Module 1-1: Preliminaries and Fun Stuff

Profs. Niknejad / Muller

EE 105

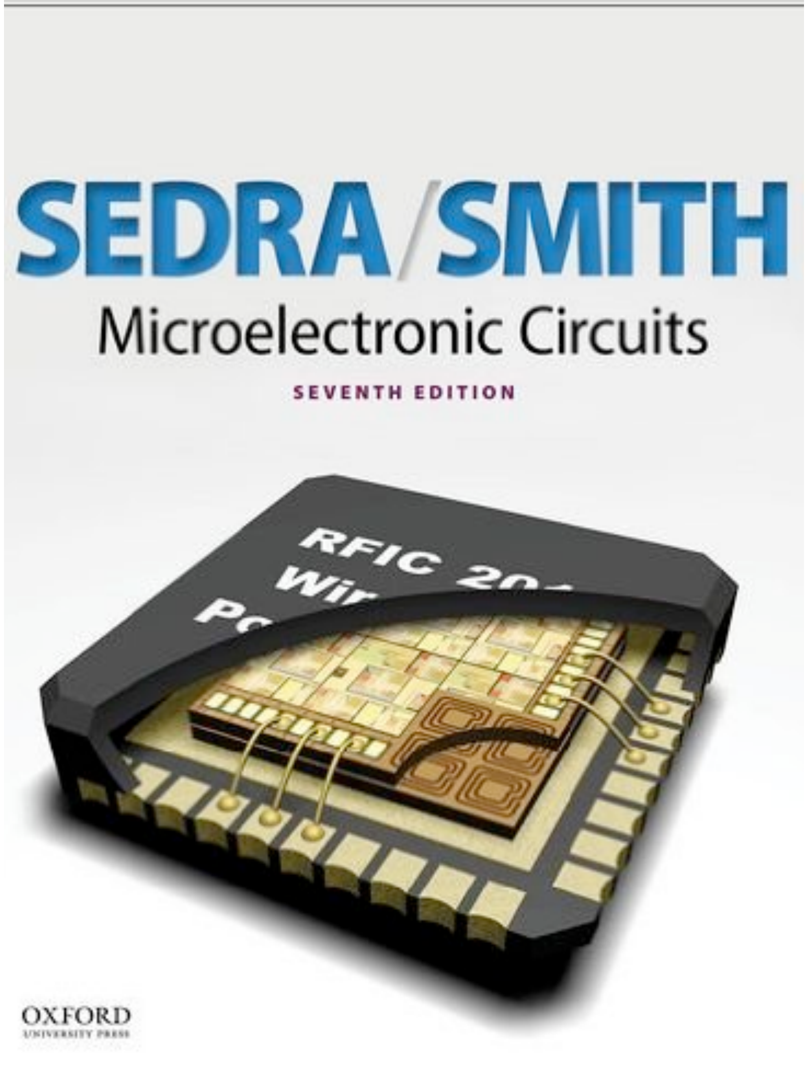
- http://rfic.eecs.berkeley.edu/105
  - Lecture notes
- bCourses for homeworks, labs and solutions
  - All homeworks must be submitted here
  - Site will be launched this week
- Piazza for online questions and discussions
  - Mostly student run
  - GSI resources are very limited this semester so don’t expect someone to be online 24/7
  - piazza.com/berkeley/spring2017/ee105/home

Course Logistics

- Instructors: Ali Niknejad & Rikky Muller
- Lectures: TuTh 3:30-5 (534 Davis)
- Discussions (mandatory):
  - W 12-1PM (299 Cory)
  - W 1-2PM (299 Cory)
- Labs (125 Cory) (mandatory):
  - M 8-11AM
  - M 2-5 PM
  - Tu 8-11 AM
  - Attend your section !
- Office Hours: TBD
  - Prof. Niknejad: 511 Cory
  - Prof. Muller: 564 Cory

Grading Policy	
Homework	25%
Labs	25%
Midterm	25%
Final	25%

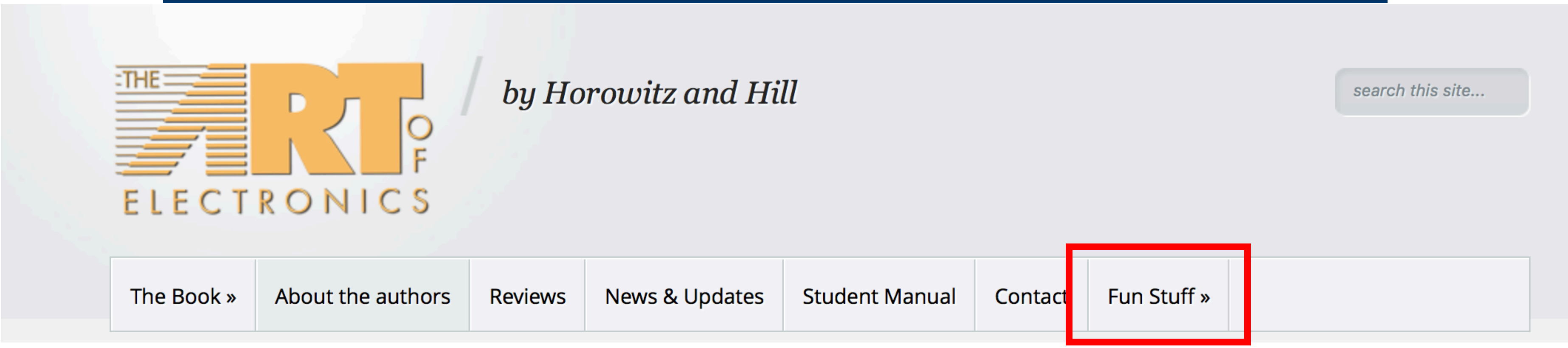
Optional Textbook



- Highly recommended textbook
  - I learned my electronics from this book (second book)
- Coverage of device physics is a bit light but a good first book to be followed by a more in depth source

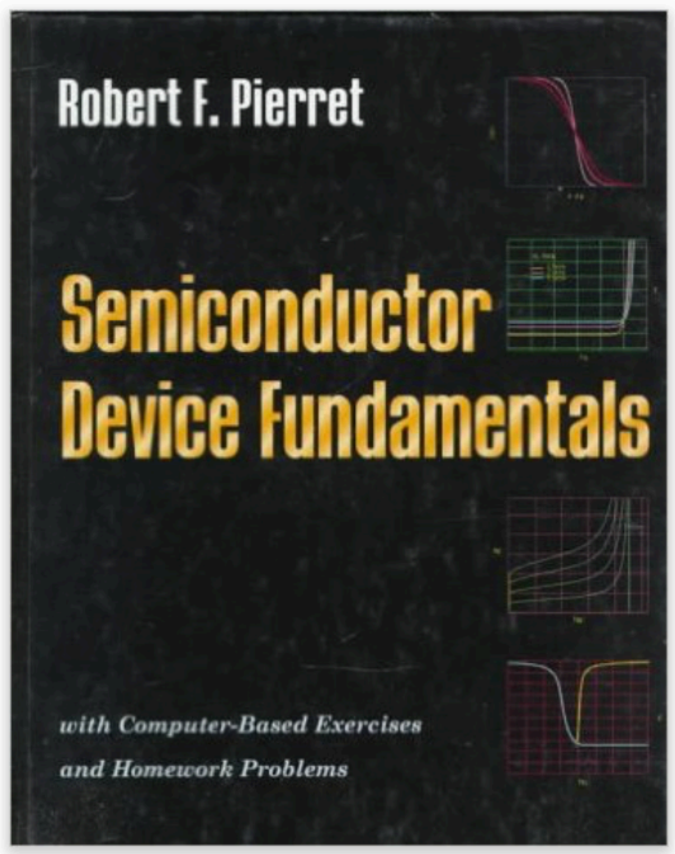
Sedra/Smith, *Microelectronic Circuits*, 7th edition
Oxford University Press

