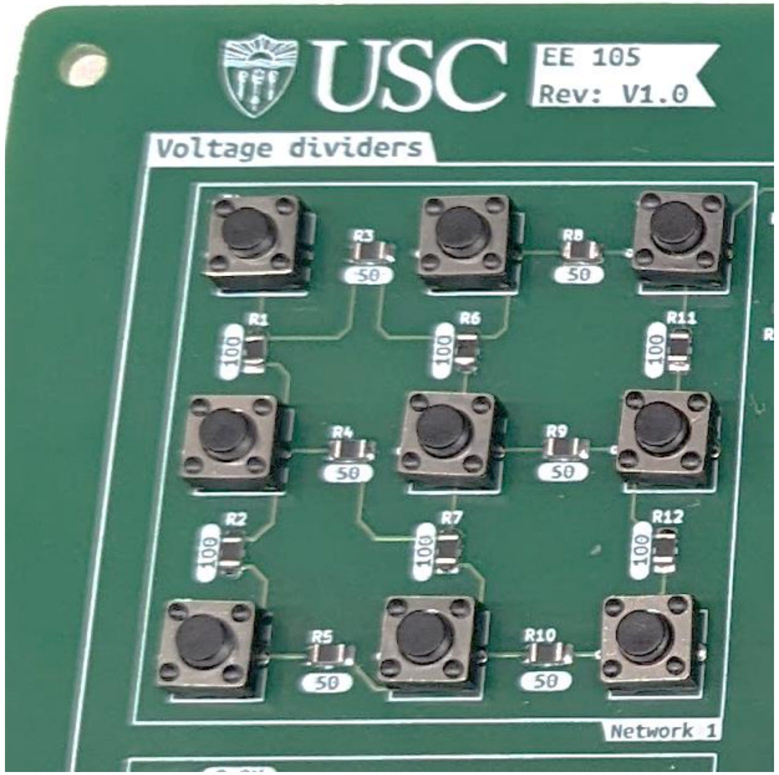
Electronic devices
Diodes
Transistors

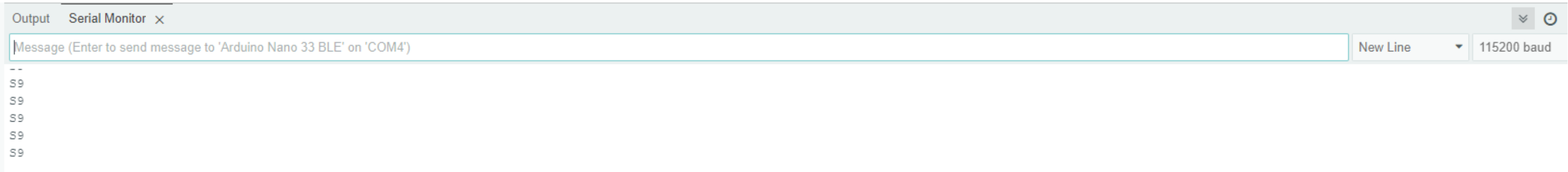
Electronic systems
Optical communication system
Oximeter

