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EE 105: Introduction to Electrical Engineering

Lecture 1

Introduction to EE, and EE 105

Yasser Khan

Rehan Kapadia

What is Electrical Engineering?

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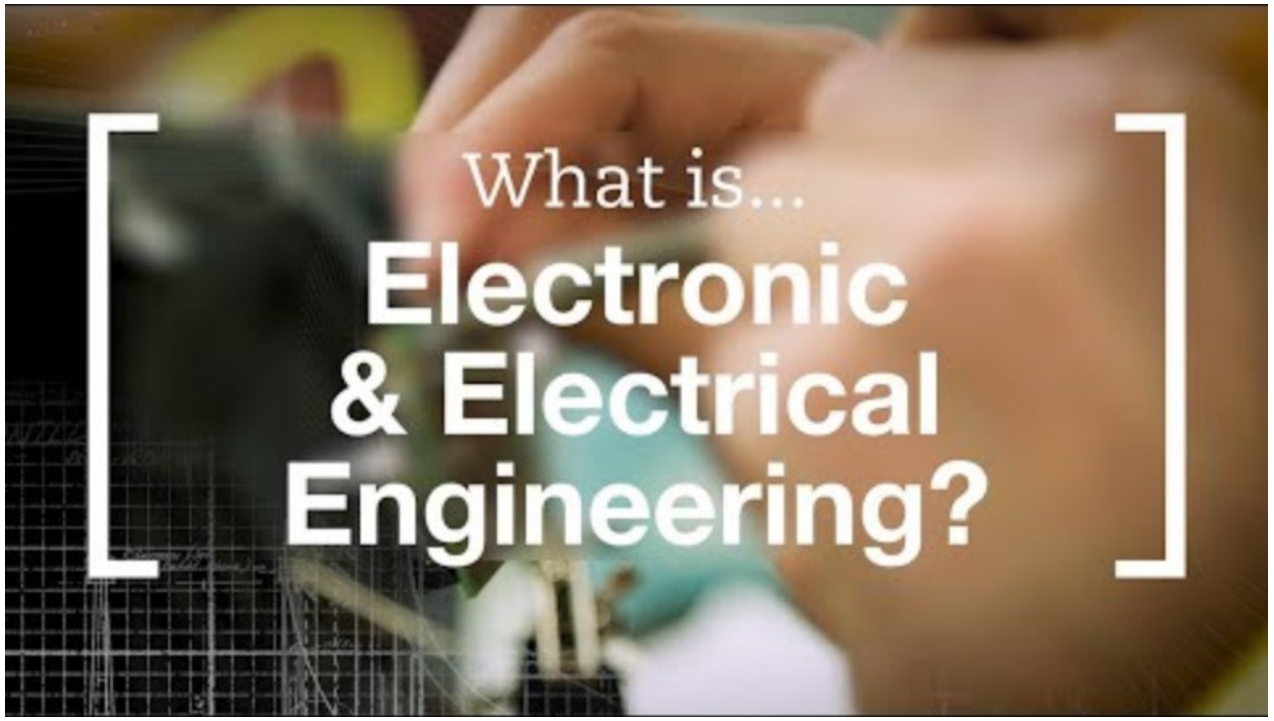
EE turns electricity, electronics and electromagnetism into useful devices and systems.

Definition

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

Subfields you will meet in EE 105

- **Circuits (Module 1) and devices (Module 2)**
- **Sensors (Module 3)**
- **Computing and machine learning (Modules 0 and 4)**
- **Communications (Module 5)**
- Signals, electromagnetics and power run through all of them



Video: What is Electronic & Electrical Engineering? (YouTube)

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

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Neuralink's 2020 demo: spikes from a pig's brain stream live to a screen.



Video: FULL REVEAL! Elon Musk's Neuralink chip tested live in pig brains (YouTube)

Neuralink: the neural implant

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Link v0.9: a coin-sized wireless implant that records 1024 channels of brain activity.





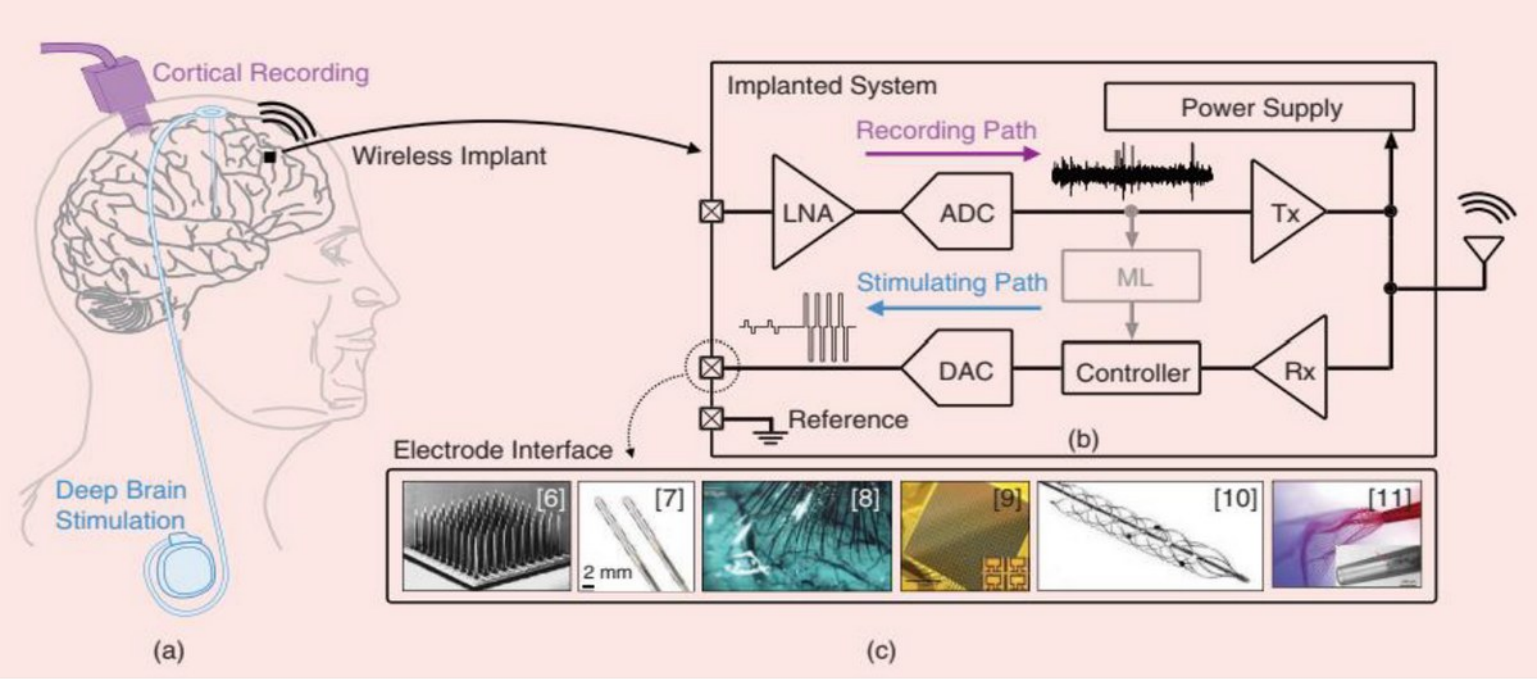
Images: Neuralink, Link v0.9 (2020).

Every step of the neural implant design and fabrication requires electrical engineering: electrodes (devices and materials), amplifiers and converters (circuits), the radio (communications), the battery and charger (power).

Neural interfaces: under the hood

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An implant records, digitizes and transmits brain signals, and can stimulate in return.



(a) Two clinical neural interfaces: a percutaneous recording implant and a deep brain stimulator. (b) Blocks of a bidirectional (black) or closed-loop (black and gray) wireless interface. (c) Electrodes, left to right: Utah array, Medtronic SenSight, Neuralink polymer threads, high-density neural matrix, Synchron Stentrode, syringe-injectable mesh.

Recording path

electrodes → LNA → ADC → Tx

Stimulating path

Rx → controller → DAC → electrodes

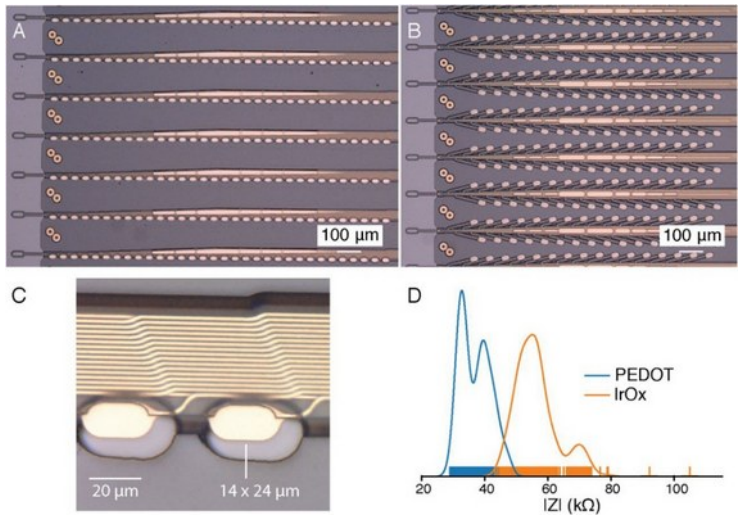
Closed loop

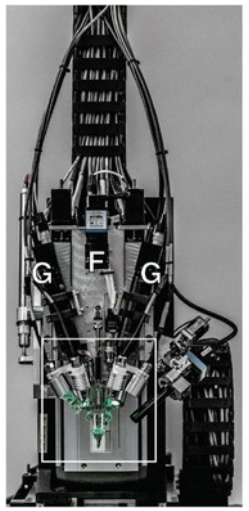
The ML block feeds the controller: respond without an outside computer

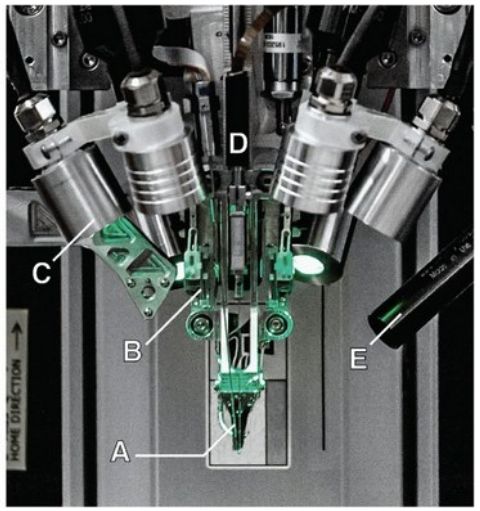
LNA low-noise amplifier
ADC / DAC analog-to-digital / digital-to-analog converter
Tx / Rx transmitter / receiver
ML machine learning

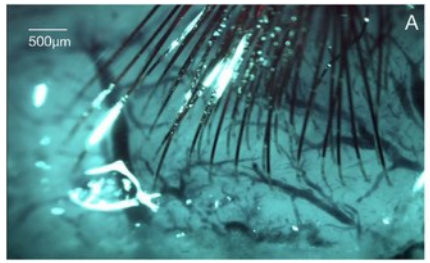
Link v0.9

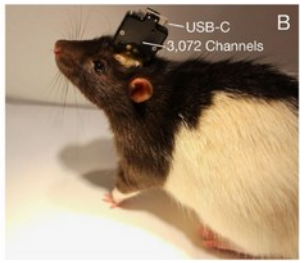
One implant, many fields: electrode threads, a surgical robot and the electronics.











Sensors

Electrode threads need electrical and mechanical engineering, materials science and chemical engineering.

Surgical robot

Robotics, electrical, mechanical and control engineering.

Implant

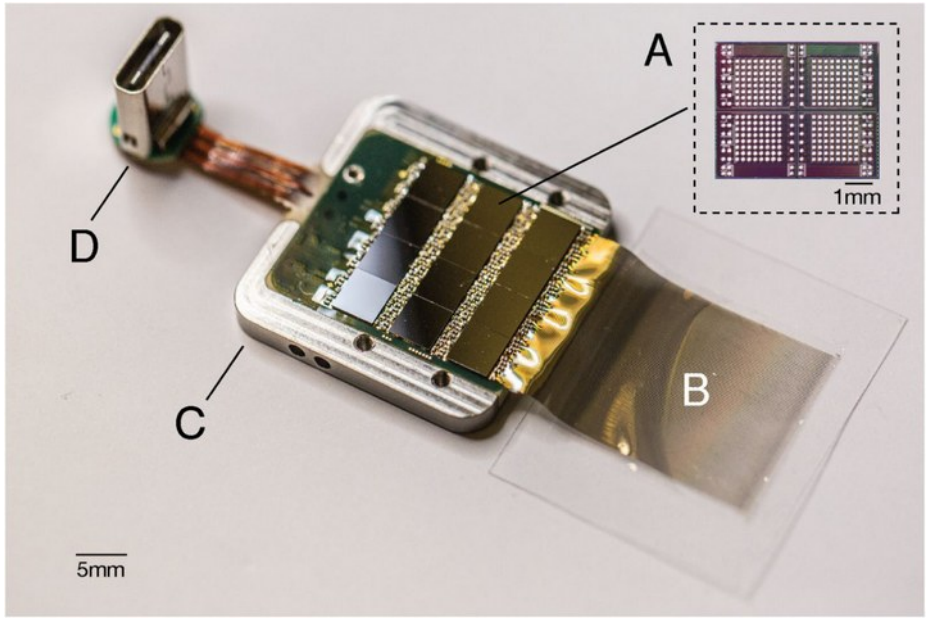
Electrical engineering and computer science. Right: a 3,072-channel device on a rat.

Figures: E. Musk and Neuralink, J. Med. Internet Res. 21, e16194 (2019).

Brain recording from 1024 analog pixels

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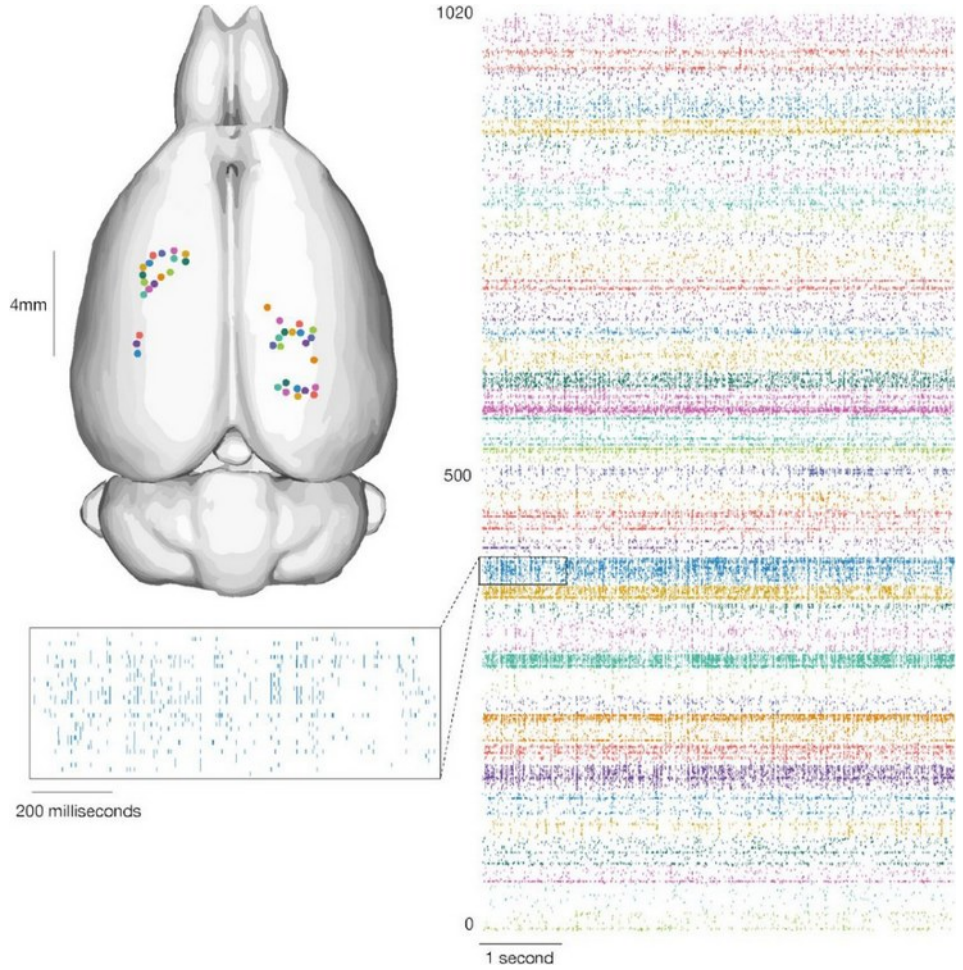
Each chip has 256 amplifiers, or “analog pixels”; this rat recording used 1020 channels.



Packaged sensor device: 12 recording chips, 3,072 channels.

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

$8 \times 8 \times 4 = 256$ per chip, $256 \times 12 = 3072$ channels

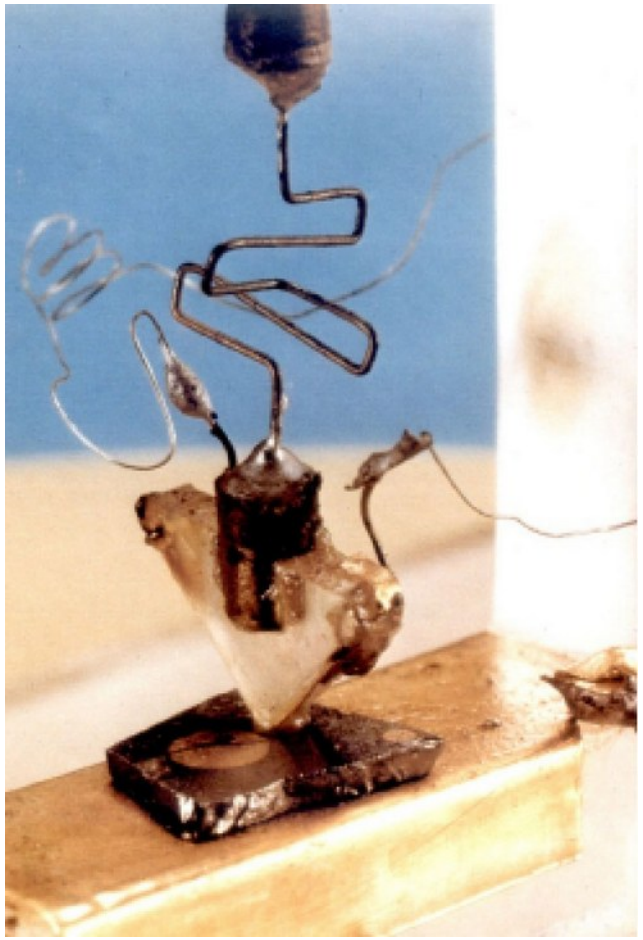


Spikes on 1020 channels over a few seconds; color marks the thread. Figures: Musk and Neuralink, JMIR 2019.