A Gem of a Book (Optional)



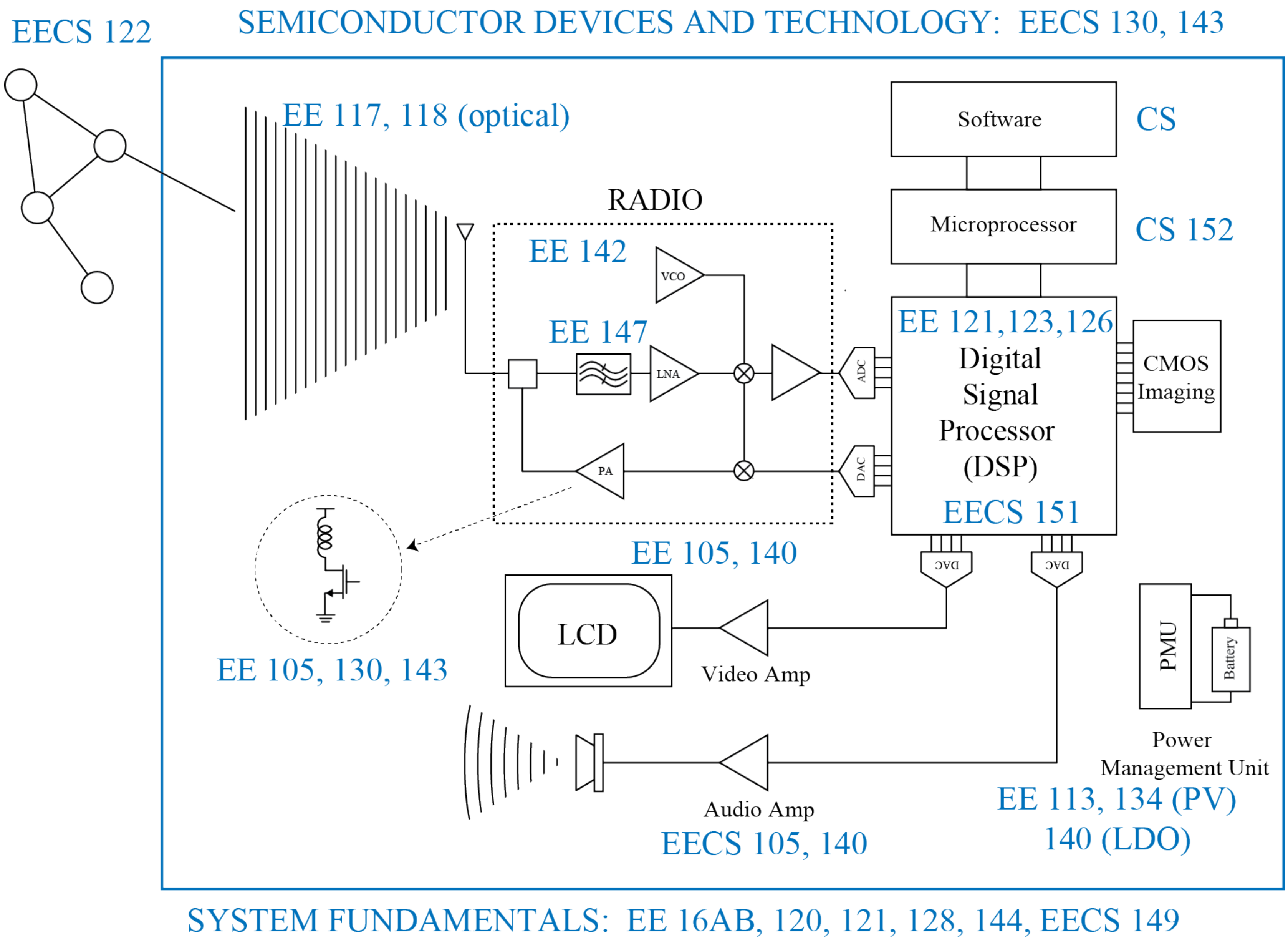
- http://artofelectronics.net
- Teaches electronics without any device physics
- Great way to learn a lot of stuff from analog to digital, low noise, instrumentation, etc.
- Definitely read this book and check out the website!

Semiconductor Device Physics

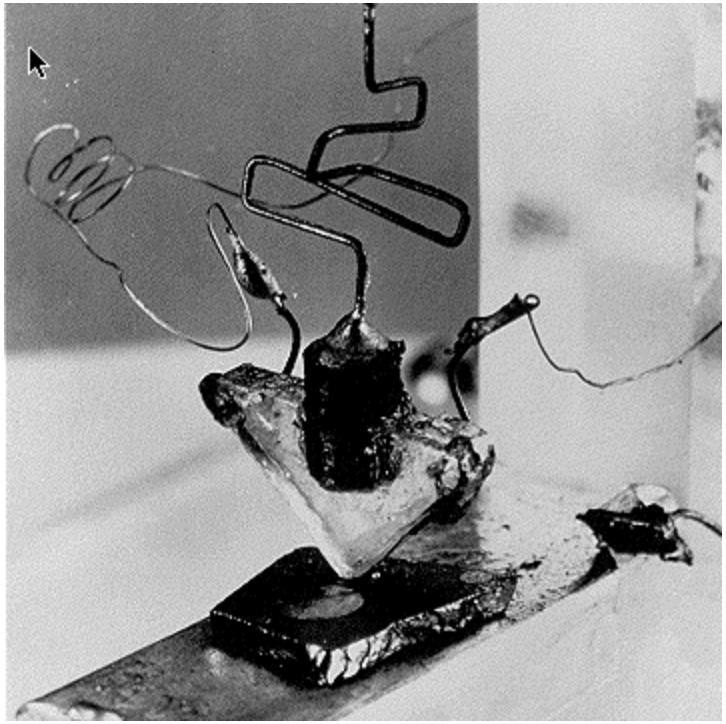


- **Semiconductor Device Fundamentals** 2nd Edition
  - by Robert F. Pierret
- Standard undergraduate textbook. Coverage is deeper than 105 and more suitable for 130 but if you're curious …

EECS Map: You Are Here



Transistors and Circuits!



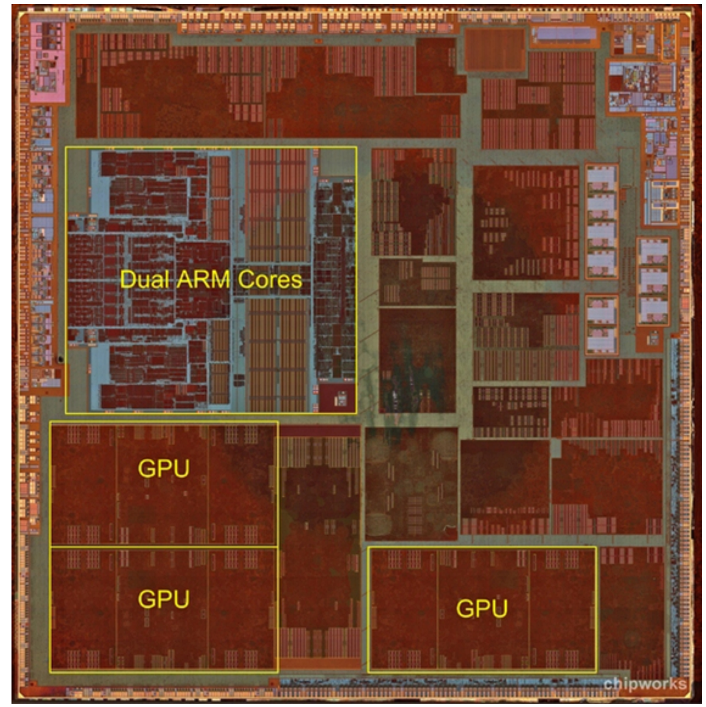
- When the inventors of the bipolar transistor (Bell Labs) first got a working device, the first thing they did was to build an audio amplifier to prove that the transistor was actually working!