Machine vision



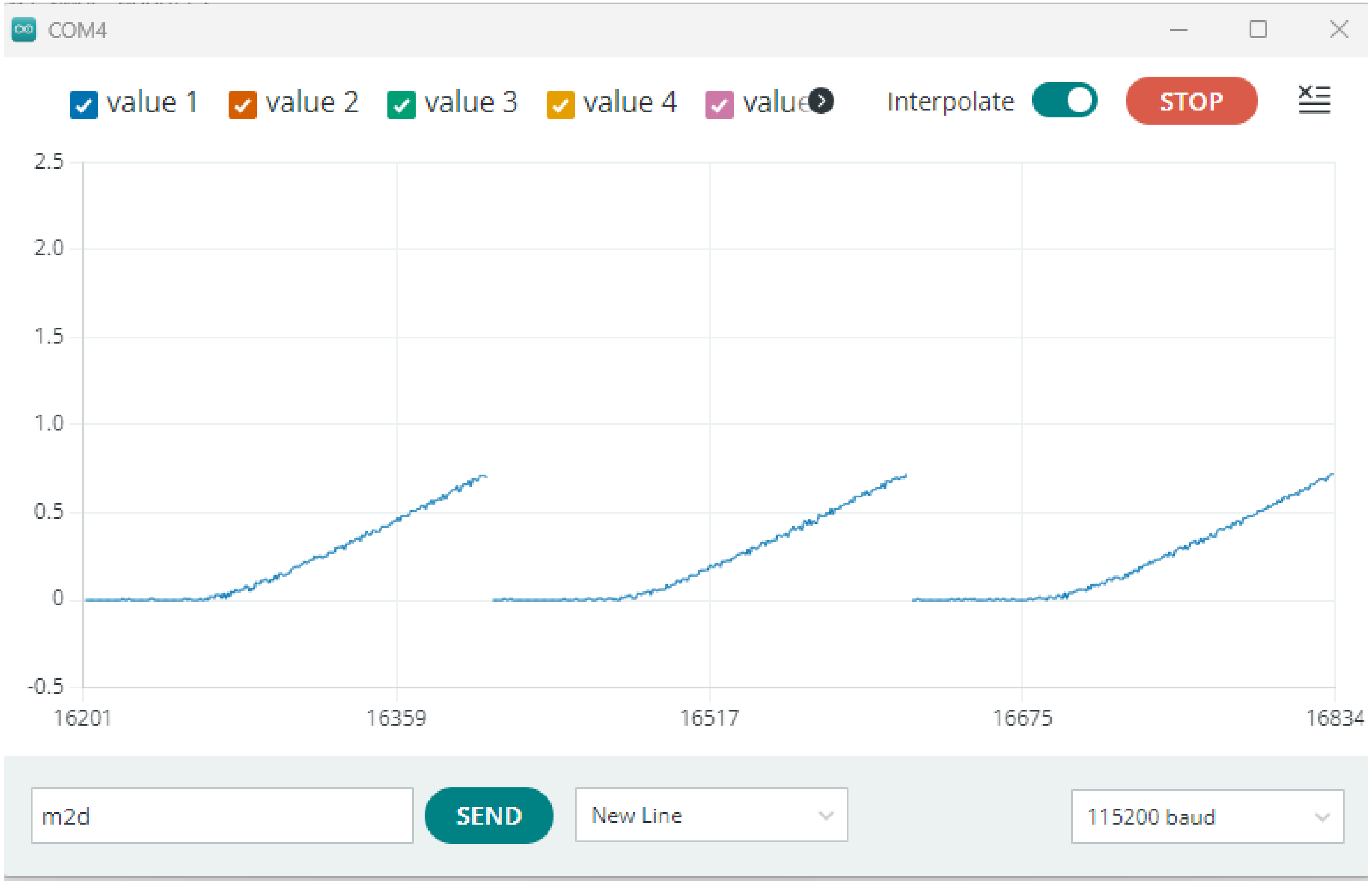
Module 1 on circuits – demo resistive touchscreen