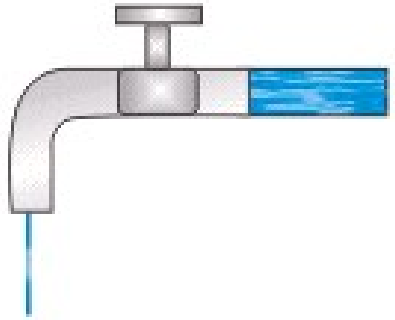
How do we carry out so much computing?

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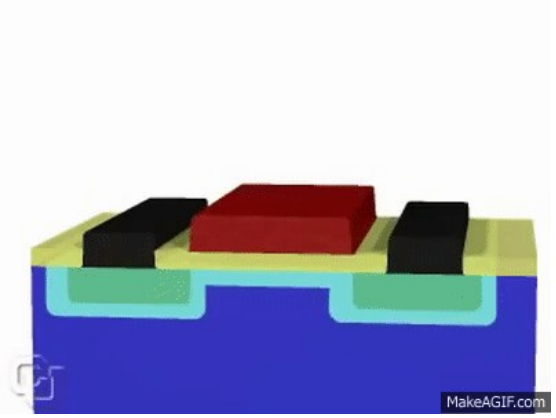
What is driving computing? Transistors: switches that a small signal turns on and off.



The first point-contact transistor, Bell Labs, 1947



A faucet: a small turn of the handle controls a big flow.



A transistor: a small gate voltage controls a big current.

We use transistors!

- A modern chip packs **billions** of these switches.
- The gate opens and closes the channel, like a faucet handle.

1956 Physics Nobel Prize

Shockley, Bardeen and Brattain shared the 1956 prize for discovering the transistor effect.

"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

Image: NobelPrize.org

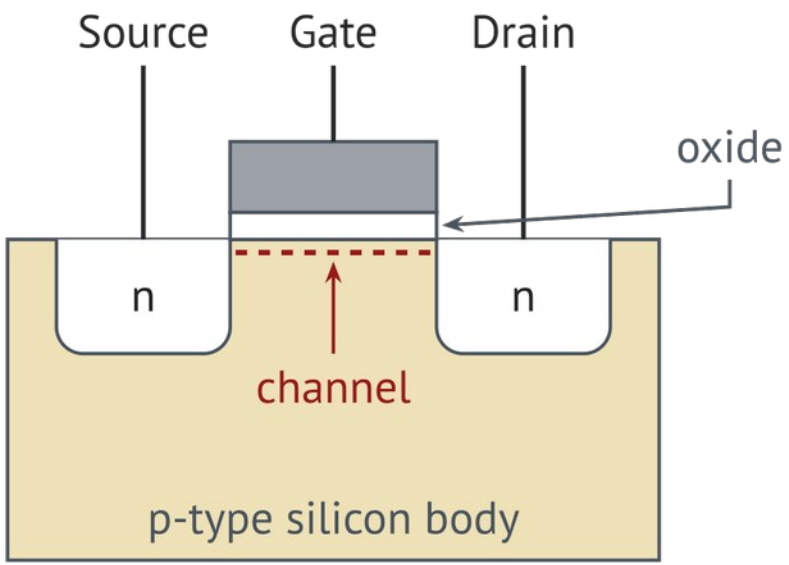
Prize citation

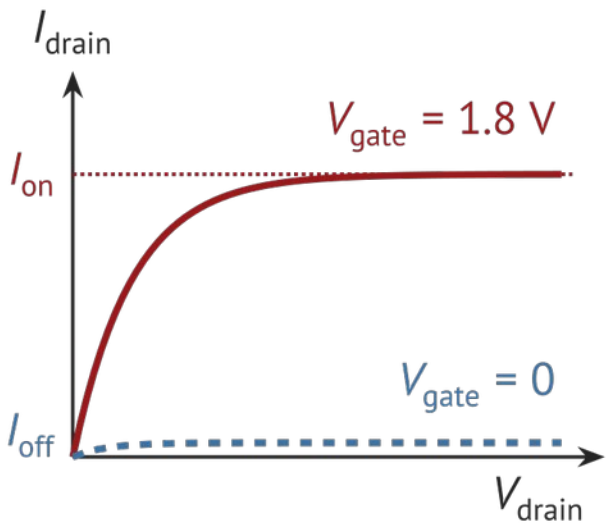
"for their researches on semiconductors and their discovery of the transistor effect"

- Bardeen and Brattain built the first point-contact transistor at **Bell Labs** in December 1947
- The transistor replaced the vacuum tube and started 70 years of shrinking electronics
- Bardeen won a second physics prize in 1972, for superconductivity

What is a transistor?

A transistor is a switch: the gate voltage turns the drain current on or off.





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** as possible.

What is desirable

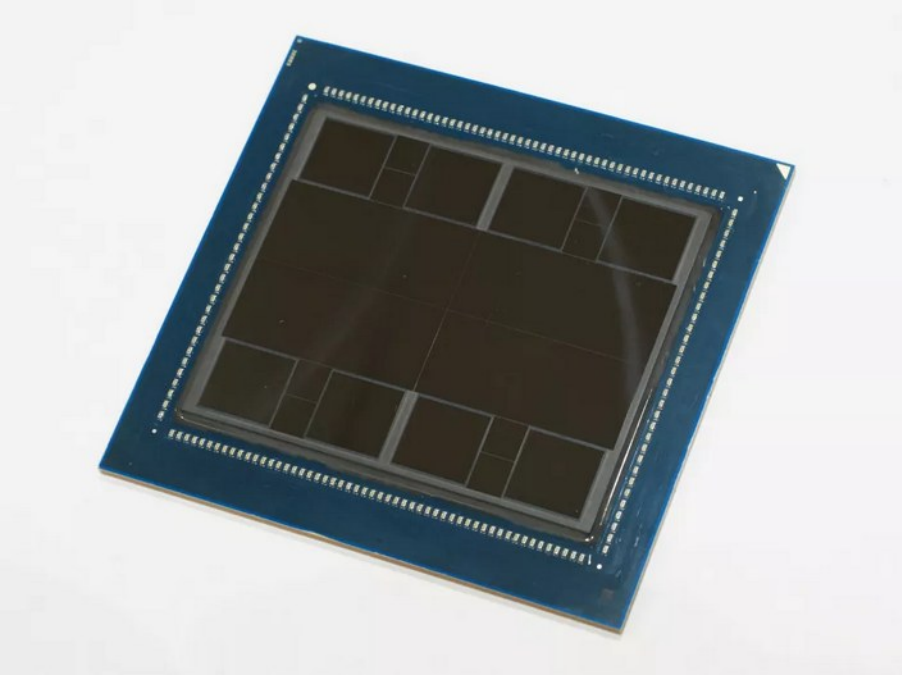
large I_{on}, small I_{off}

Billions of switches run at once on a chip, so each one must be fast and frugal.

What do modern day integrated circuits look like?

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A modern AI accelerator: about 150 billion transistors in one package.



AMD Instinct MI300 accelerator

- About **150 billion** transistors, made with **5 nm** technology
- 130 to 230 million transistors per mm^2: about 100 thousand to 1 million in the area of one cell
- Parts of the chip are **3-D stacked dies**: computing, memory, sensing and stimulation can be integrated together
- About **8×** the performance of the previous MI250: enough to train the largest AI models

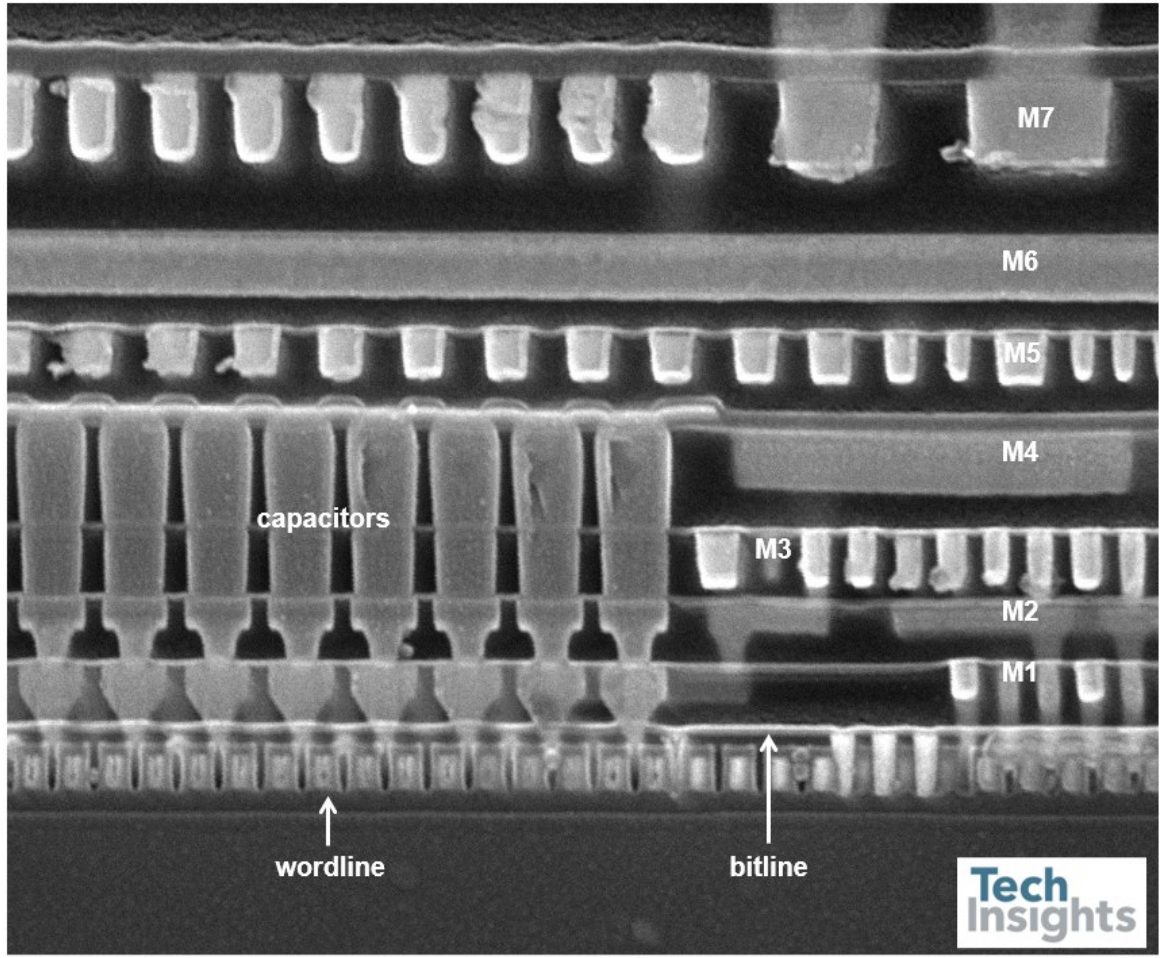
One cell's worth of silicon (30 µm × 30 µm)

$$9 \times 10^{-4}\ \text{mm}^2 \times 1.3 \times 10^{8}\ \frac{\text{transistors}}{\text{mm}^2} \approx 1.2 \times 10^{5}\ \text{transistors}$$

What do these look like?

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Cut a chip open: a thin layer of transistors at the bottom, a tall stack of wiring above.



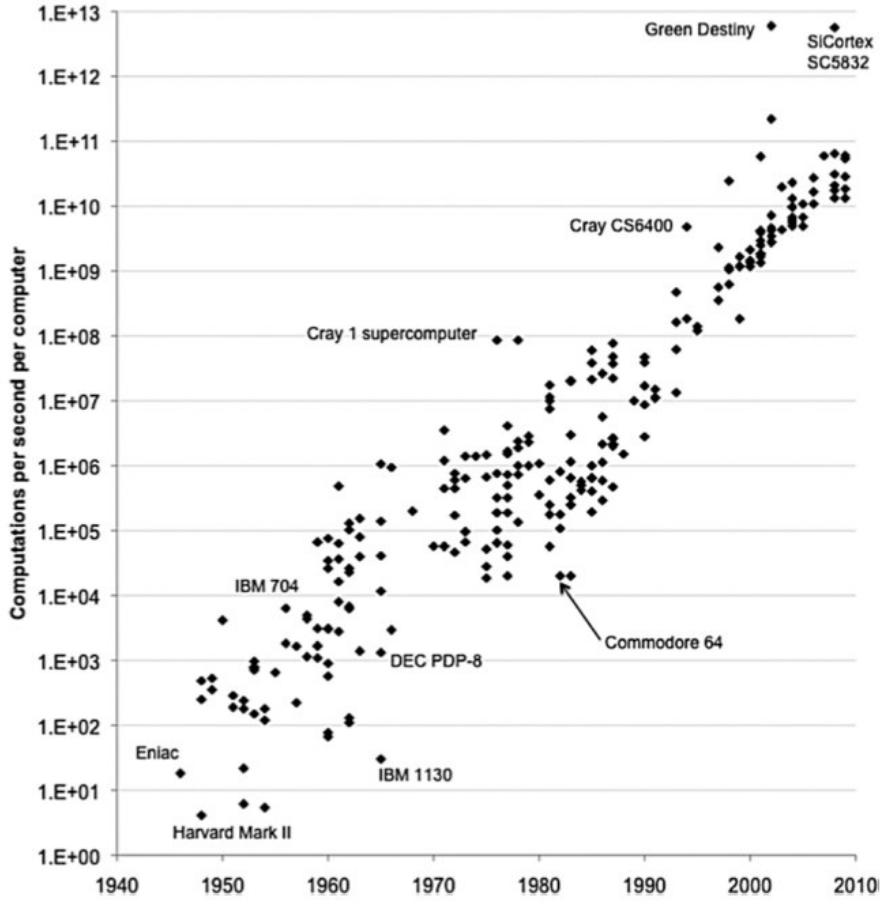
Wires to connect all the transistors together

Active devices (silicon transistors)

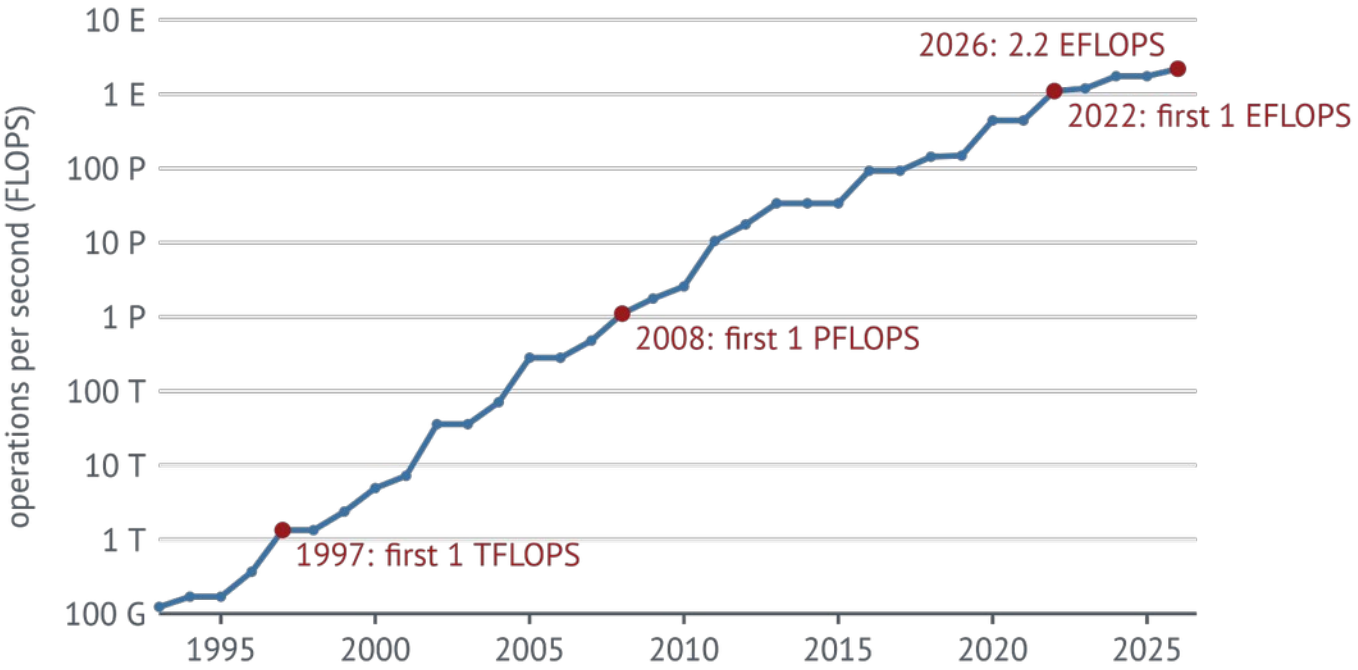
Cross section (electron microscope); M1 to M7 are metal wiring layers. Image: TechInsights

How much has computing power increased?

How did we get here? The fastest supercomputer is about 18 million times faster than in 1993.



Computations per second per computer, 1940 to 2010



0.124 TFLOPS (1993) to 2.2 EFLOPS (2026): about **18 million** times faster

Data: TOP500.org, No. 1 system each year.