Modern ICs

Source: Texas Instruments

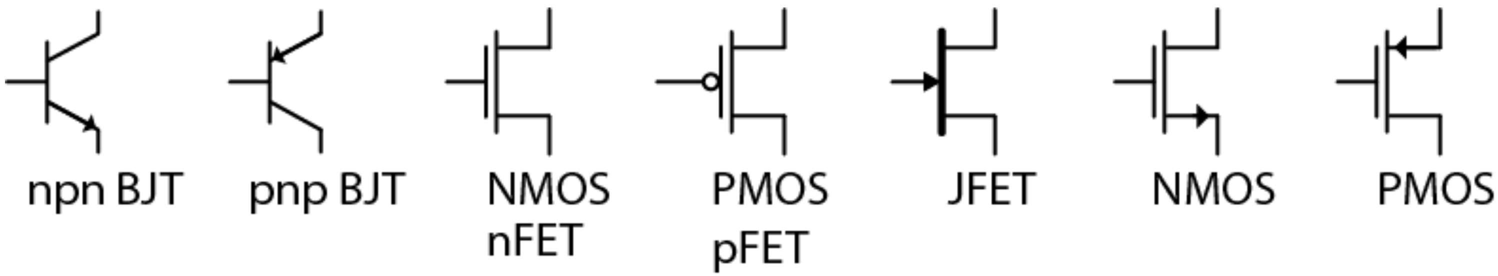
- First IC
  - Texas Instrumetns, Jack Kilby, 1958: A couple of transistors

- Modern IC: Apple 64-bit A7 (> 1 billion transistors, >1.4 GHz)



- “Robert Noyce of Fairchild Semiconductor invented a way to connect the IC components (aluminium metallization) and proposed an improved version of insulation based on the planar technology by Jean Hoerni.” (Wikipedia) Noyce later co-founded Intel with Gordon Moore.

What is a Transistor?

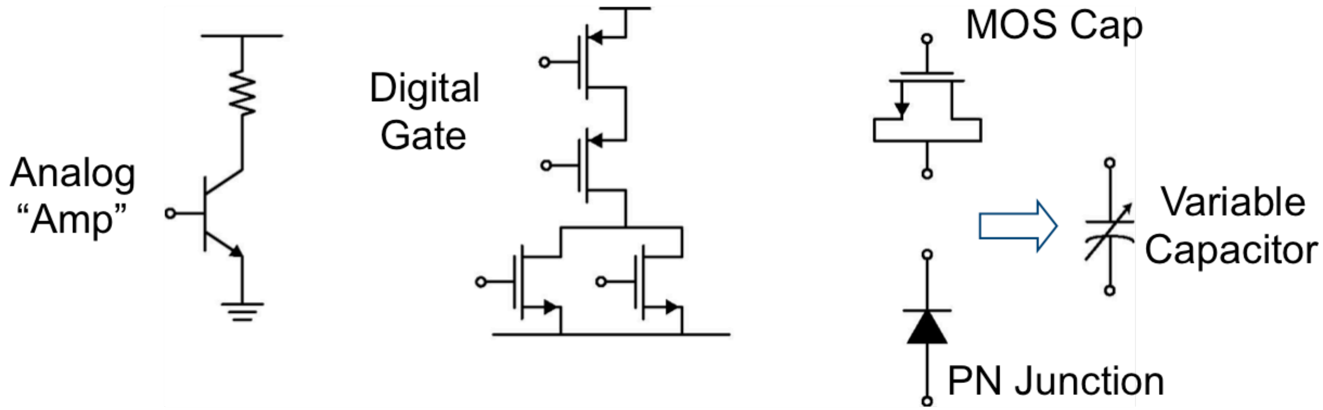


- Transistors are the building blocks of all modern integrated circuits.
  - Transistors amplify signals (controlled source)
  - Transistors control signals (switch)
- With a transistor and a "wire", you can build an endless possibility of circuits that do useful things. Resistors, capacitors, and inductors are also occasionally needed.

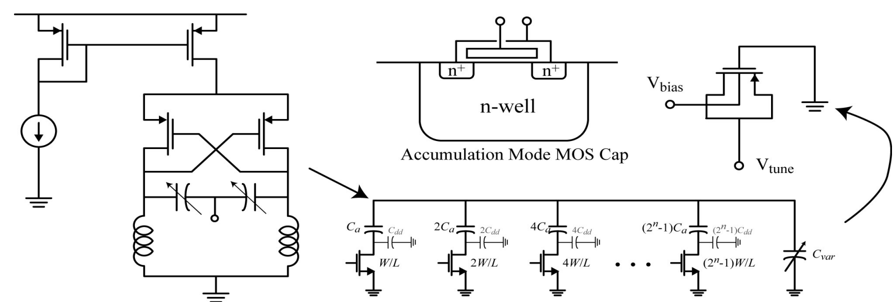
Very Simple Picture of Transistor

- Conductivity of channel modulated by gate voltage
  - Voltage controlled resistor
  - Switch
- Interesting behavior:
  - Device can act like a current source when biased correctly … more on this later

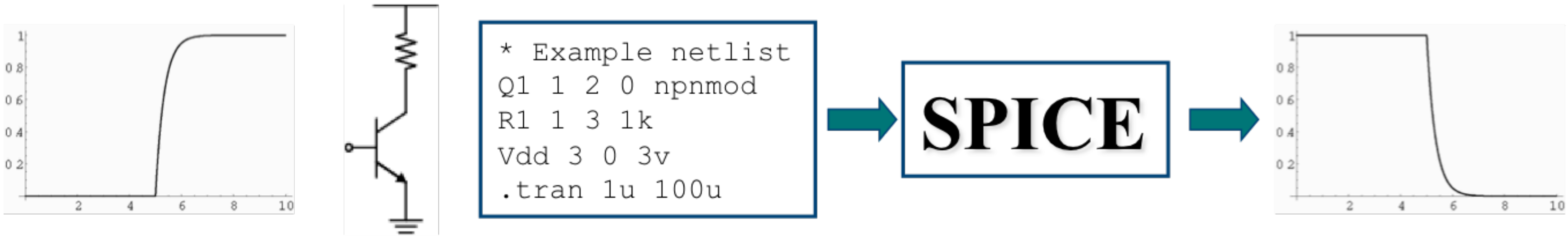
Transistor as Si Brick



- Logic gates and memory
- Small-Signal amplifier
- Large-Signal power device
- Low-loss switching devices (mixers)
- Low cost RF Example
  - Enabled the 2G, 3G, and 4G and WiFi revolutions