Finds the pressed button location automatically

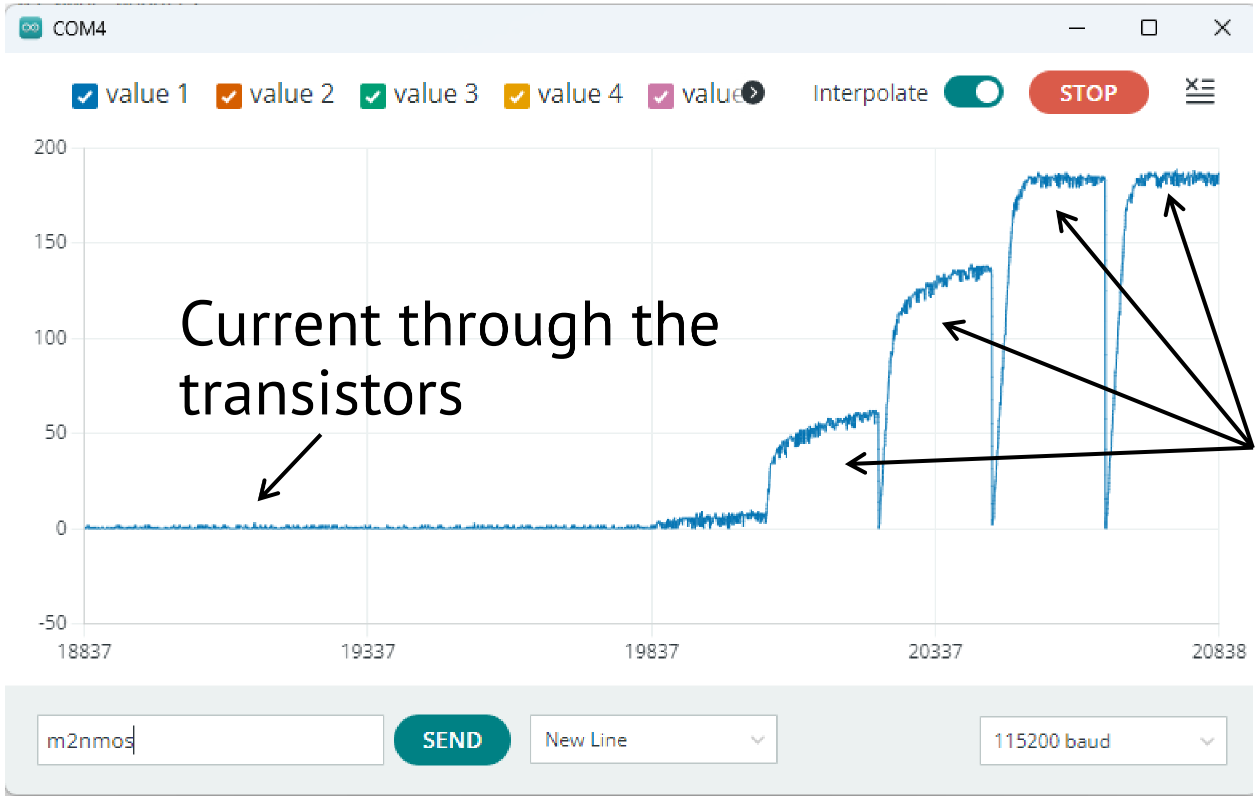
Module 2: diodes and transistors



Characterize semiconductor diode – how do they work

Module 2: diodes and transistors

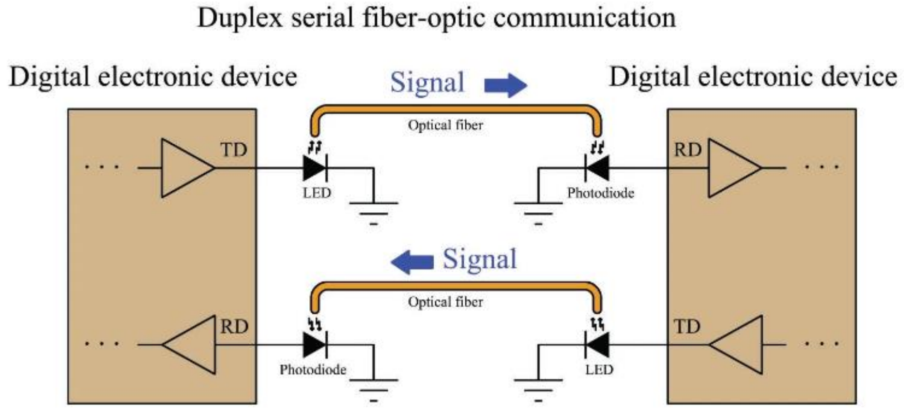
USC University of Southern California



Characterize semiconductor transistors – how do they work

Increasing gate voltage / opening faucet in the water analogy

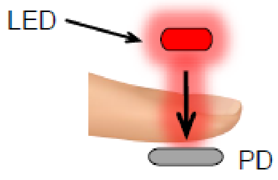