Chart after Our World in Data: ourworldindata.org/grapher/supercomputer-power-flops

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

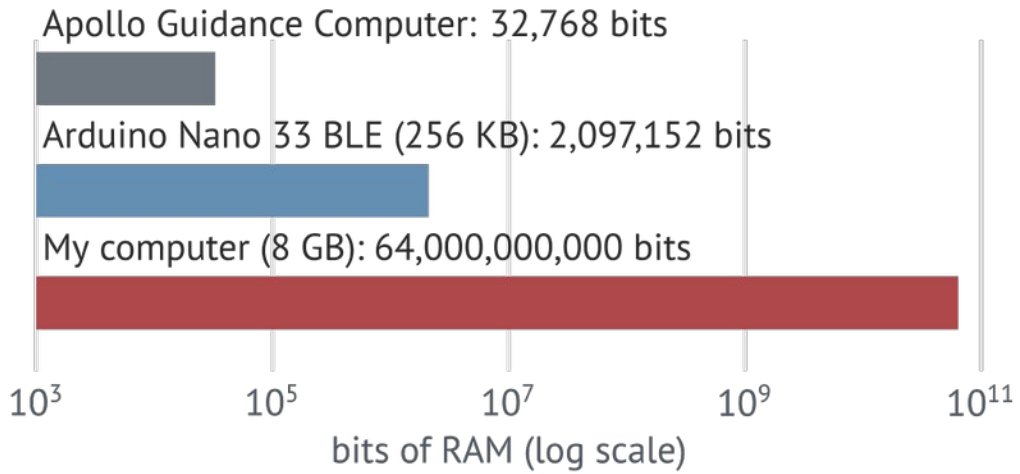
Apollo 11's guidance computer had 32,768 bits of RAM; my laptop has about 2 million times more.



Apollo Mission Control, Houston, with the July 1969 Apollo 11 displays

$$\frac{64 \times 10^9 \text{ bits}}{32\,768 \text{ bits}} \approx 2 \times 10^6$$

- On board Apollo 11: the **Apollo Guidance Computer**
- 2,048 words of RAM for temporary results (lost when power is off); each word is 16 bits
- 2,048 × 16 = **32,768 bits** of RAM
- My computer: 64,000,000,000 bits, about **2,000,000 times** more



Scaling: how much have we scaled devices?

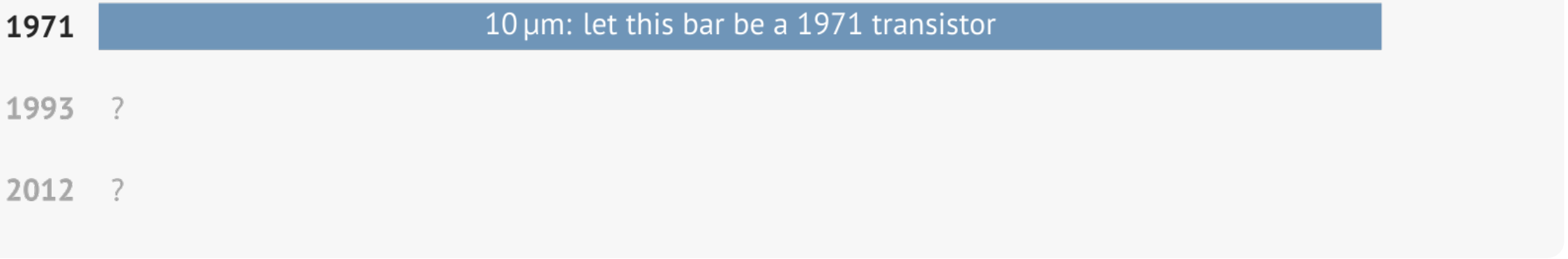
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How do we make transistors faster? Make them smaller. 1971: the first microprocessor.

- **1971: Intel 4004**, the first commercial microprocessor
- 4 bits; less than 1 square inch in area
- Transistors **10 µm** long; about 750 kHz clock
- More powerful than earlier computers that weighed 30 tons



Intel 4004 chips (C4004)

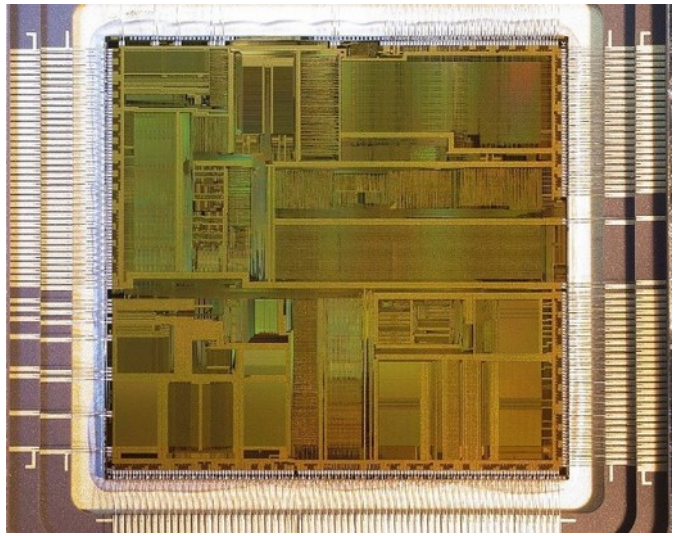


Scaling: how much have we scaled devices?

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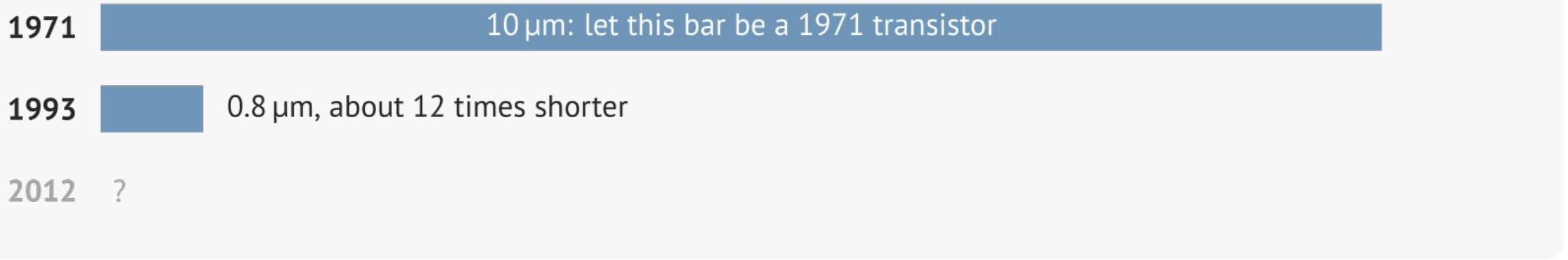
By 1993 transistors were about 12 times shorter and clocks nearly 100 times faster.

- **1993: the first Pentium** processor
- **66 MHz**: nearly 100 times faster than the 4004 of 1971
- Transistors about **0.8 µm** long



Pentium (A80501, 66 MHz) die

TRY IT Can you think of anything else that has improved by 100× in 20 years?

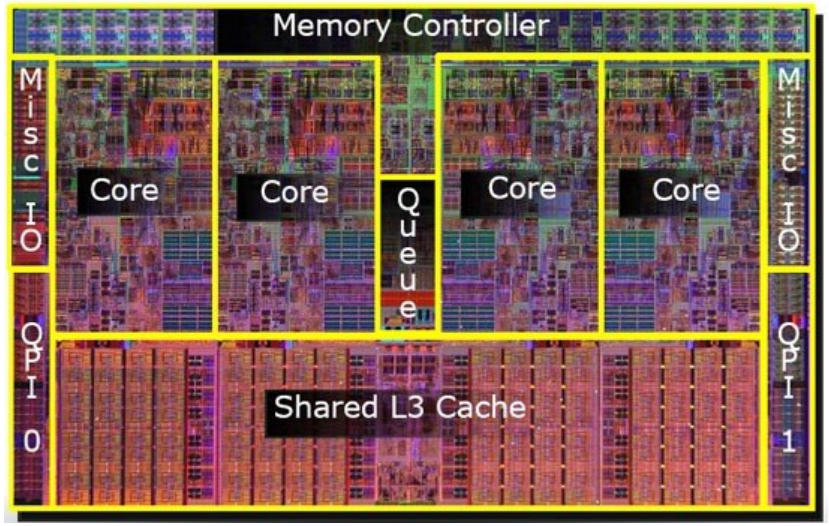


Scaling: how much have we scaled devices?

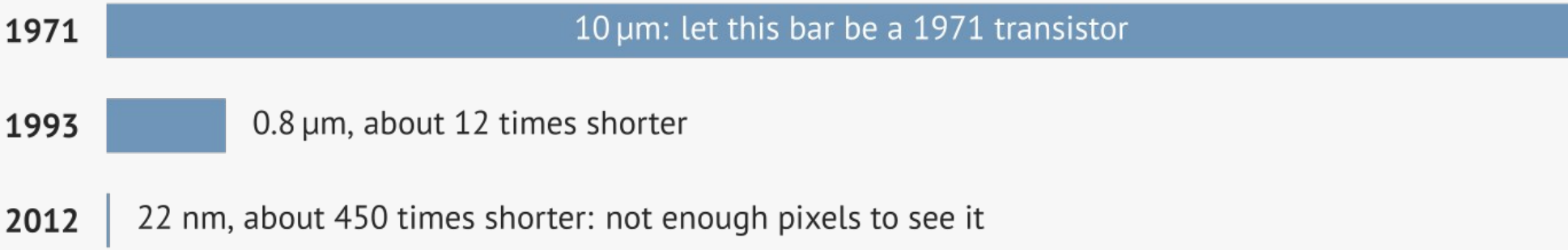
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By 2012 transistors were about 450 times shorter than in 1971.

- **2012**: 1 to 3 GHz clocks
- **Multi-core**: several processors on one chip
- Transistors about **22 nm** long: about 450 times shorter than in 1971 (200,000 times smaller in area)



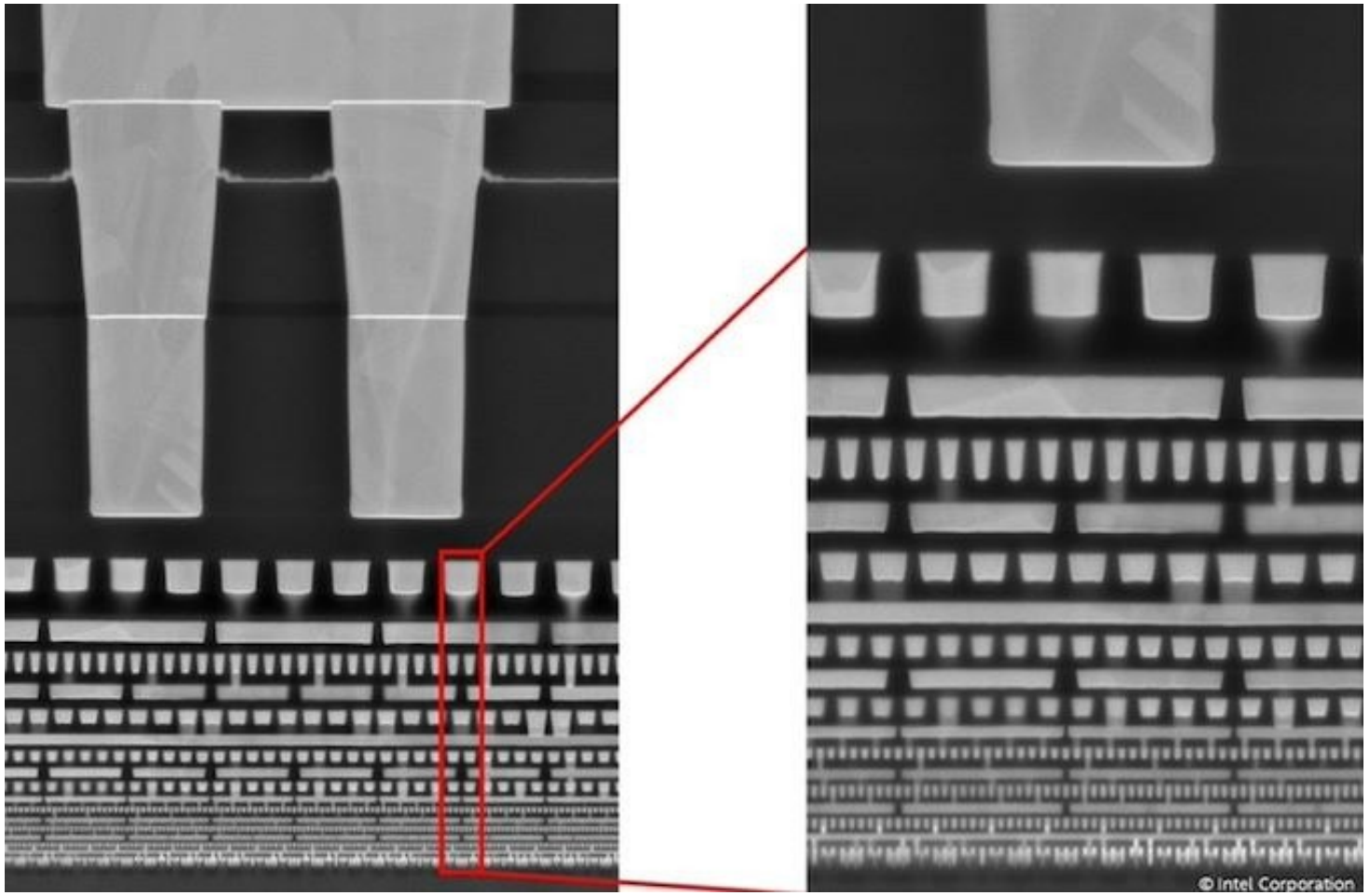
Intel Core i7 (Nehalem) die: four cores share an L3 cache



Scaling: how much have we scaled devices?

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A modern CPU cross section: almost everything you see is wiring.



Intel 4 process cross section, with a zoom into the lower layers. Image: Intel Corporation

CHECKPOINT

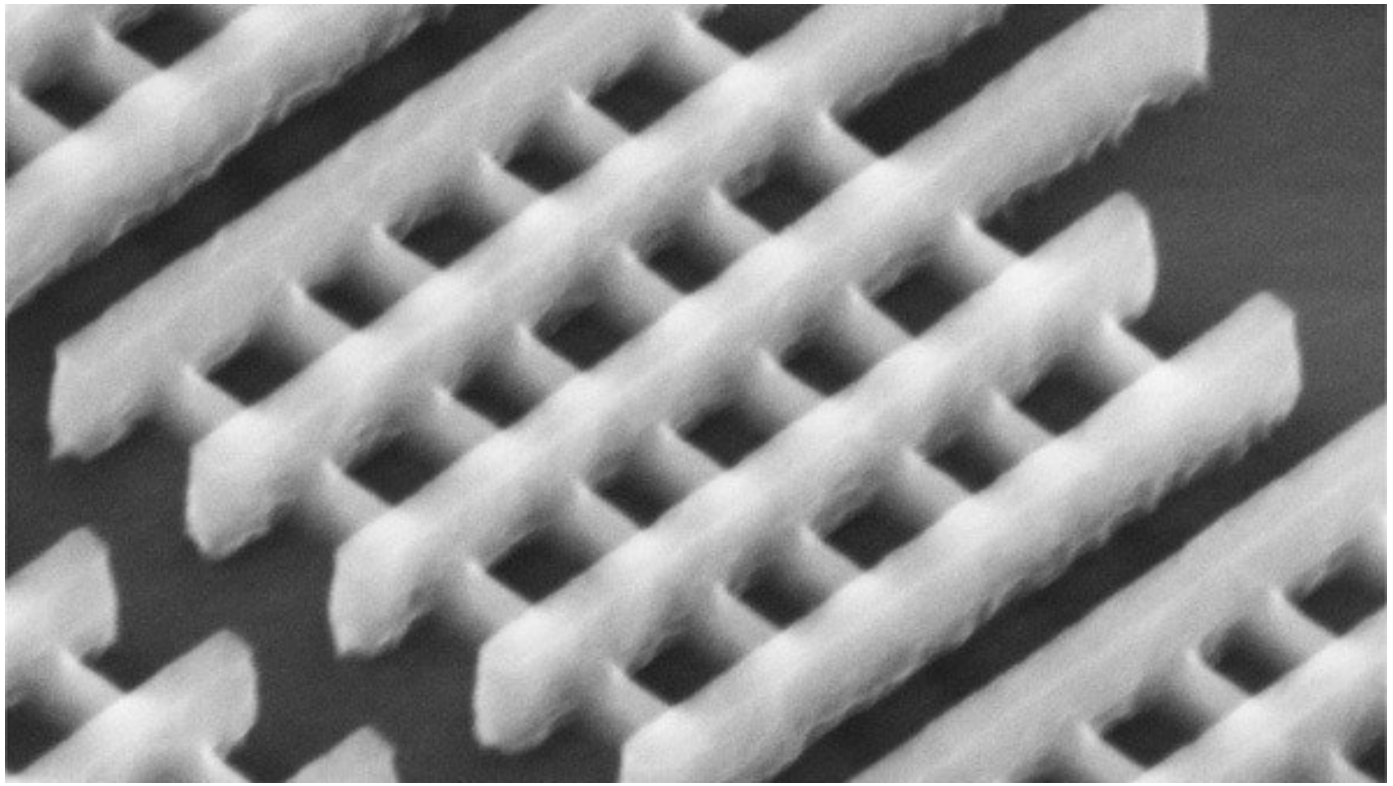
- What does a modern CPU cross section look like?
- Where are the transistors?
- What are we looking at?

Intel 4 went into production in 2023.

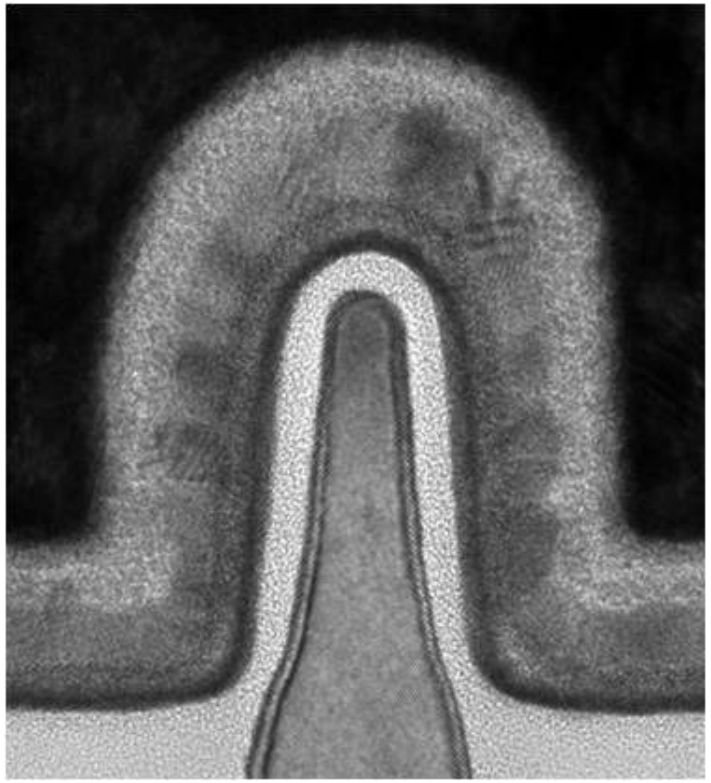
FinFET Transistors (May 2011 and After)

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From 2011, transistors stopped being flat: the channel rises out of the wafer.