Berkeley SPICE

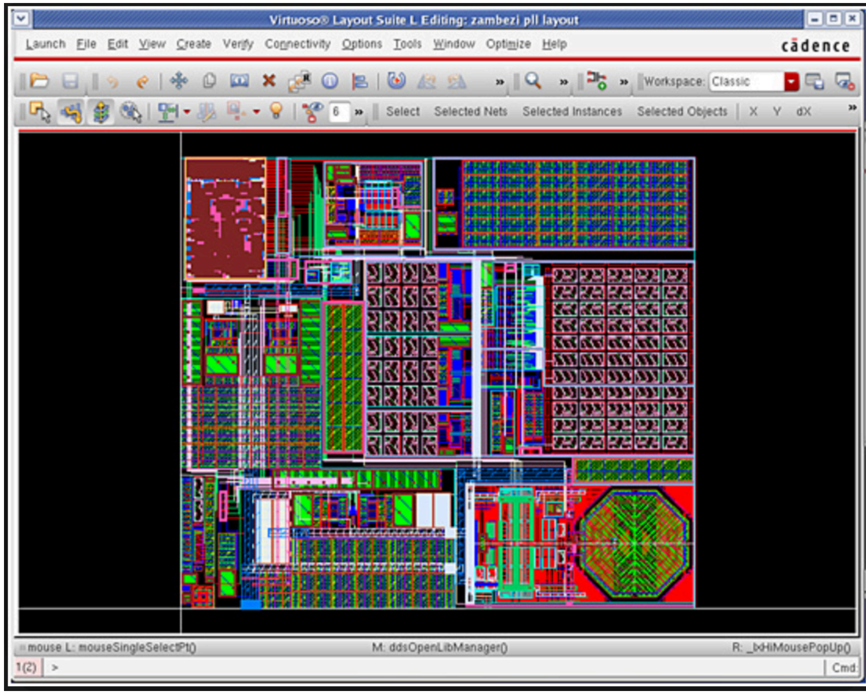


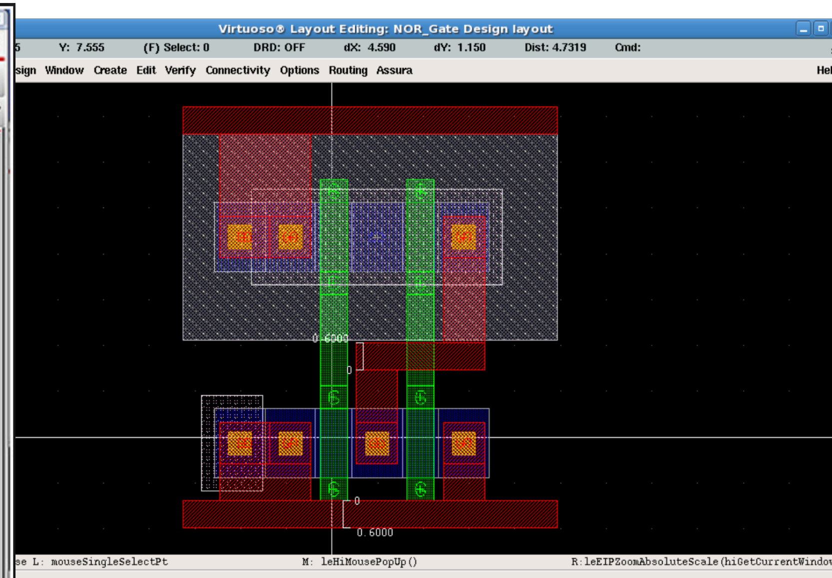
stimulus netlist response

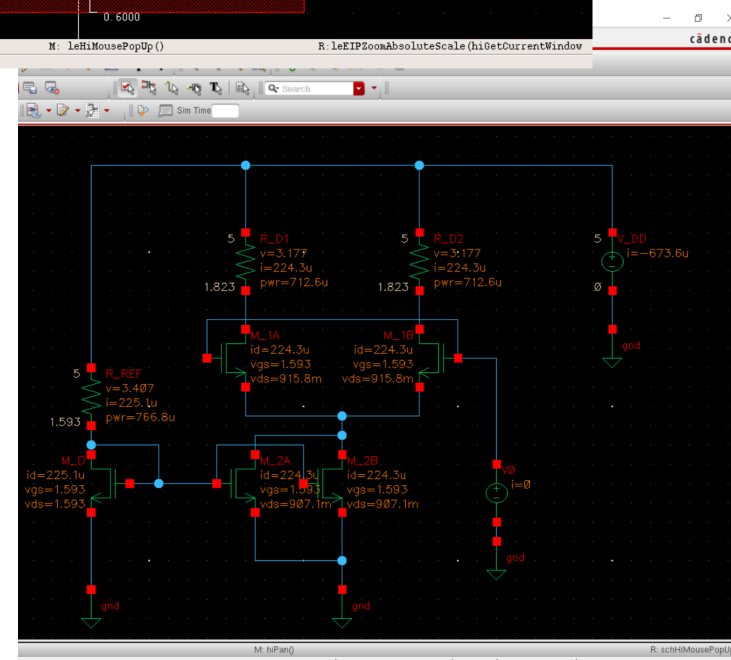
SPICE was developed at the Electronics Research Laboratory of the University of California, Berkeley by Laurence Nagel with direction from his research advisor, Prof. Donald Pederson. SPICE1 …. SPICE1 was first presented at a conference in 1973.

- Designing circuits with dozens of transistors by hand is quickly challenging.
- Today we routinely design analog circuits with hundreds to thousands of transistors, and digital circuits with millions
- Computer simulation is important for design and verification of these circuits
  - SPICE was born at Berkeley and it's the heart of many commercial simulation engines