Module 3: optical communication



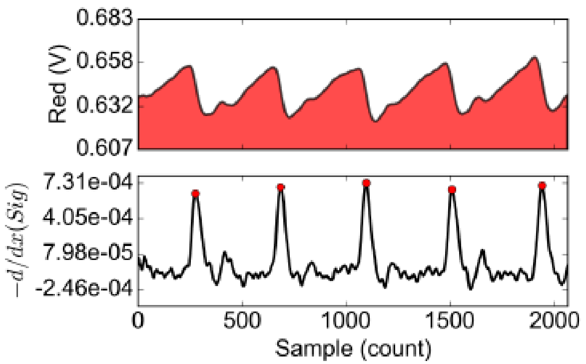
Light on

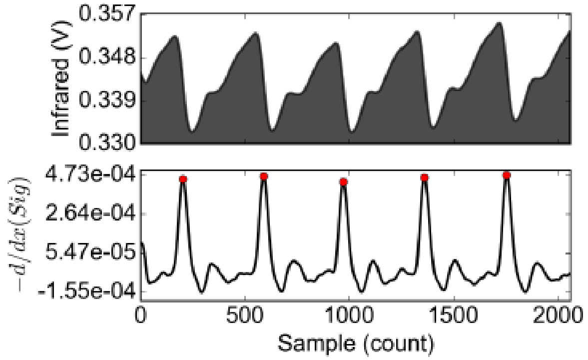
Light off

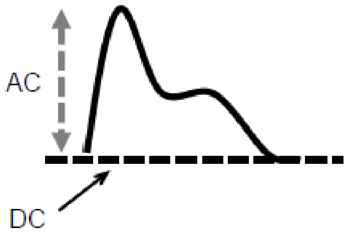
Module 3: oximeter

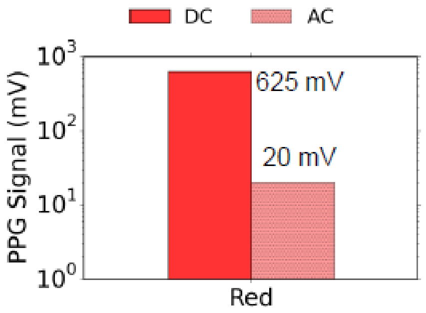


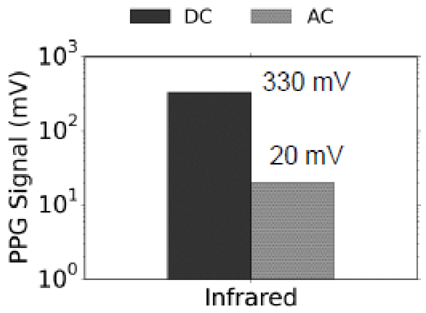
Measuring
Transmission Mode
PD Current











$$R = \frac{AC_{rd}/DC_{rd}}{AC_{ir}/DC_{ir}}$$

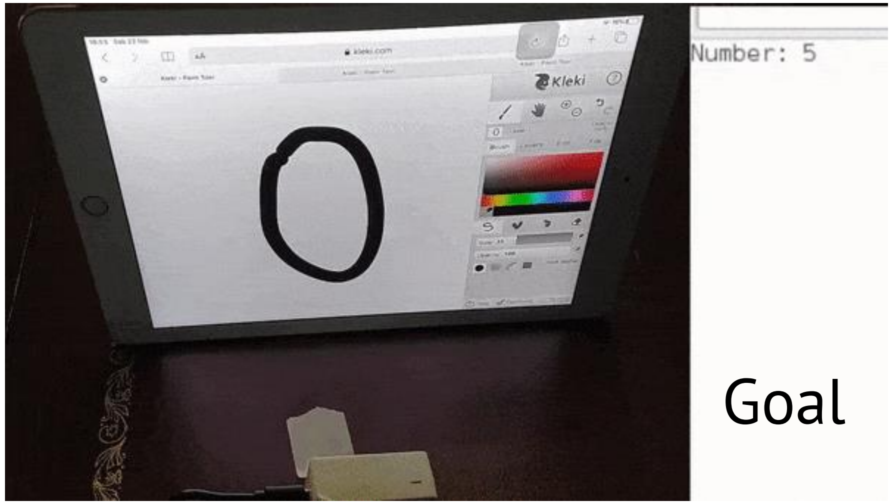
$$R = \frac{20mV/625mV}{20mV/330mV} = .528$$