Gate lines crossing rows of silicon fins (electron micrograph)



One fin under the gate, in cross section

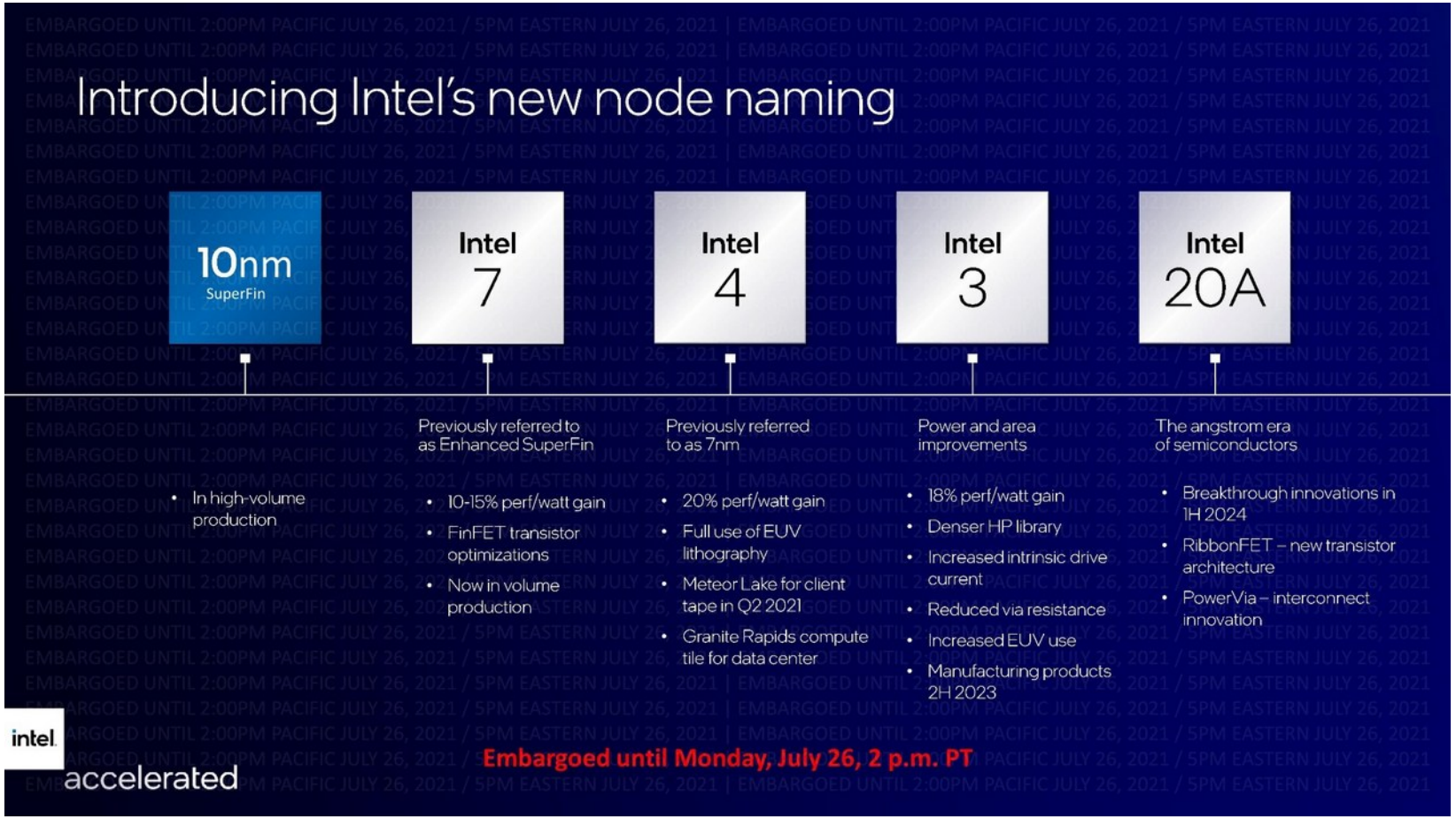
CHECKPOINT

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

Scaling: how much have we scaled devices?

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A recent roadmap for Intel's transistor scaling plans, with new node names.



Intel Accelerated, July 2021. Image: Intel

- 10 nm SuperFin is renamed **Intel 7**
- **Intel 4**: full use of EUV lithography
- **Intel 3**: more performance per watt
- **Intel 20A**: the angstrom era, with RibbonFET transistors and PowerVia

Scaling: how much have we scaled devices?

The next step after the FinFET: the nanoribbon (nanowire) transistor.

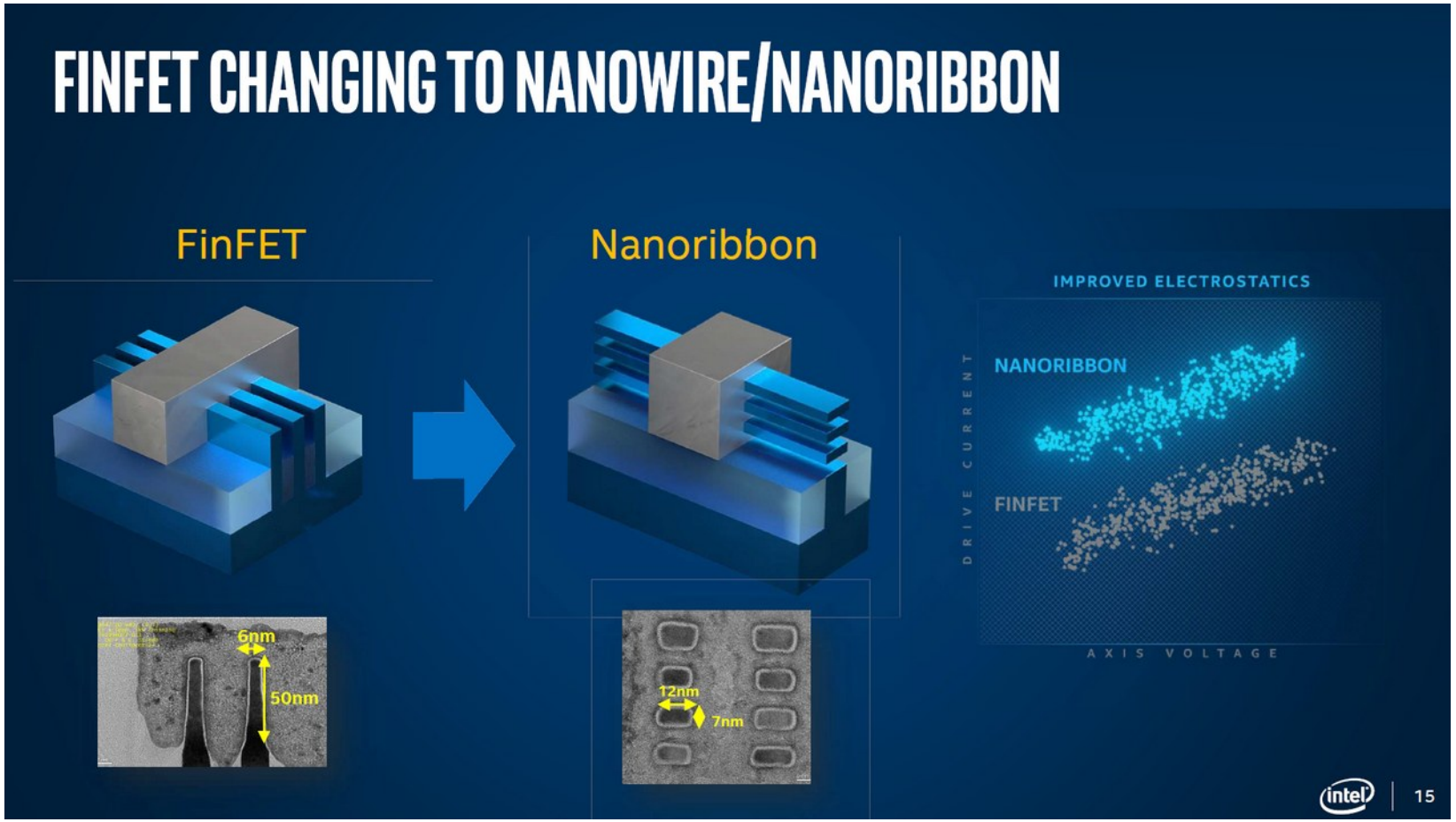


Image: Intel

CHECKPOINT

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

Hint: compare how much of the channel the gate touches in each picture.

My background and research

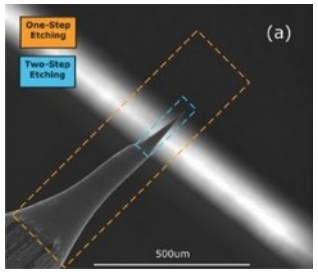
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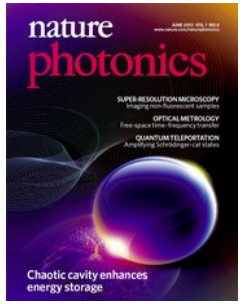
From electrical engineering and materials science to flexible bioelectronics and wearables.

BS, EE, 2010
MS, EE, 2012

UT DALLAS The University of Texas at Dallas KAUST

zyvex LABS

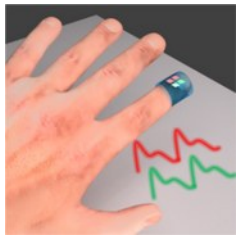




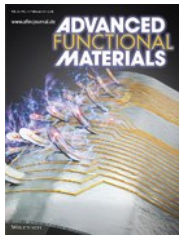
Electrical Engineering and Materials Science

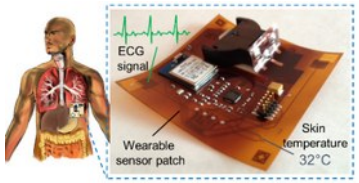
Started PhD, 2013
PhD, EECS, 2018

Berkeley UNIVERSITY OF CALIFORNIA











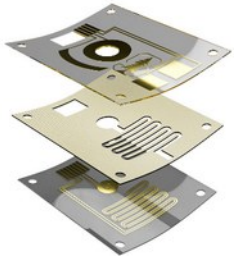


2014 2015 2016

Bioelectronic and Biophotonic Systems → Flexible Hybrid Electronics

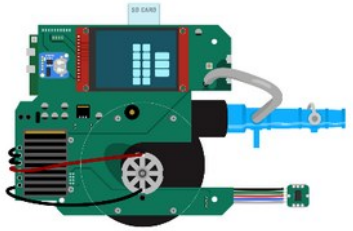
Started postdoc, 2019

Stanford





Wearables for precision health and psychiatry



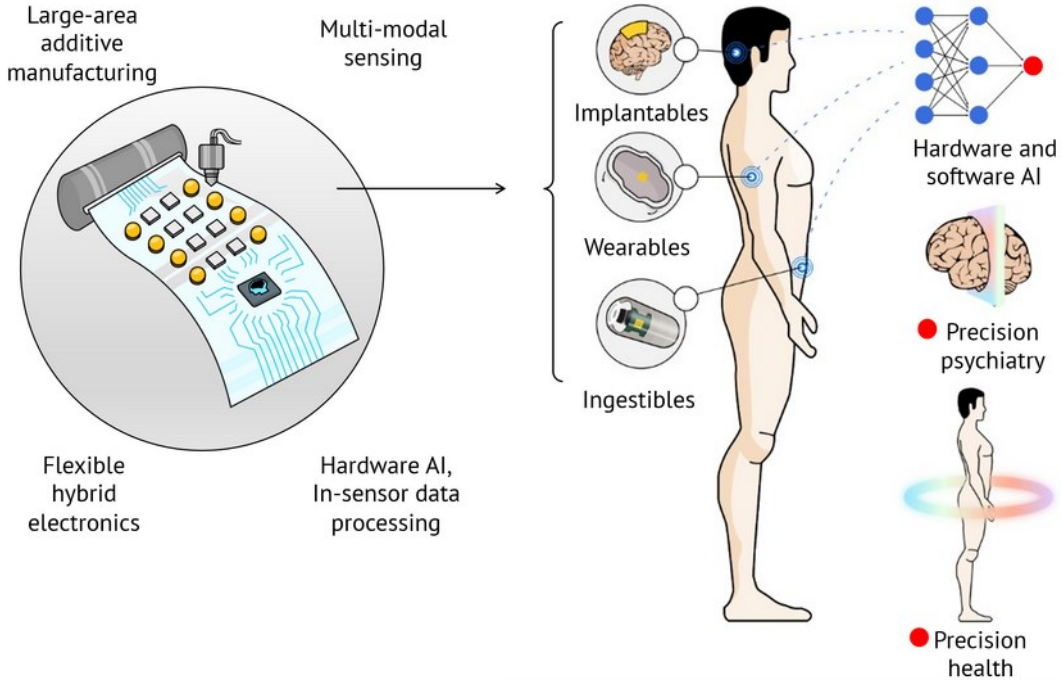
Ventilator for COVID-19

Khan Lab @ USC

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Large-area additive manufacturing, multi-modal sensing and hardware AI for health.





USC Viterbi School of Engineering

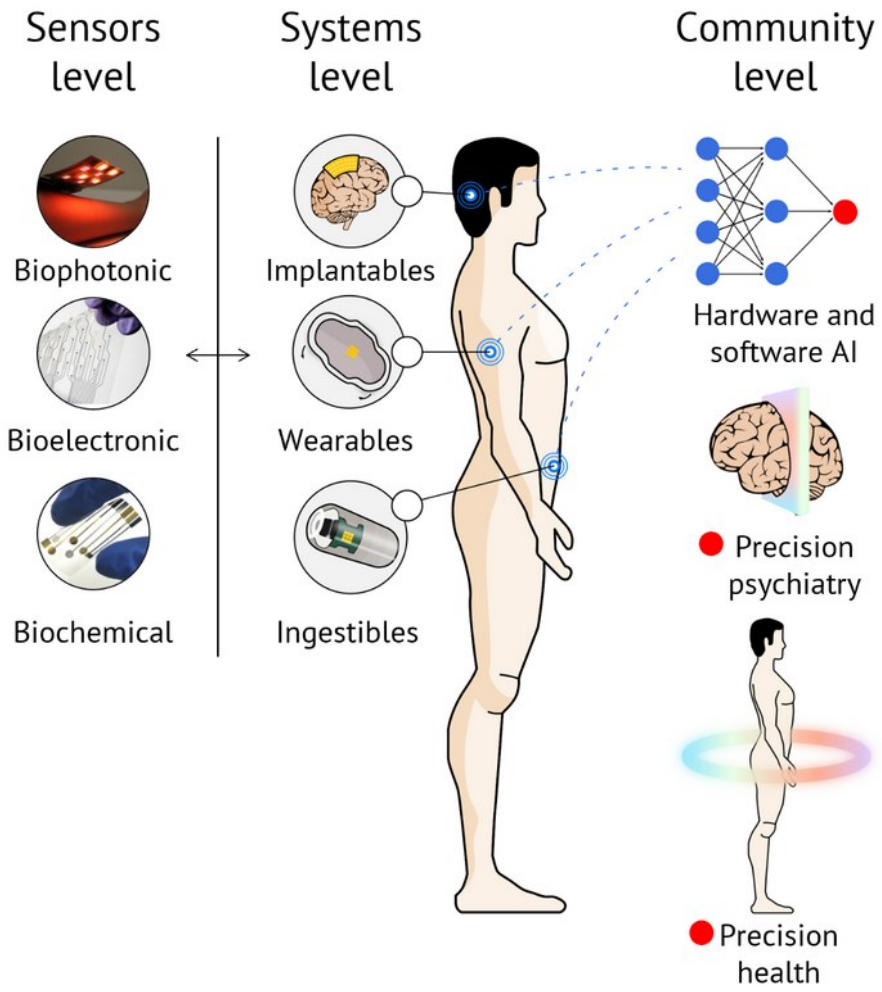
Keck School of Medicine of USC

USC Institute for Technology And Medical Systems Innovation

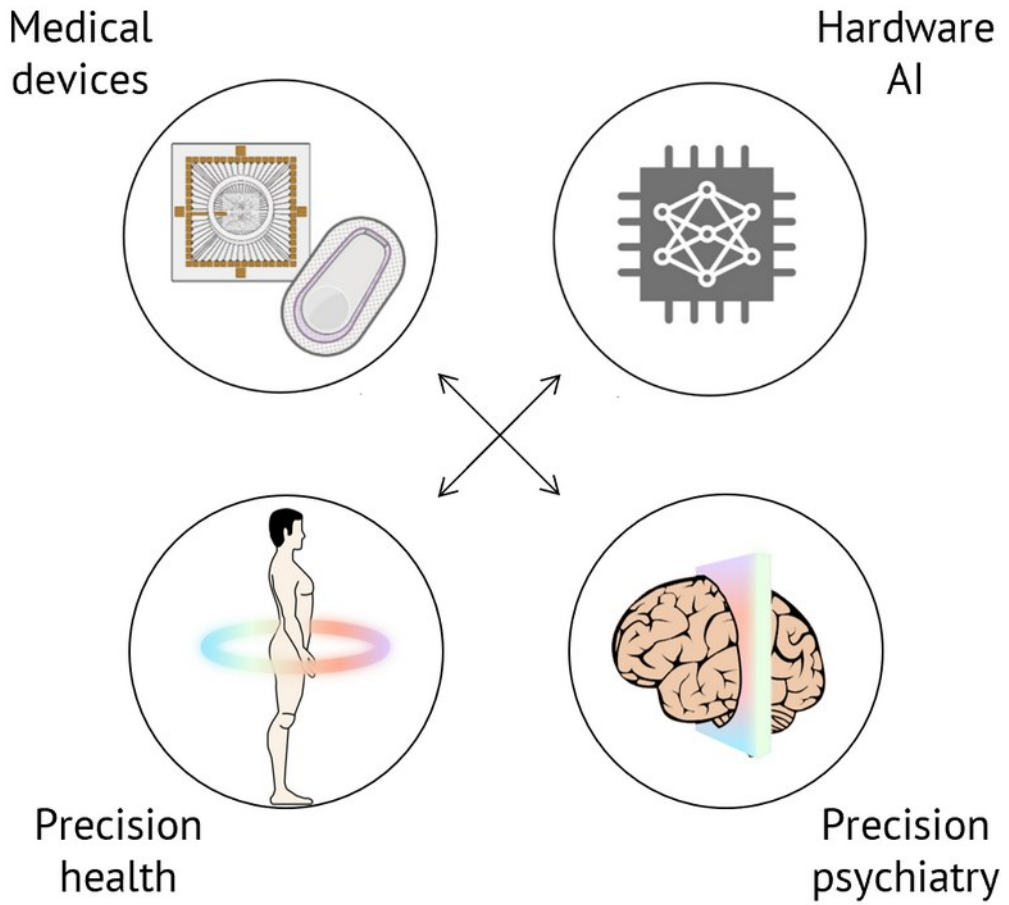
Khan Lab @ USC

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Research at three levels, sensors, systems and community, for precision health and psychiatry.