Cadence EDA CAD Tools

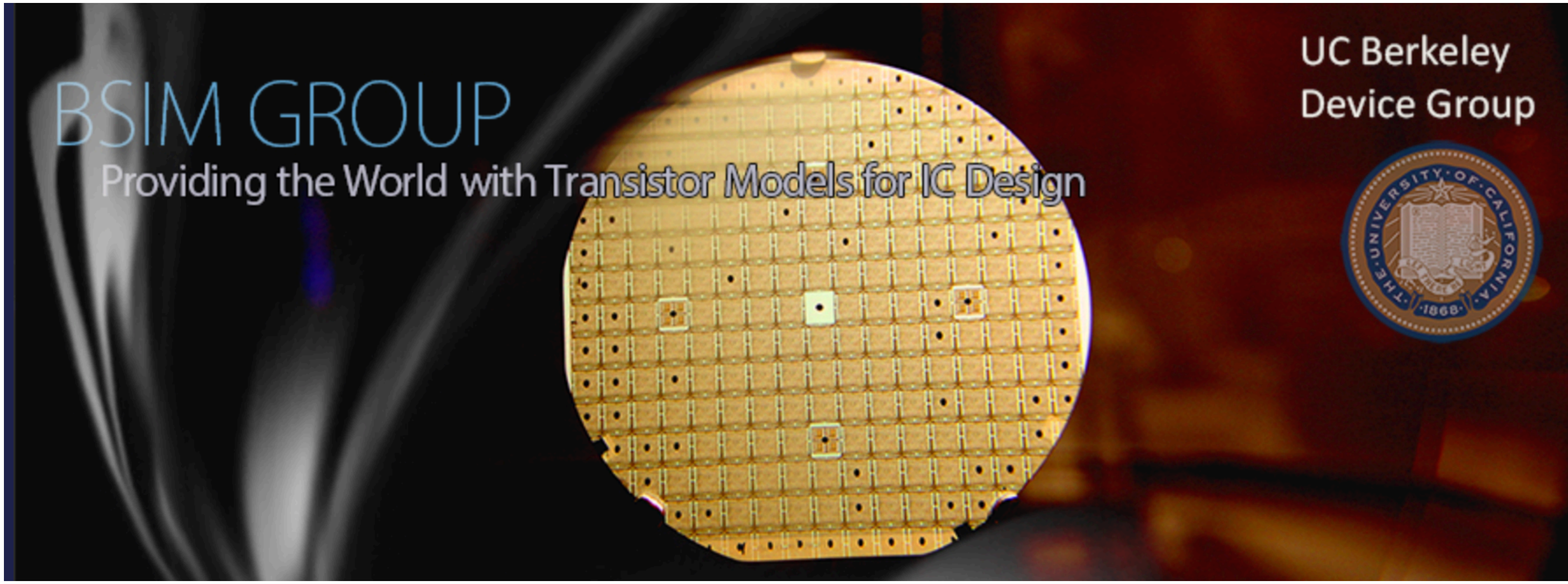






- A modern implementation of SPICE (Spectre) with a graphics front-end for schematics and layout.
- A collection of hundreds of tools for doing analog, digital mixed-signal, and RF design.
- We'll use ("touch") Cadence in this course

Modeling Transistors



- Transistors are very complicated if you want all the gory details ...
- In a high level language, a single transistor is described with thousands of lines of code (10X more in a lower level language like "C")
- *Berkeley* builds and maintains the world standard compact models for a family of transistors in the BSIM model

Switch

- Three terminal device with one control terminal
- Voltage at control terminal changes resistance between two terminals from “open” to “closed” state (from “on” to “off”
- The switch model is key to building logic circuits
- Switching speed limited by capacitance
- Note: Early computers built with mechanical switches …

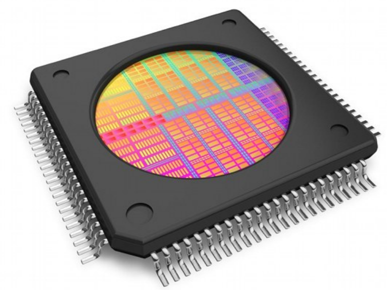
Amplifier

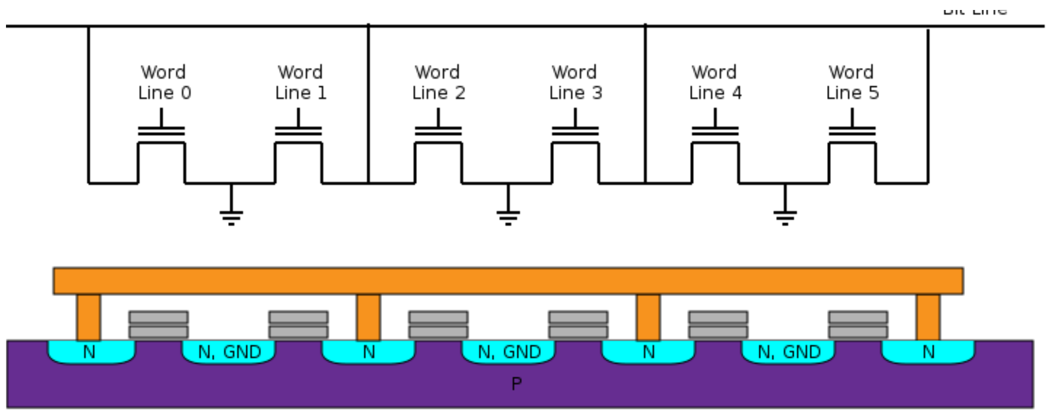
- Instead of a switch, imagine a value … you can vary the rate of flow by turning valve.
- A large current can be controlled by turning the valve... There’s gain in the system. The large current can be doing a lot of work, but turning the value is easy

Memory Element

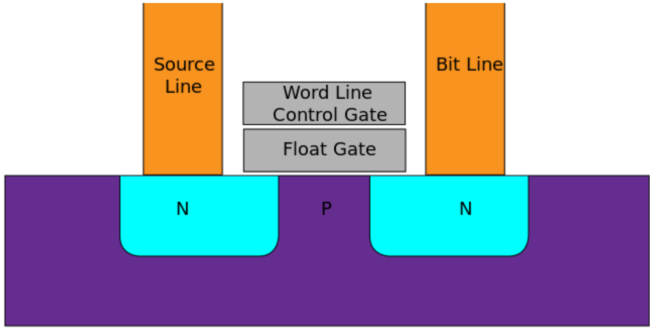
- Transistors in *positive feedback* form bi-stable circuits
- As long as power is applied to the circuit, the feedback ensures that the state is stored
- This is how SRAM works