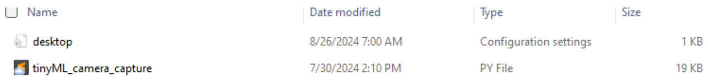
$$SpO_2 = 110 - 25 * R = 97\%$$

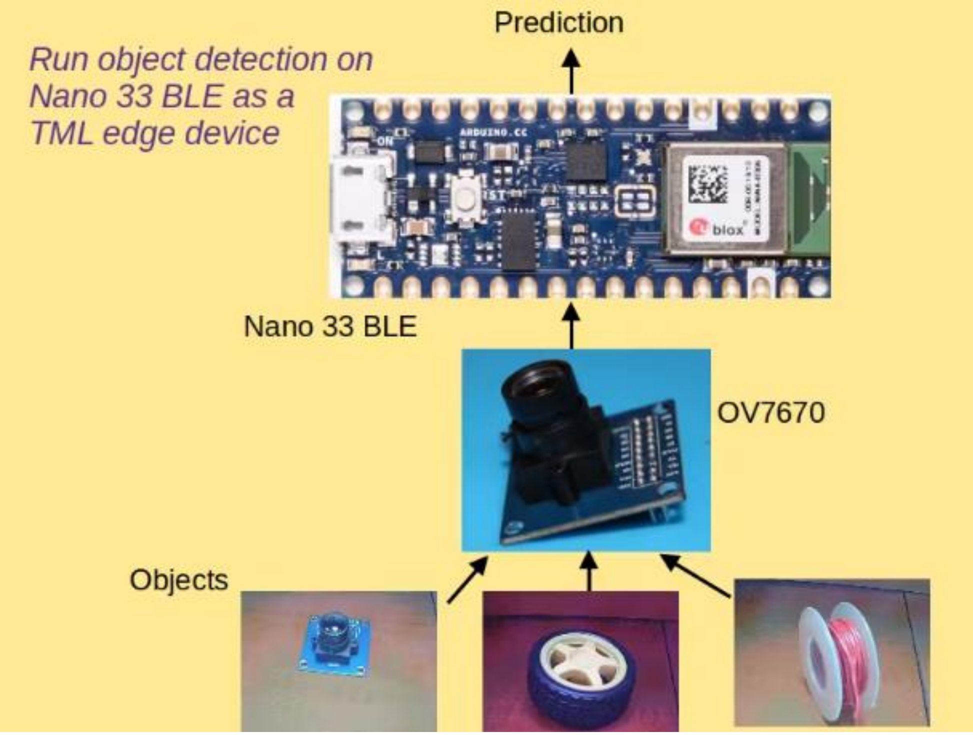
Module 3: oximeter

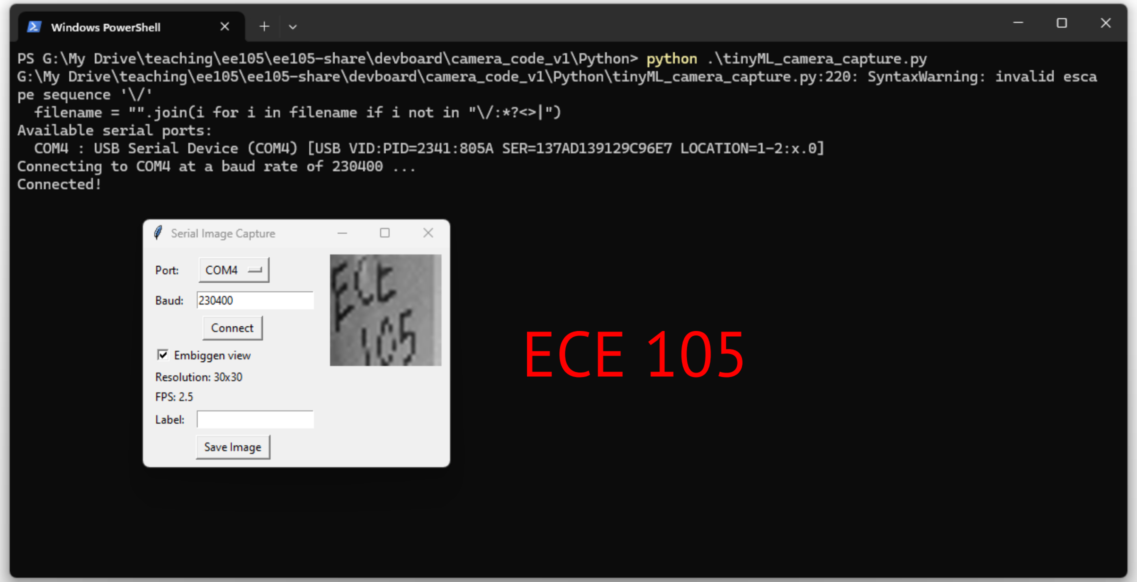
Module 4: Machine vision

USC
University of
Southern California









Arduino + camera + ML = identify objects / letters / faces / anything

Next lecture: system design