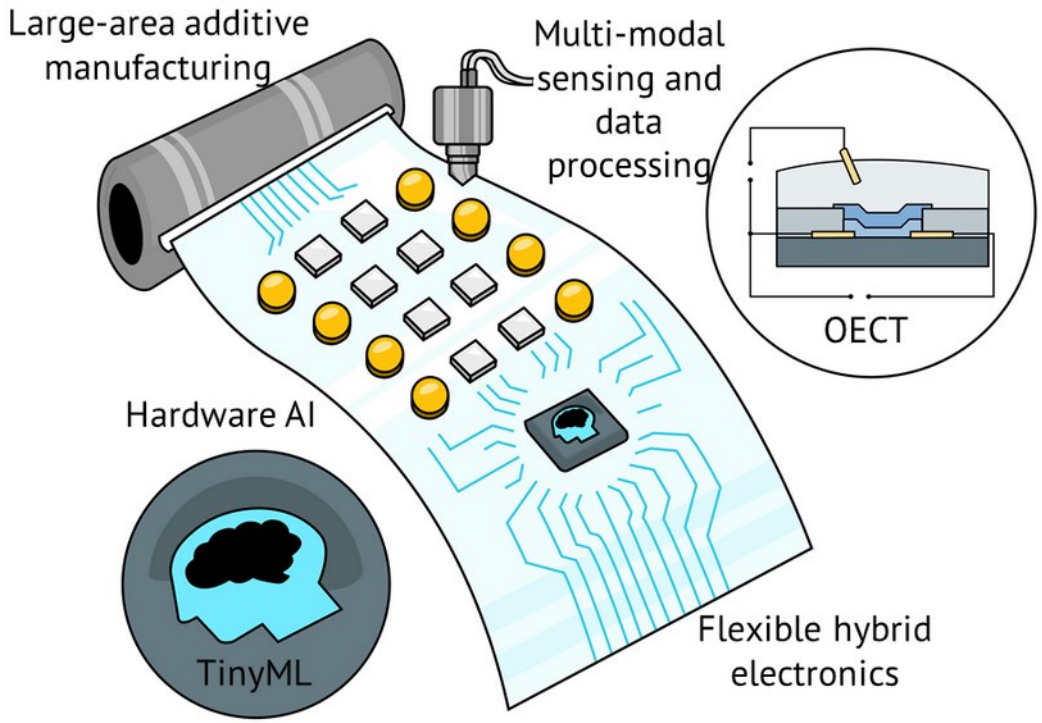
Research focus

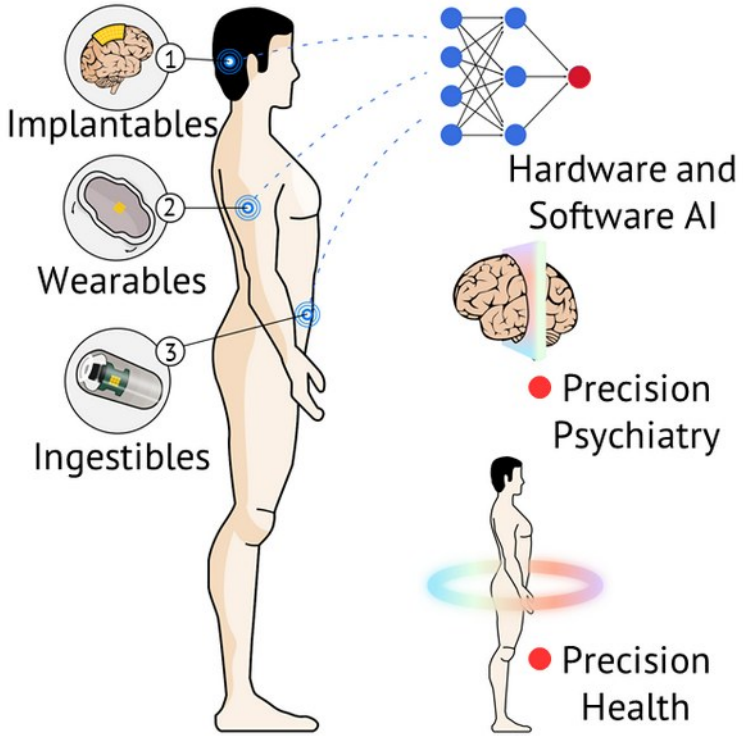


Soft sensor systems for precision health and psychiatry

USC University of Southern California

From materials and devices to complete systems on, in and inside the body.





Materials, Manufacturing, Design, Devices, and Circuits

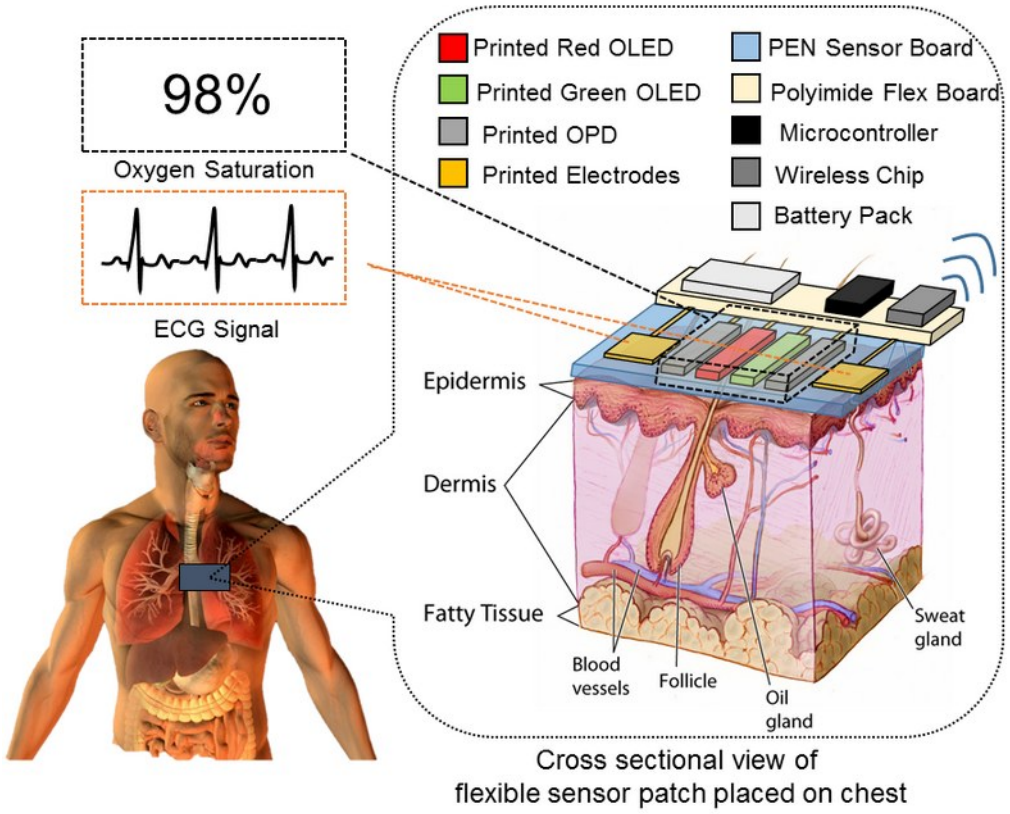
Systems and Applications

Sensors for precision health and psychiatry

USC University of Southern California

From big, wired bedside machines to a flexible patch that measures vital signs.





Cross sectional view of flexible sensor patch placed on chest

Current state

Big machines with many wired, rigid sensors that limit the patient's comfort

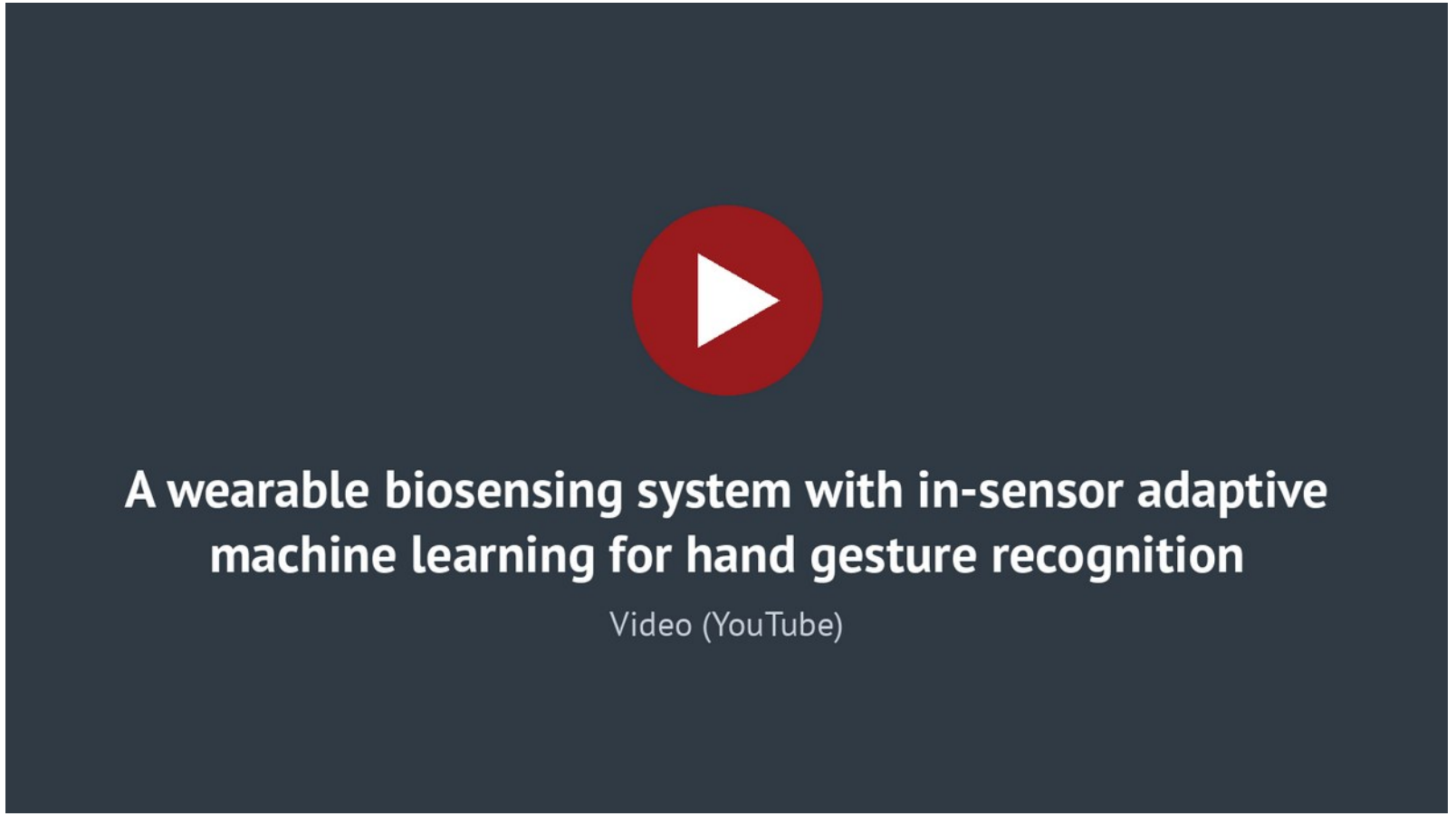
Vision

A flexible sensor patch that measures vital signs: the body's most basic functions

AI-powered biosensor for detecting hand gestures

USC University of Southern California

Biopotential sensing for gesture recognition, with machine learning inside the sensor.



Video: wearable biosensing with in-sensor machine learning for gestures (YouTube)

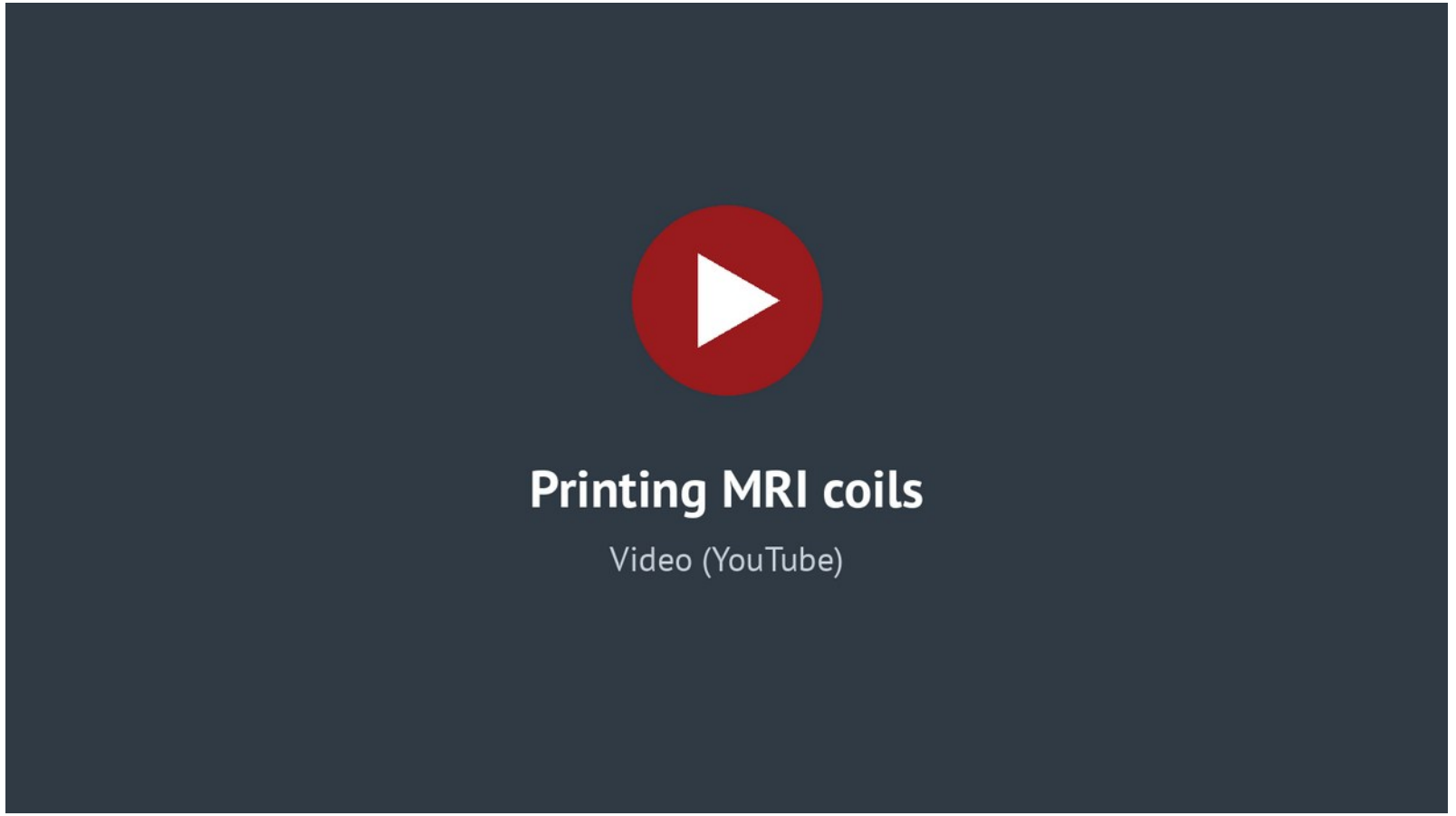
Biopotential sensing for gesture recognition

- Sensors on the skin pick up electrical signals from the muscles
- A learning model in the sensor turns them into gestures

Screen-printed MRI receive coils

USC University of Southern California

Printing makes sensors quickly and at scale, in far fewer steps than photolithography.