Non-Volatile Memory



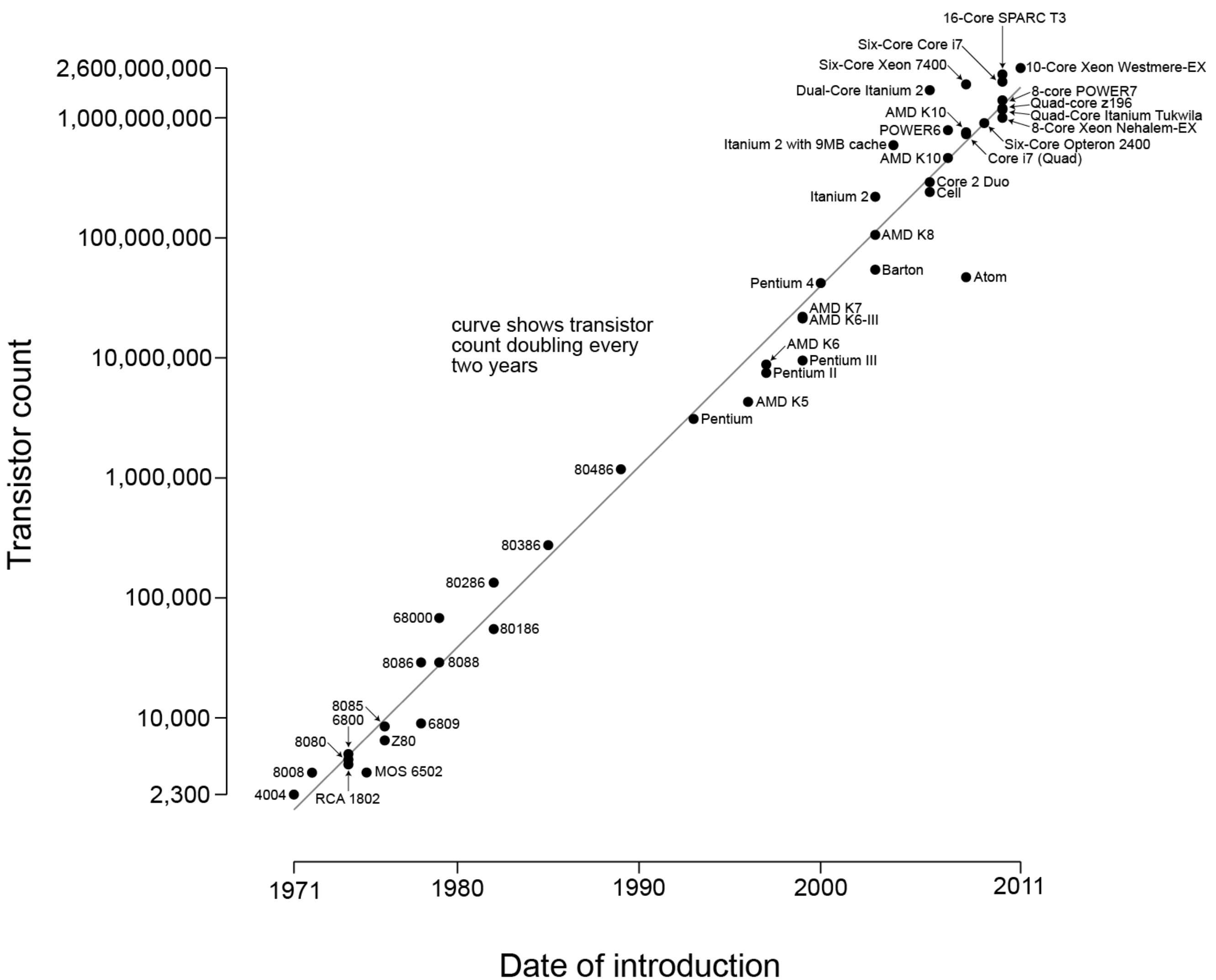


- By designing a special transistor with a floating gate, we can store charge (through quantum mechanical tunneling) onto the gate to keep the information even in the absense of a supply voltage.
- This is how FLASH memory works…



Moore's Law

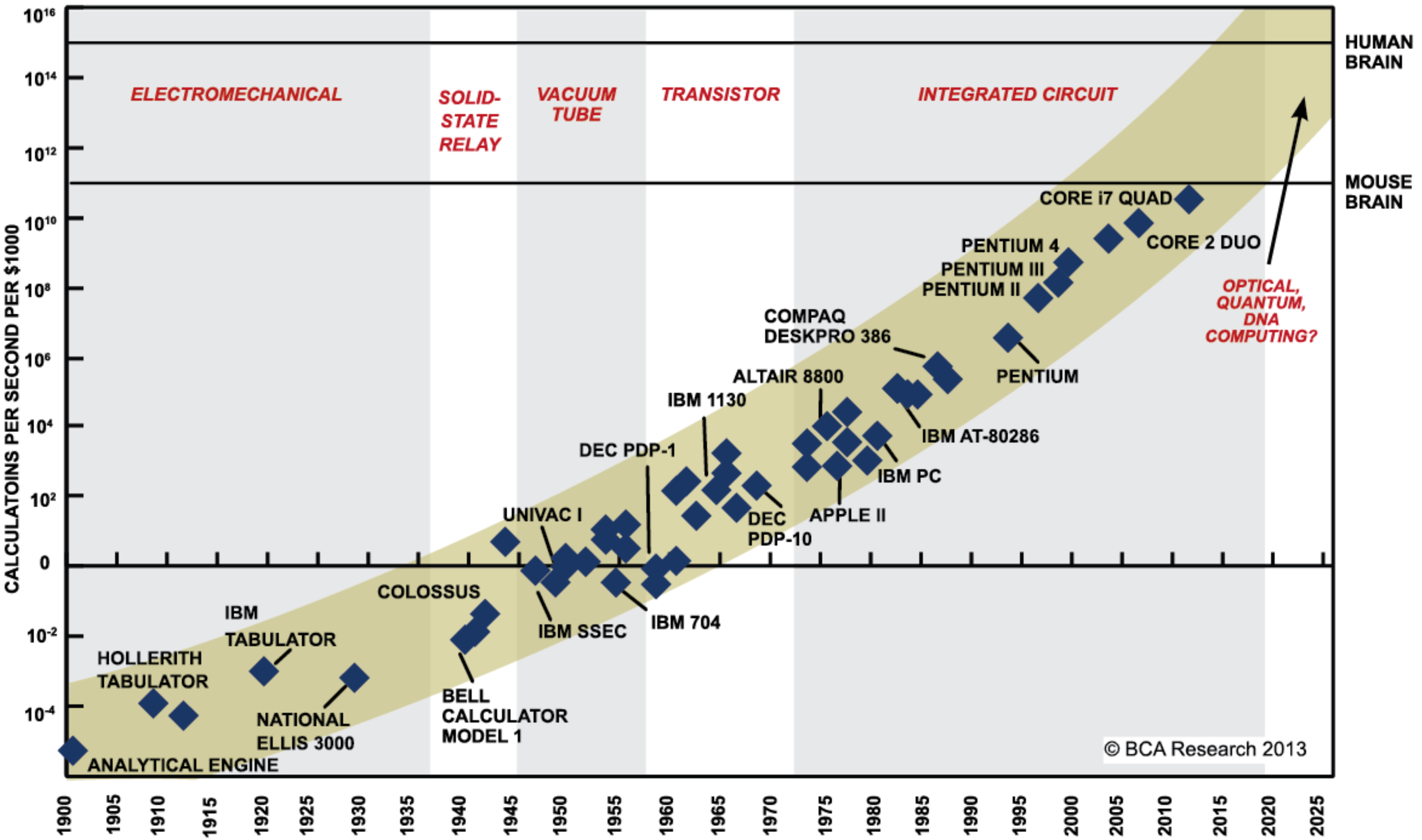
Microprocessor Transistor Counts 1971-2011 & Moore's Law



- Transistor count doubles every 2 years (18 months)
- You've no doubt heard about this before. It has held true for decades driving advancements in the semiconductor industry.
- A mainframe filling an entire room now fits inside your pocket

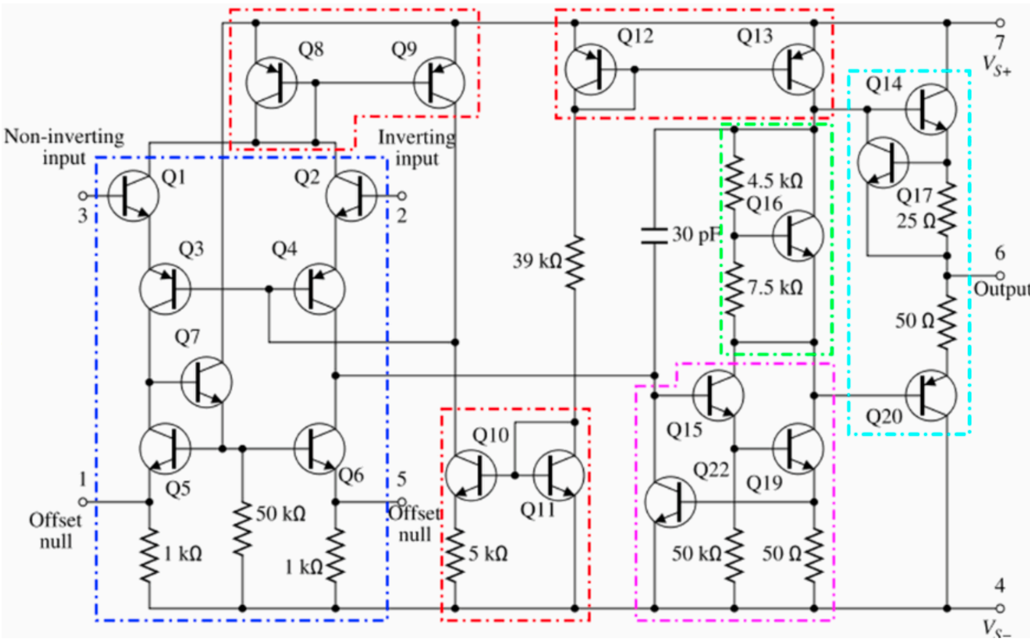
https://en.wikipedia.org/wiki/Transistor_count

Another Perspective on Moore



SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

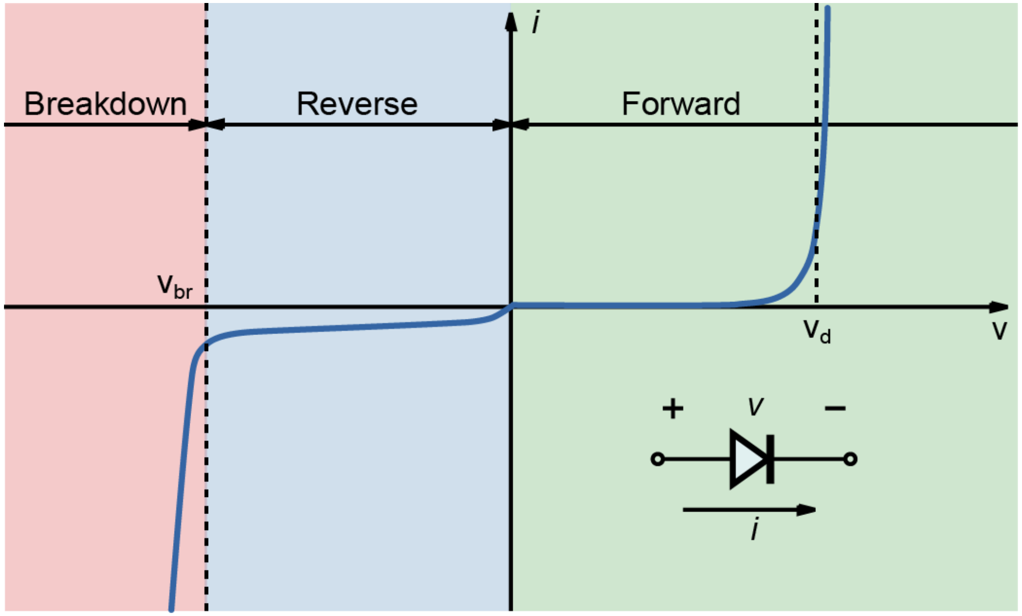
741 Op-Amp (Historical)…



The 741 is one of the best known IC op-amps. It's *not the best* and there are hundreds of others out there that are specialized for different applications.

- Analog integrated circuits have also benefited greatly from IC technology by integrated complex circuits onto a single die
- The op-amp is a well crafted amplifier that you know and love … building it discretely is impractical as we will learn

Diodes

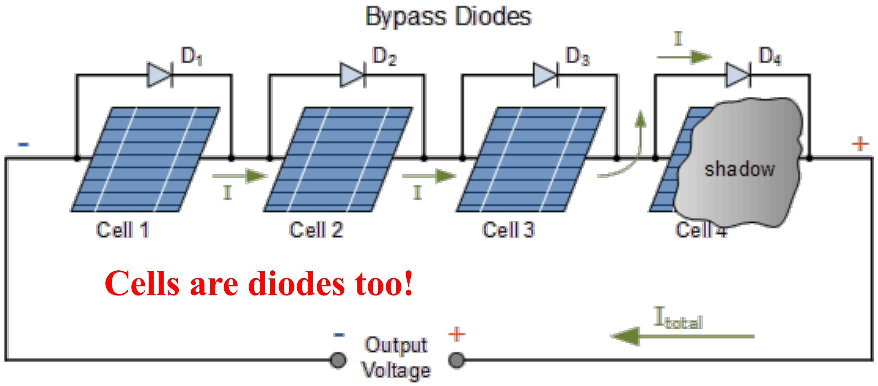


- Inside every transistor, there's a few diodes
- In some transistors, these diodes are the key (as we'll learn) to the device functionality
- A diode is a non-linear element that only allows current to flow in one direction …

Rectifiers

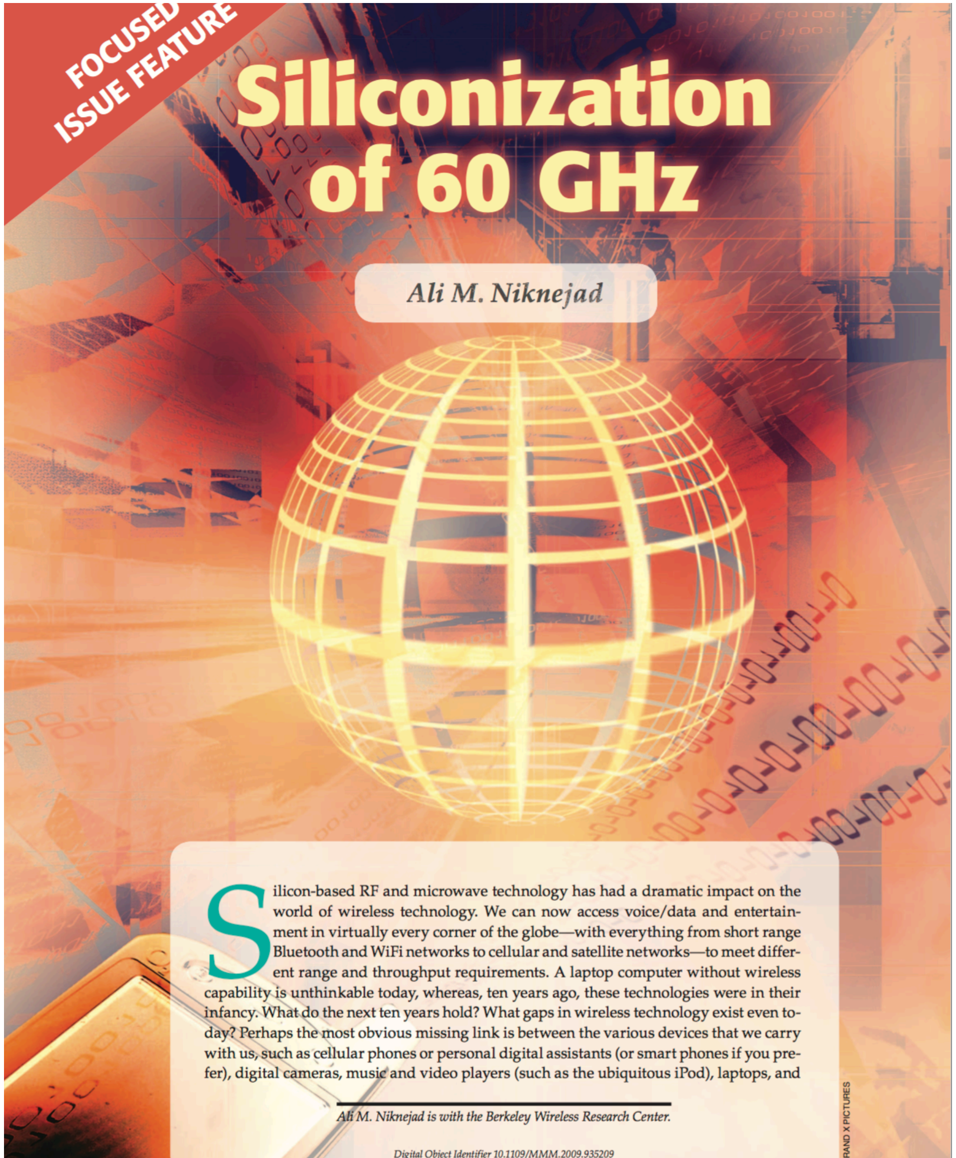
- AC to DC conversion is routinely performed by diode rectifiers
- The same circuit can also detect the peak or average value of a signal

Solar Cell Diodes



- Diodes are also the best way to convert solar energy into electricity
- Solar energy is “free” and advancements in the technology have reduced the cost, improved the efficiency, and also decreased the energy to manufacture solar cells