Video: Printing MRI coils (YouTube)

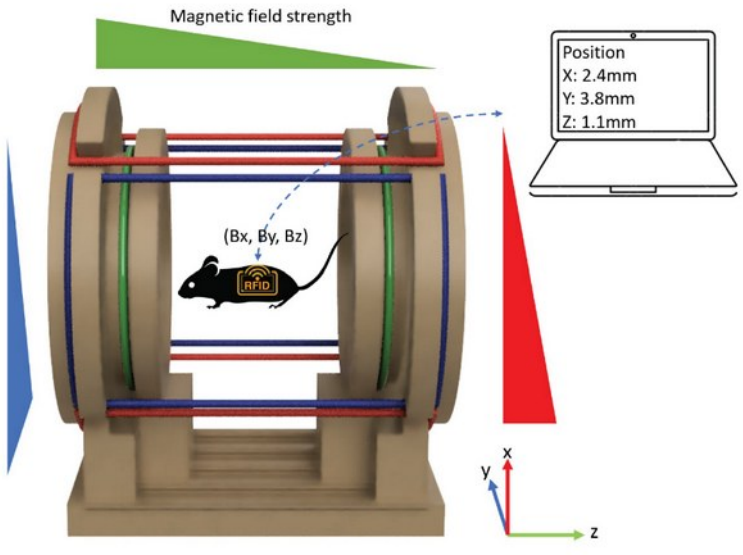
- **High-throughput**
- **Scalable**
- **Fast**
- Significantly fewer process steps than photolithography

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

USC University of Southern California

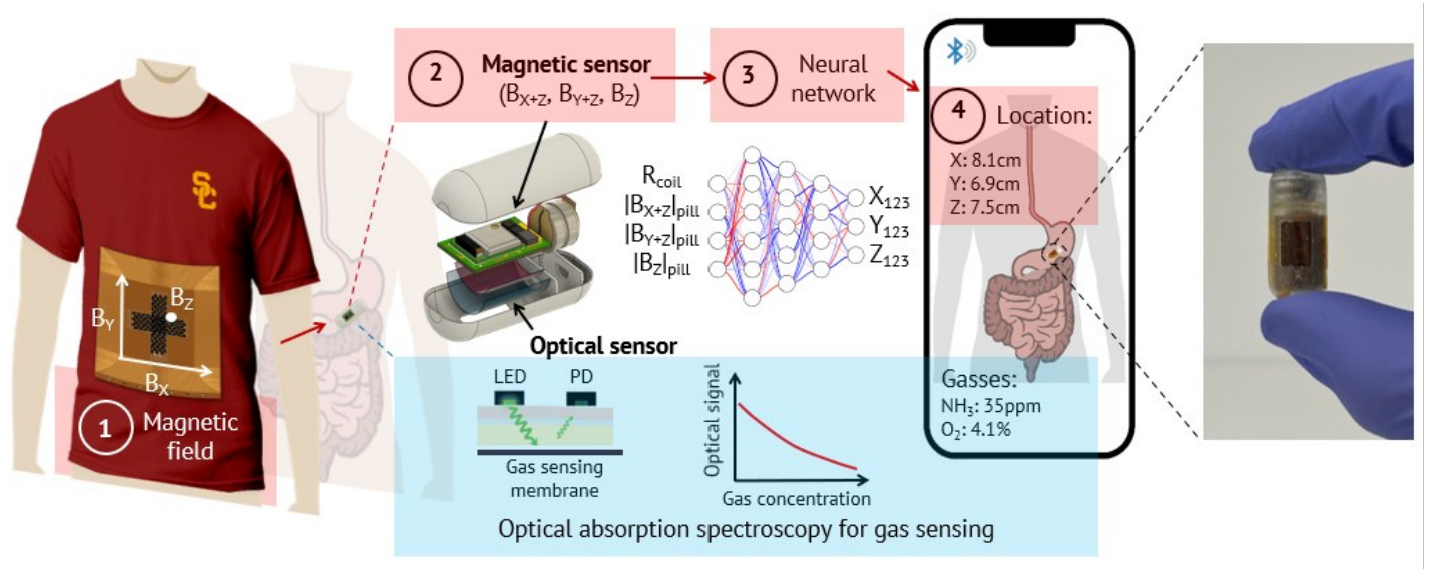
Locating a gas-sensing pill in 3D: from a lab coil around the animal to a coil you wear.

Existing approach



A **Helmholtz coil** produces a region of nearly uniform magnetic field and localizes the ingestible inside the coil.

Our approach



A **wearable multi-layer coil** creates a 3D field gradient, and a **bend sensor** accounts for movement.

In the pill: a magnetic sensor feeds a neural network that outputs x, y, z; an optical sensor measures gases such as NH_3 and O_2.

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

USC University of Southern California

Smart pills that report where they are and which gases they sense.

USC Viterbi School of Engineering

About Academics Admission Research Innovation

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

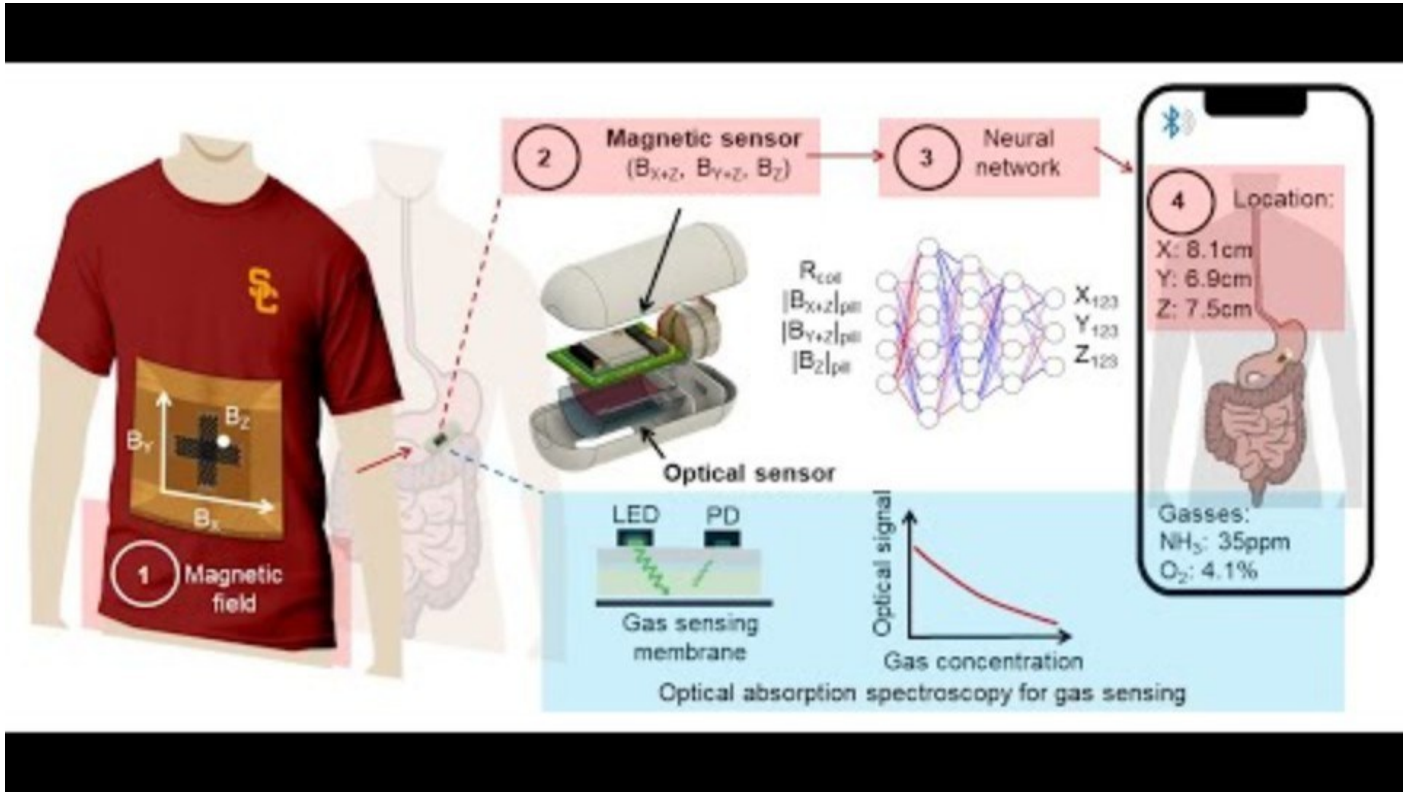
Amy Blumenthal | June 12, 2024

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

USC Viterbi news, 2024



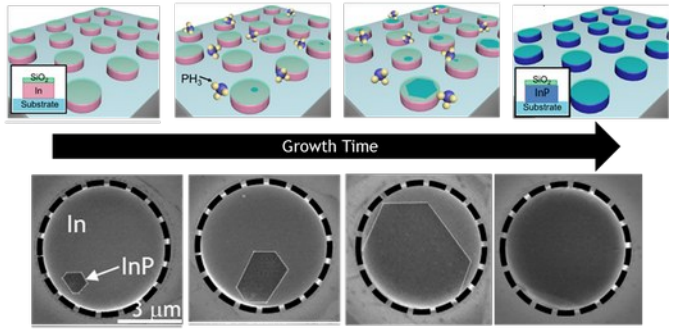
[Video: 3D gas mapping in the gut (YouTube): https://youtu.be/nmVMDQnRuhw](https://youtu.be/nmVMDQnRuhw)

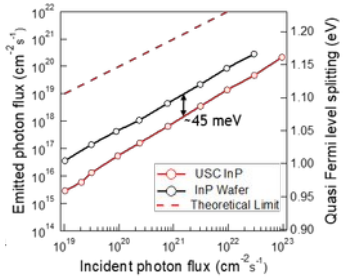
Kapadia Lab Research Portfolio

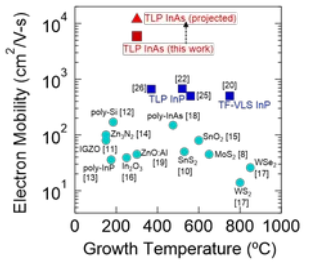
USC University of Southern California

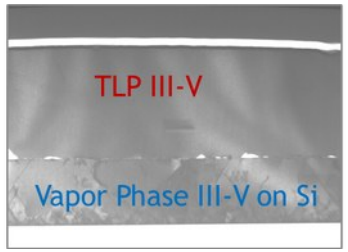
Three directions: III-V materials on silicon, electron emitters for GHz to THz, low-power computing.

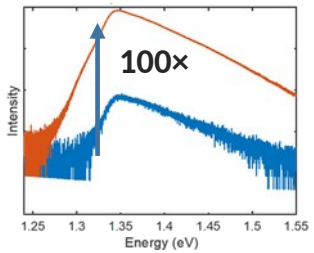
Back-End Materials Growth and Heterogeneous Integration



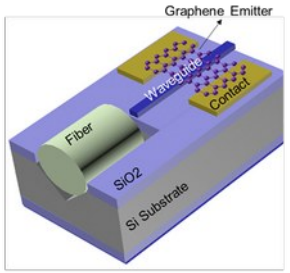


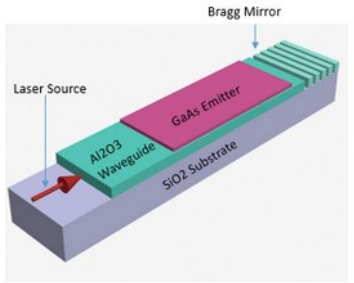


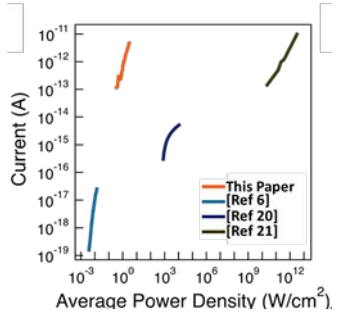


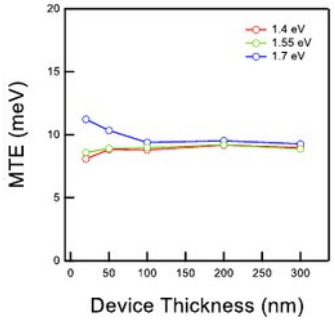


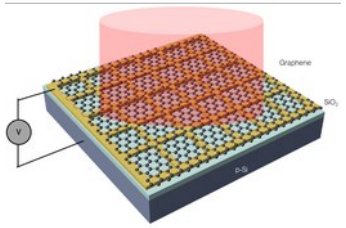
Electron Emission Devices for GHz to THz Applications

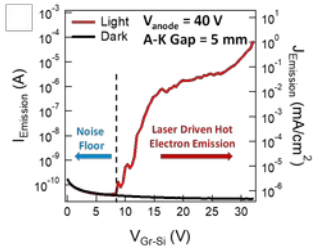




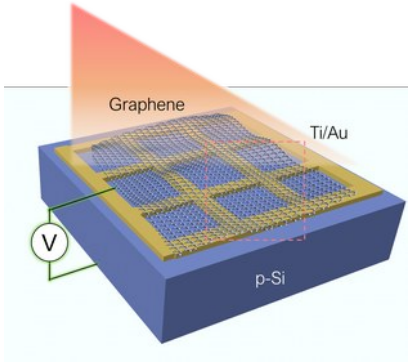


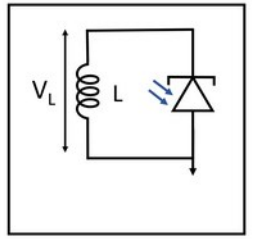






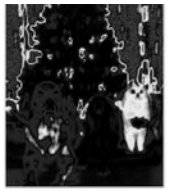
Ultra-Low Power Computing







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

USC's cleanroom for making devices: etch, deposition, lithography, wet processing, packaging.



Etch | Deposition | Lithography | Wet processing | Packaging | Infrastructure

Facility

- $50M, 12,000 sq. ft. facility, plus 24,000 sq. ft. of automated space 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 100 mm (min) and 150 mm (subset, but all III-V)

Scalability

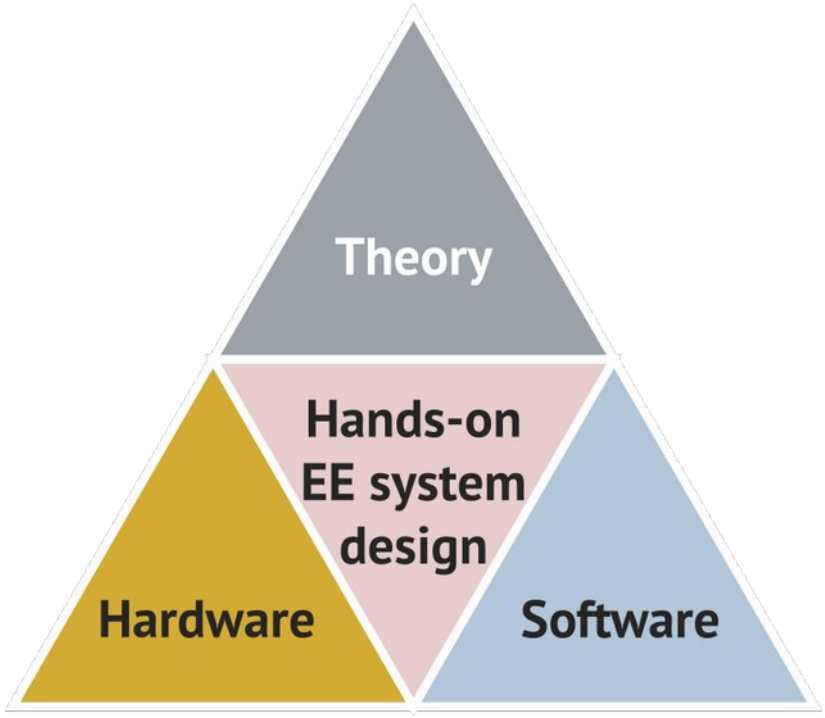
- 200+ users (2024), with expansion to 500+ planned; the lab can handle 100 active users
- Space available in the current facility for more capacity and capability

EE 105 Course objectives

USC University of Southern California

Theory, hardware and software meet in hands-on design of complete electronic systems.

- 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

Course logistics

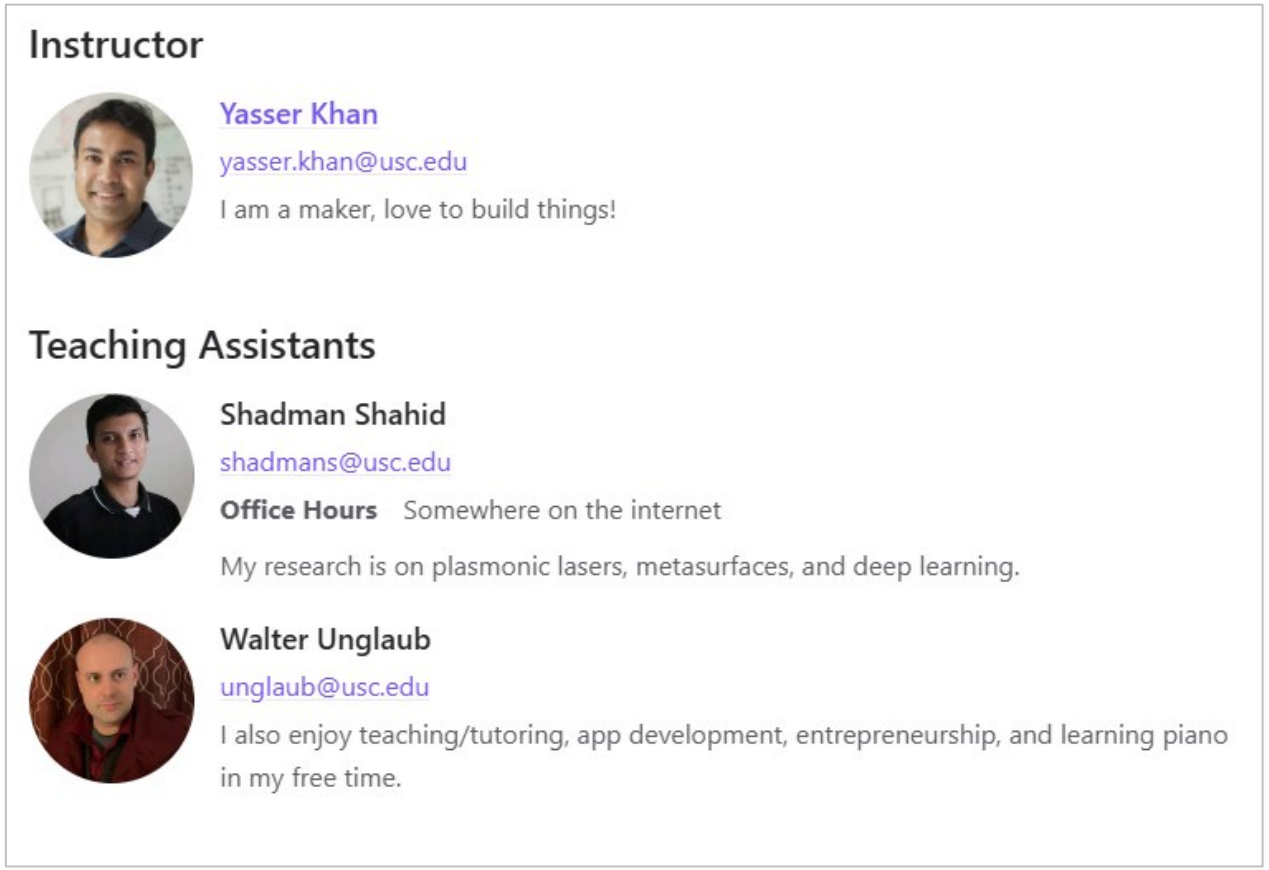
Course content and schedule live on ee105.org; announcements and grades on Brightspace.

- Course content and schedule: **ee105.org**

  https://ee105.org

- Announcements and grading: **Brightspace**

Instructor and teaching assistants, with contact details, are listed on the course page.



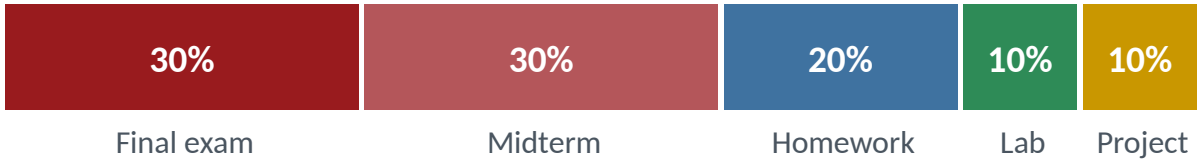
Instructor and teaching assistants (from ee105.org)

Course structure

Lectures and discussions are enough for the homework and the final exam.

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

Grading

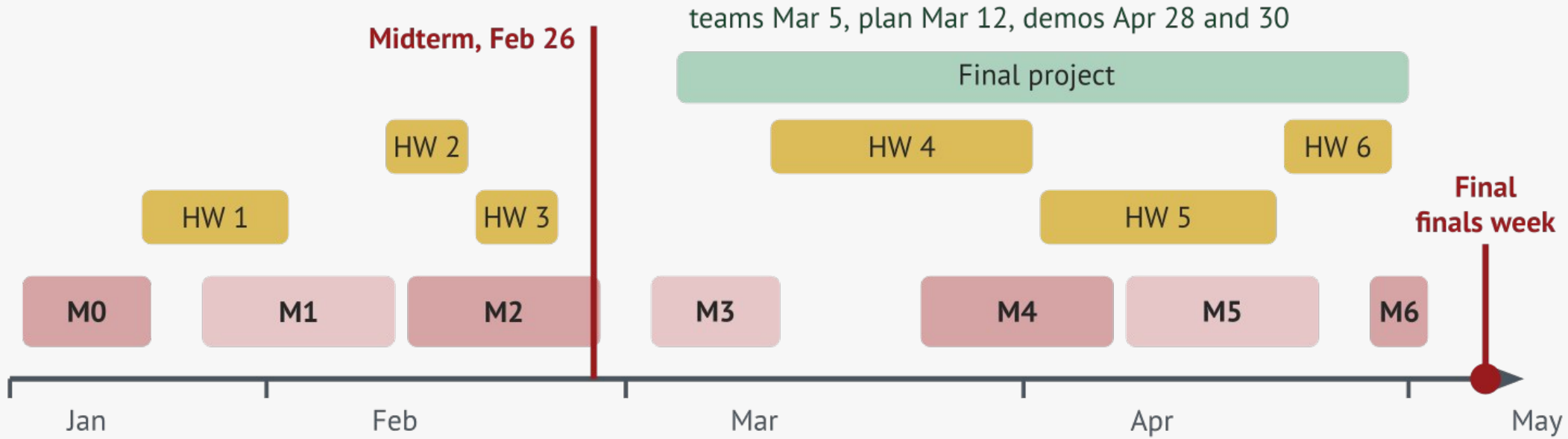


Component	Weight	Details
Final Exam	30%	Cumulative; two pages of handwritten notes allowed (no printing).
Midterm Exam	30%	Covers circuits and devices; one page of handwritten notes allowed (no printing).
Homework	20%	Six assignments: 1. Arduino/Python, 2. Circuits, 3. Devices, 4. Sensors, 5. Neural Networks, 6. Optical Communications
Lab	10%	Ten labs (0.1 to 5.1), one notebook each; upload its submission file on ee105.org/portal (graded automatically)
Final Project	10%	Group project (teams of 5) using demo board and Arduino. Project ideas due by **Oct 23** via email. Deliverables: 1. Class presentation / 2-min YouTube video (5 min): 5%; 2. Report (2 pages): 2.5%; 3. Source code (zip file): 2.5%

Approximate schedule

Six modules, six homework assignments, a midterm in February and a final in finals week.

- Course homepage: **ee105.org**
- **6 homework** assignments
- **Midterm:** Feb 26, in class
- **Final:** in finals week



Course content

USC University of Southern California

Six homework assignments follow the six modules; the midterm covers circuits and devices.

- **6 homework** on 6 modules:
  - Arduino/Python
  - Circuits
  - Devices
  - Sensors
  - Neural network
  - Communication systems
- **Midterm** covers circuits and devices
- **Final** covers everything

Module	Date	Class	Lab	Homework, exams
0 Intro	Jan 13	Intro to electrical engineering	Hand out the boards	
	Jan 15	Intro to electronic systems	Demo of the board	
	Jan 20		Lab 0.1: Arduino and board	
	Jan 22		Lab 0.2: Python bootcamp	HW 1 released
1 Circuits	Jan 27	Circuits 1		
	Jan 29		Lab 1.1: touch panel	
	Feb 3	Circuits 2		HW 1 due
	Feb 5	Circuits 3	Lab 1.2: circuit analysis	
	Feb 10	Tutorial: circuit problems	Lab 1.2: circuit analysis	HW 2 released
2 Devices	Feb 12	Device 1		
	Feb 17	Device 2		HW 2 due, HW 3 released
	Feb 19		Lab 2.1: diode, transistor I-V	
	Feb 24	Device 3		Practice midterm; HW 3 due
	Feb 26			**Midterm**

Course content

USC University of Southern California

Second half: sensors, machine learning, communications, then final project demos.

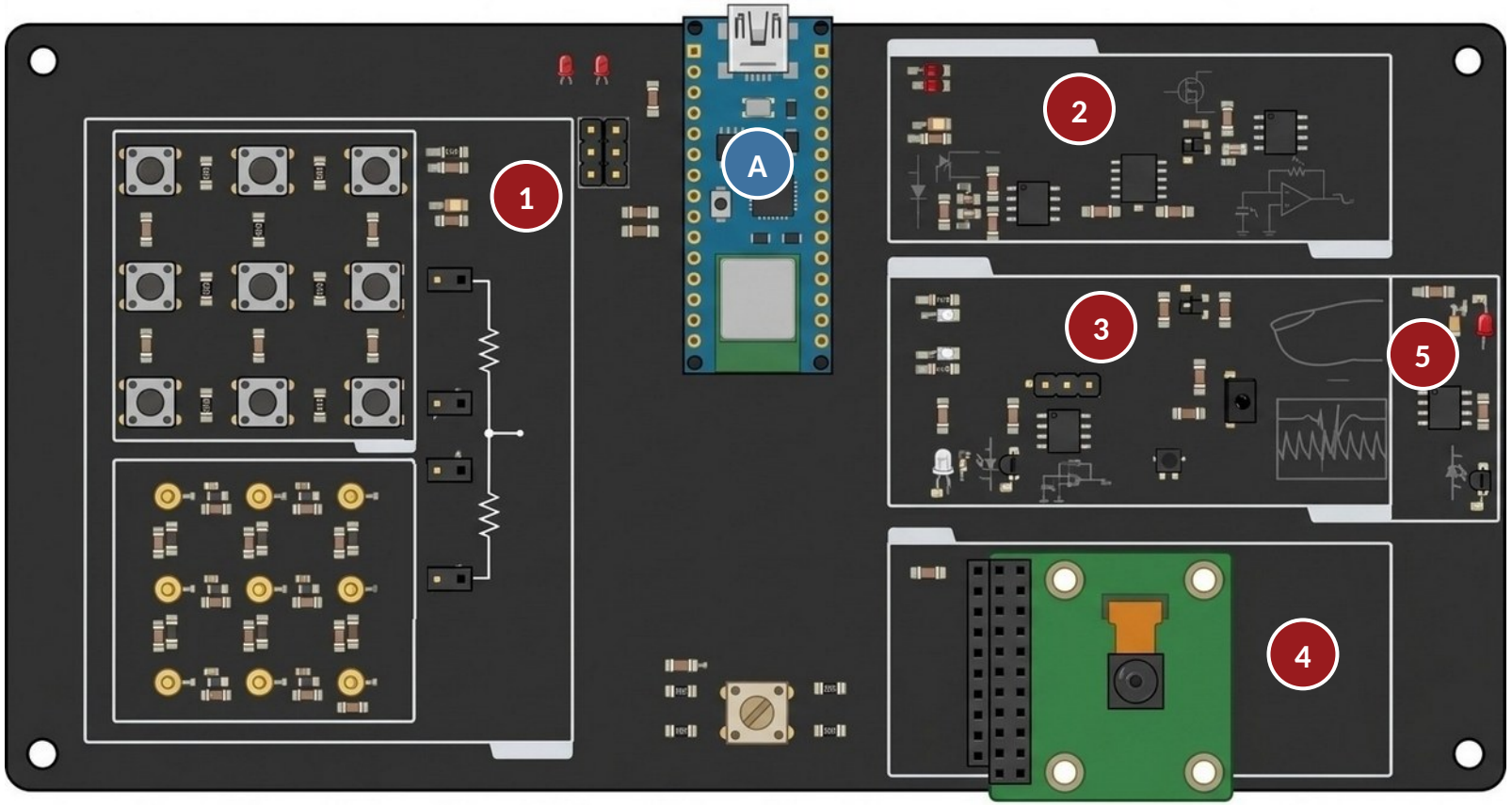
Module	Date	Class or lab	Homework, project
3 Sensors	Mar 3	Sensors 1; Lab 3.1: temperature sensor	
	Mar 5	Sensors 2	Final project teaming (groups of 5)
	Mar 10	Lab 3.2: oximeter data collection and processing	
	Mar 12	Sensors 3	Project plan due; HW 4 released
4 Machine learning	Mar 24	Neural network 1	
	Mar 26	Neural network 2; Lab 4.1: image/text classification	
	Mar 31	Neural network 3; Lab 4.1: image/text classification	
	Apr 2	Neural network 4; Lab 4.2: camera classifier	HW 4 due, HW 5 released
	Apr 7	Lab 4.1: image/text classification	

Module	Date	Class or lab	Homework, exams
5 Comm	Apr 9	Communications 1	
	Apr 14	Lab 5.1: LiFi	
	Apr 16	Communications 2; demo: sensor fusion	
	Apr 21	No class	HW 6 released; practice final; final topic list; HW 5 due
	Apr 23	No class: project work	
6 Projects	Apr 28	Teams 1 to 4 present	
	Apr 30	Teams 5 to 9 present	HW 6 due

Custom demonstration board for EE 105

USC University of Southern California

One board holds the hardware for every module; its printed block labels match the module numbers.



A **Arduino Nano 33 BLE**
runs every module

1 **Module 1: Circuits**
dividers, touch

2 **Module 2: Devices**
diode, transistor

3 **Module 3: Sensors**
oximeter

4 **Module 4: ML**
machine vision with the camera

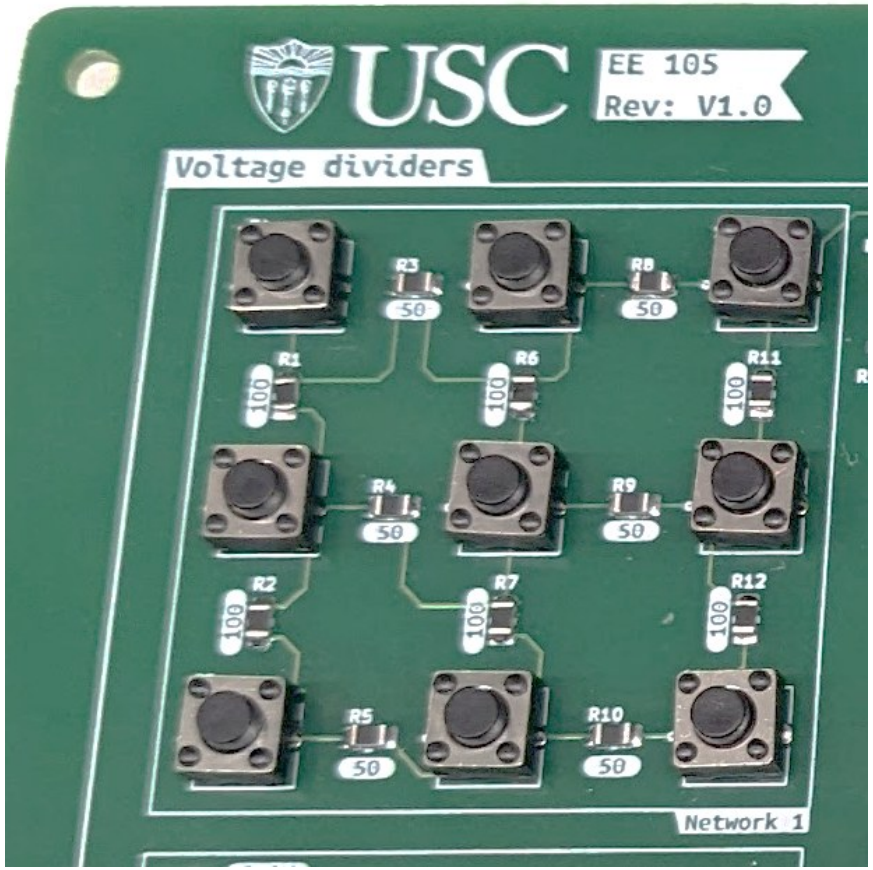
5 **Module 5: Comm**
light link: LED and photodiode



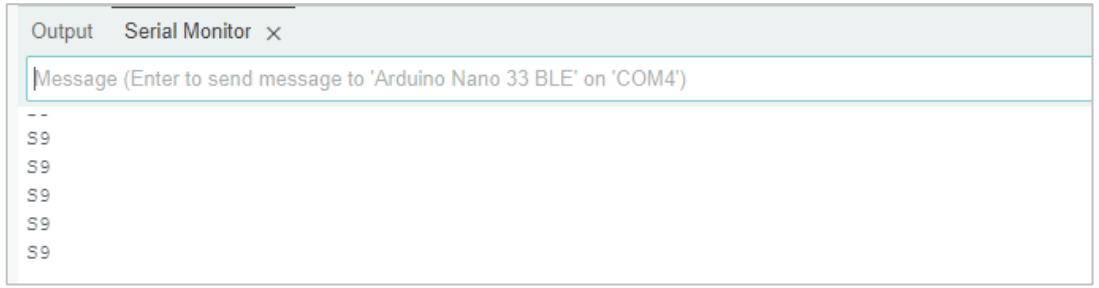
Machine vision

Module 1 on circuits: demo resistive touchscreen

Finds the pressed button location automatically.



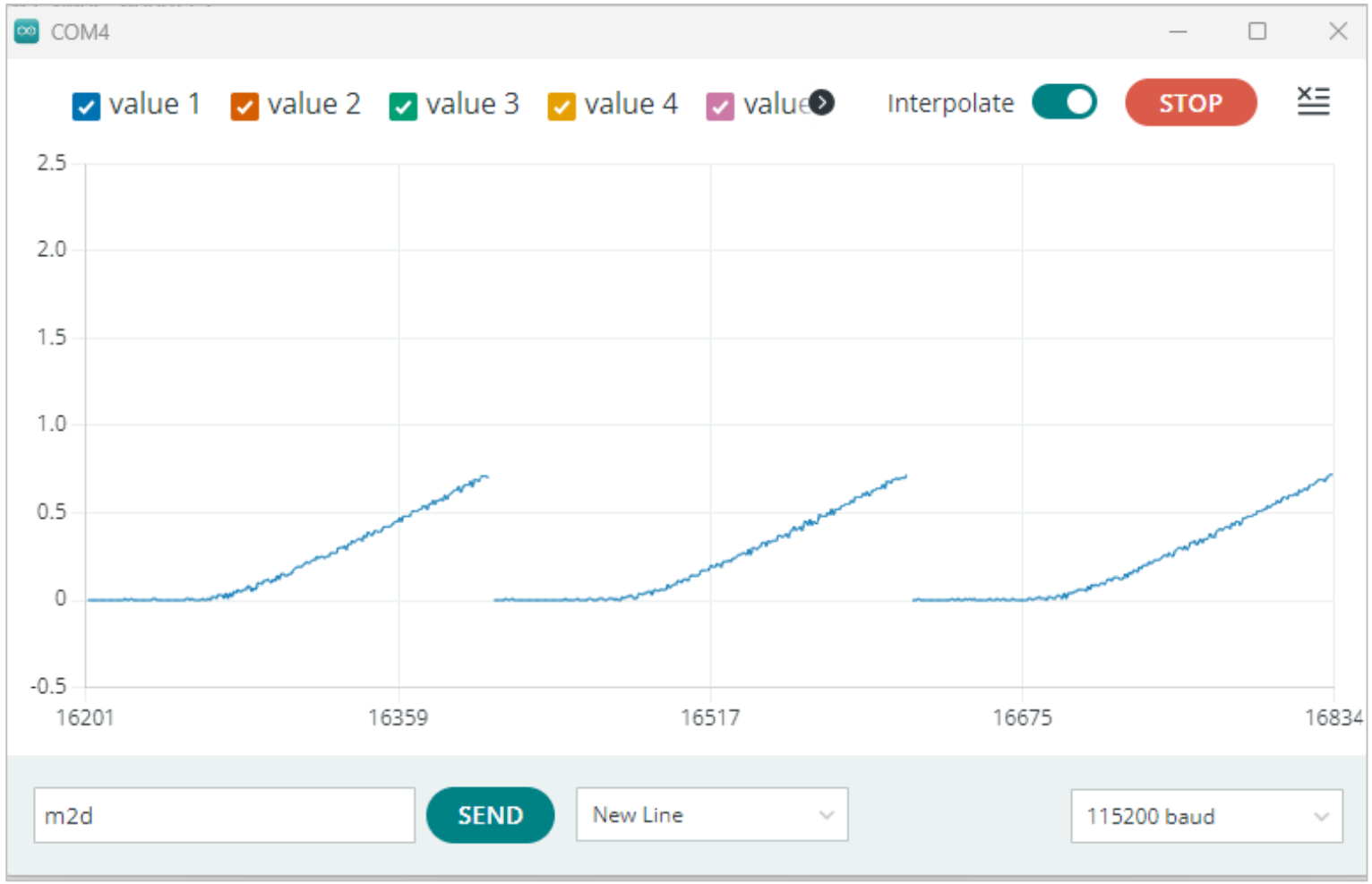
- A 3 × 3 grid of buttons on a **resistor network**
- Each node sits at a different voltage between 3.3 V and 0 V
- A press connects its node to analog pin **A0**
- The Arduino measures the voltage and names the button



Serial Monitor: the Arduino reports button S9

Module 2: diodes and transistors

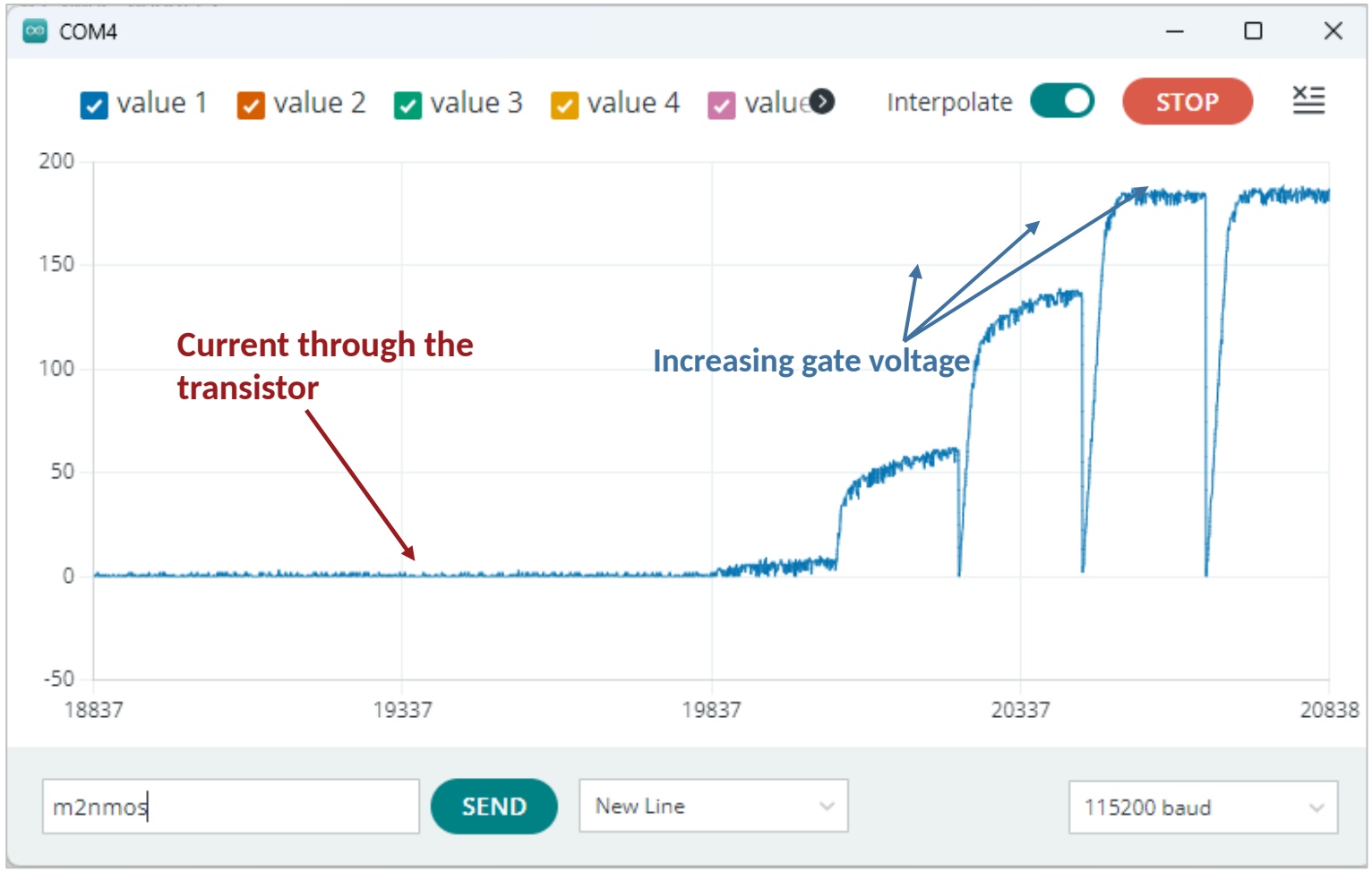
Characterize a semiconductor diode: how does it work?



- The board sweeps the **voltage** across the diode and measures its **current**
- Each ramp in the plot is one sweep
- The current stays near zero, then rises once the diode turns on

Module 2: diodes and transistors

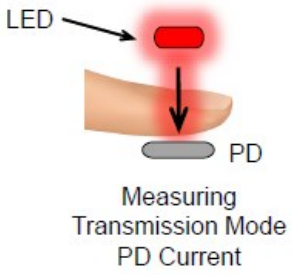
Characterize semiconductor transistors: how do they work?

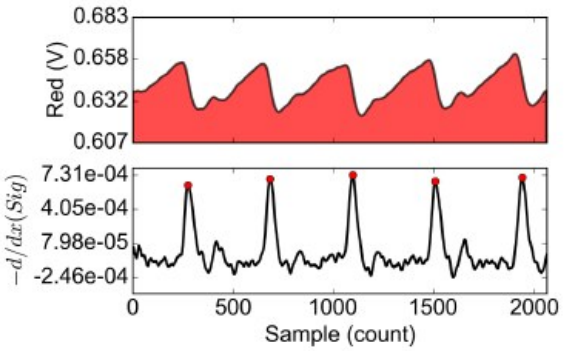


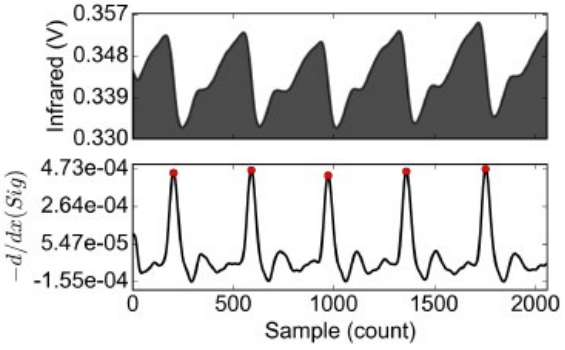
- Each step raises the **gate voltage**
- The current through the transistor jumps to a higher level
- Water analogy: raising the gate voltage is **opening the faucet**

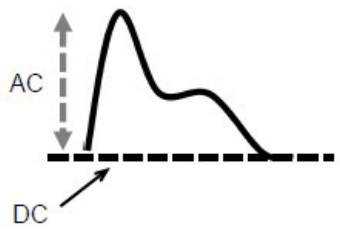
Module 3: sensors

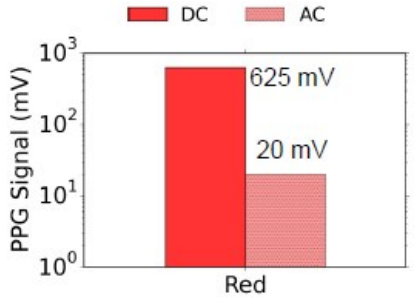
A pulse oximeter compares how red and infrared light pass through the finger.

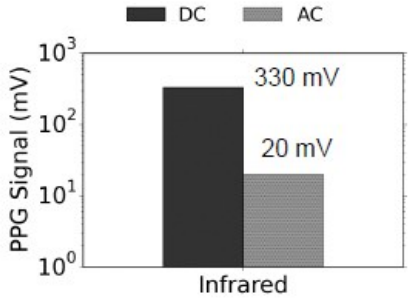












Ratio of ratios

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

This finger

$$R = \frac{20\ \text{mV}/625\ \text{mV}}{20\ \text{mV}/330\ \text{mV}} = 0.528$$

Blood oxygen

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

Module 3: sensors: oximeter

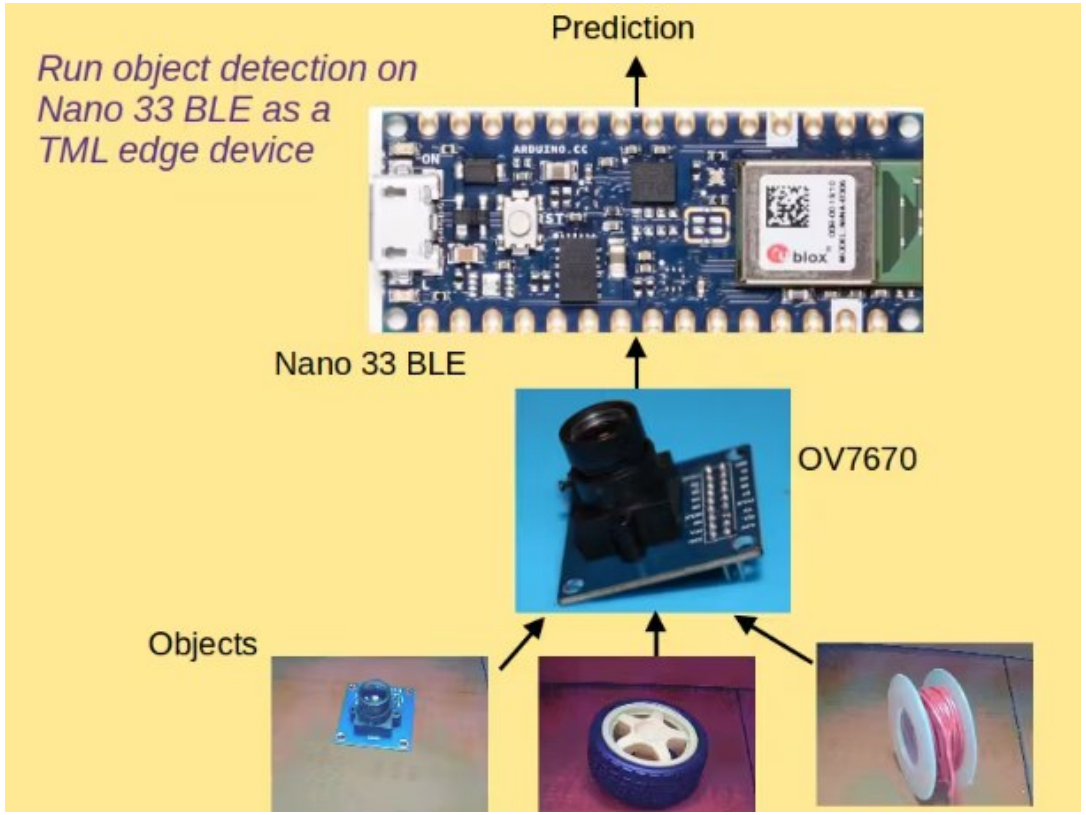
The board streams the pulse waveform to the laptop: one peak per heartbeat.



- Light passes through the fingertip; a photodiode measures it
- The blood volume changes with each heartbeat, so the signal pulses
- Module 3 turns this waveform into **heart rate** and **blood oxygen**

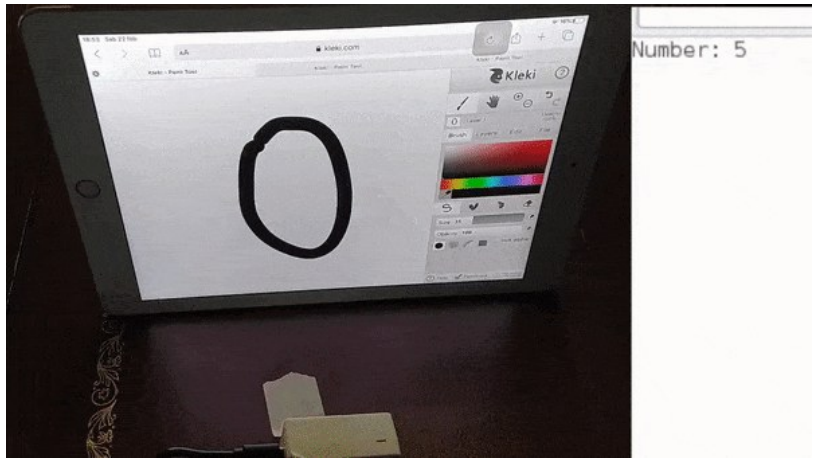
Module 4: Machine vision

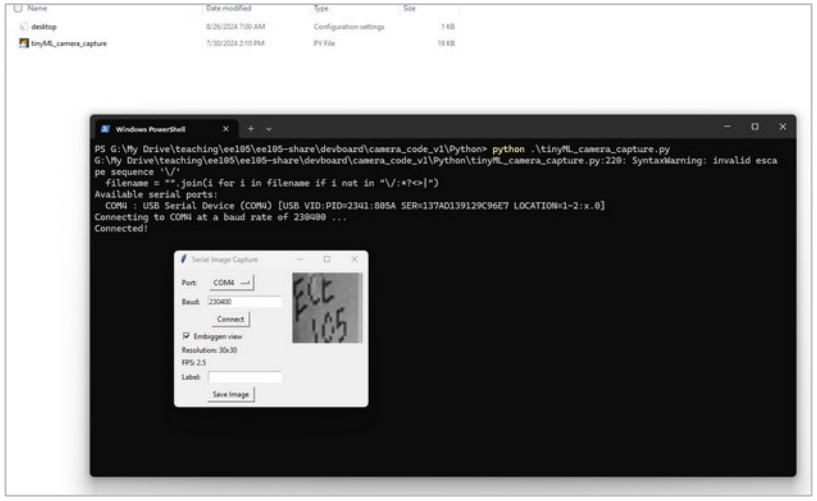
Arduino + camera + ML = identify objects / letters / faces / anything.



Arduino + camera + ML = identify anything

Goal

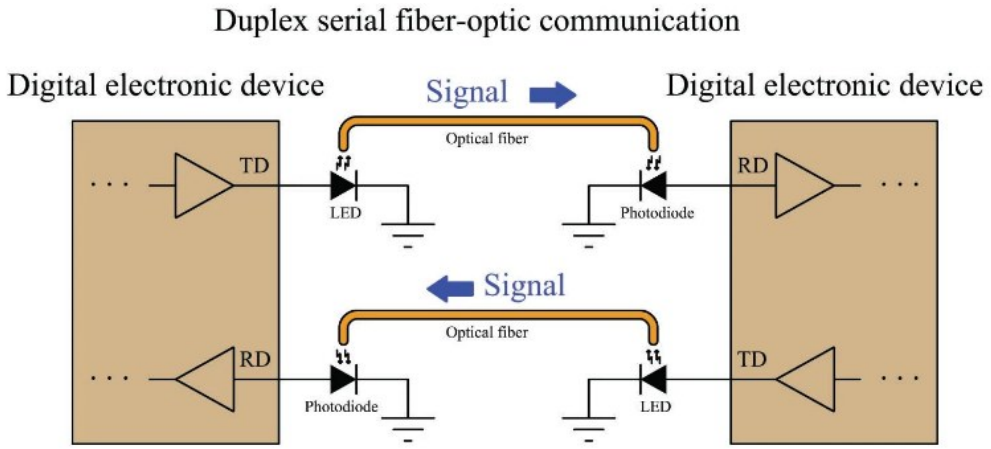




Camera frames captured in Python: **handwritten text**

Module 5: optical communication

Send data as light: an LED blinks, a photodiode reads light on and light off.

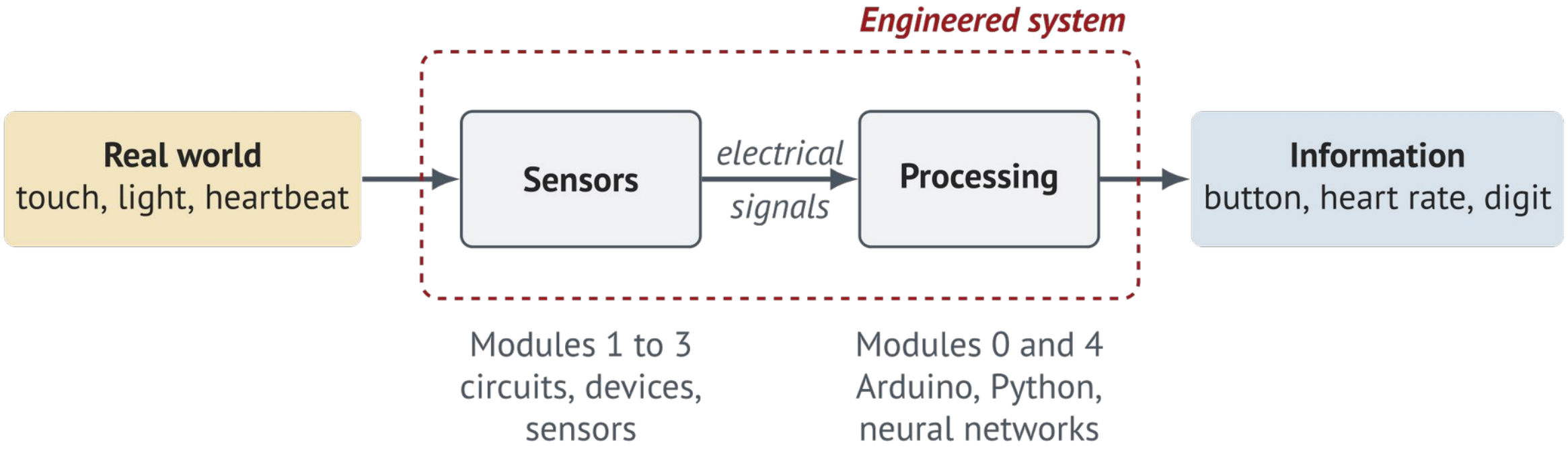




- An **LED** sends bits as flashes of light
- A **photodiode** turns the light back into a signal

Next lecture: system design

Any electronic system: sensors turn the real world into signals; processing turns them into information.



Lecture 2: how each EE 105 module fits this chain.