Silicon RF



FOCUSED ISSUE FEATURE

Siliconization of 60 GHz

Ali M. Niknejad

Silicon-based RF and microwave technology has had a dramatic impact on the world of wireless technology. We can now access voice/data and entertainment in virtually every corner of the globe—with everything from short range Bluetooth and WiFi networks to cellular and satellite networks—to meet different range and throughput requirements. A laptop computer without wireless capability is unthinkable today, whereas, ten years ago, these technologies were in their infancy. What do the next ten years hold? What gaps in wireless technology exist even today? Perhaps the most obvious missing link is between the various devices that we carry with us, such as cellular phones or personal digital assistants (or smart phones if you prefer), digital cameras, music and video players (such as the ubiquitous iPod), laptops, and

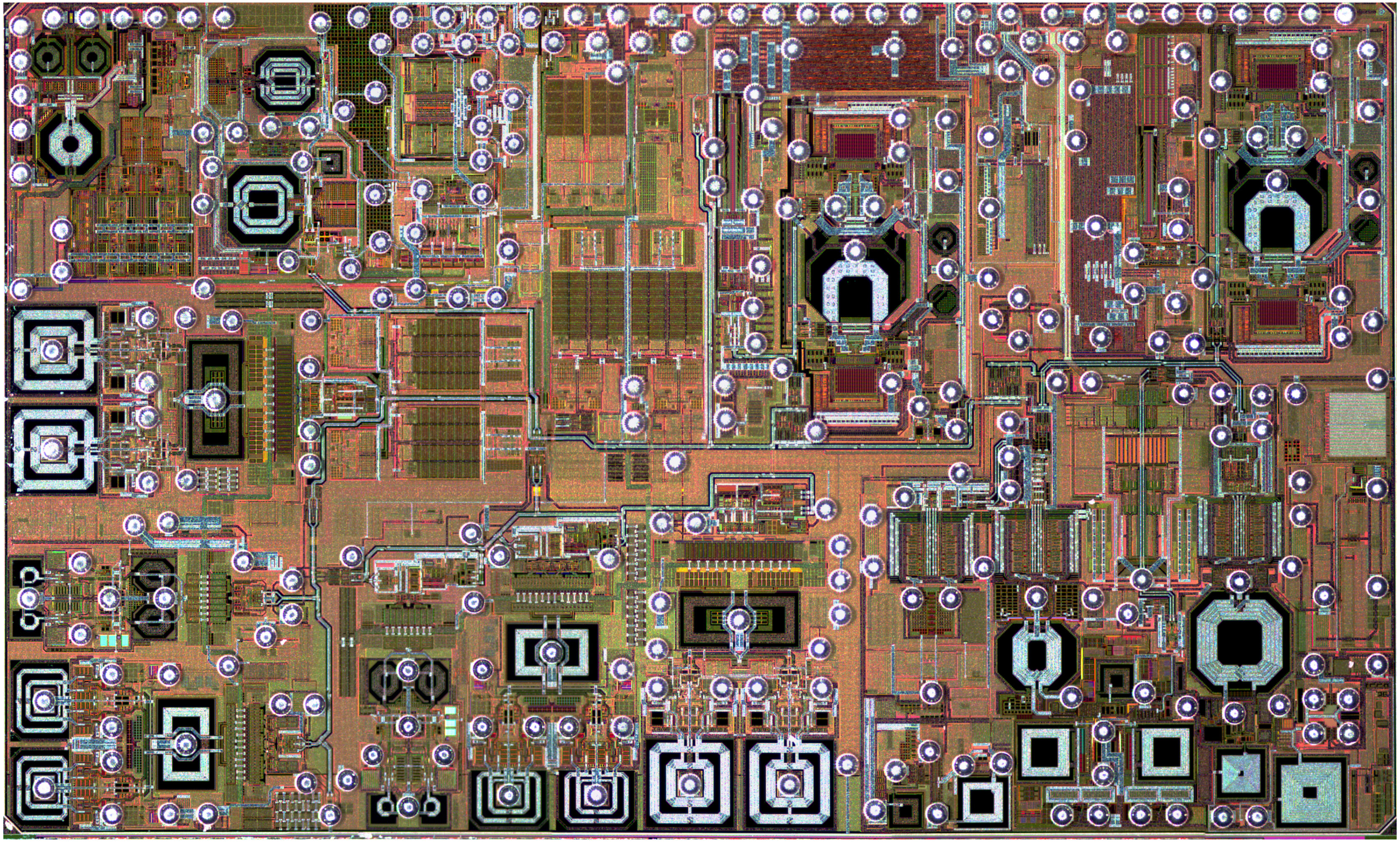
Ali M. Niknejad is with the Berkeley Wireless Research Center.

Digital Object Identifier 10.1109/MMM.2009.935209

© BRAND X PICTURES

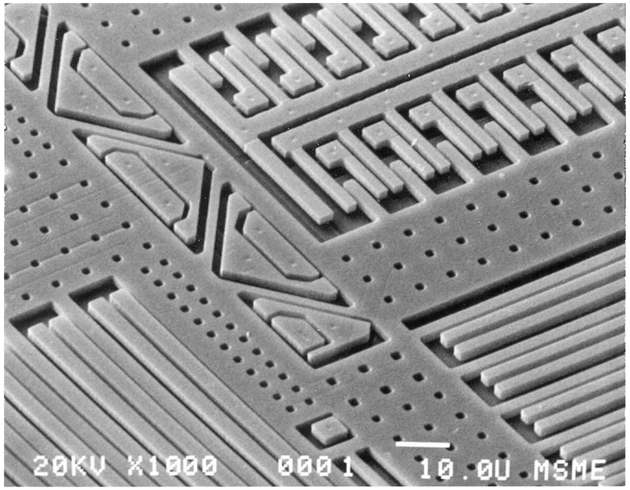
- Radio frequency circuits use transistors in countless ways.
- In the past 20 years RF circuits have become completely integrated circuits, mostly in CMOS technology:
  - WiFi and Mobile Cellular
  - 100 MHz to over 100 GHz !

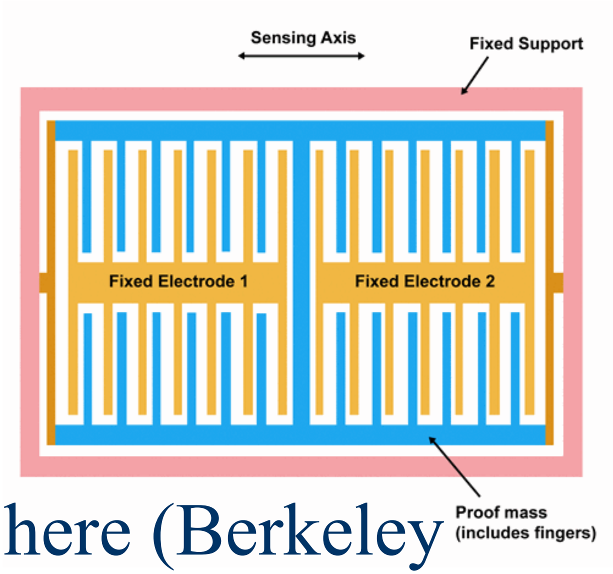
RF Multi-Band Transceiver IC's



Dozens of inductors/transformers are used in Qualcomm's RTR8600, a multi-band multi-mode RF transceiver found in the Apple iPhone and Samsung Galaxy phones.

The World of Si Sensors

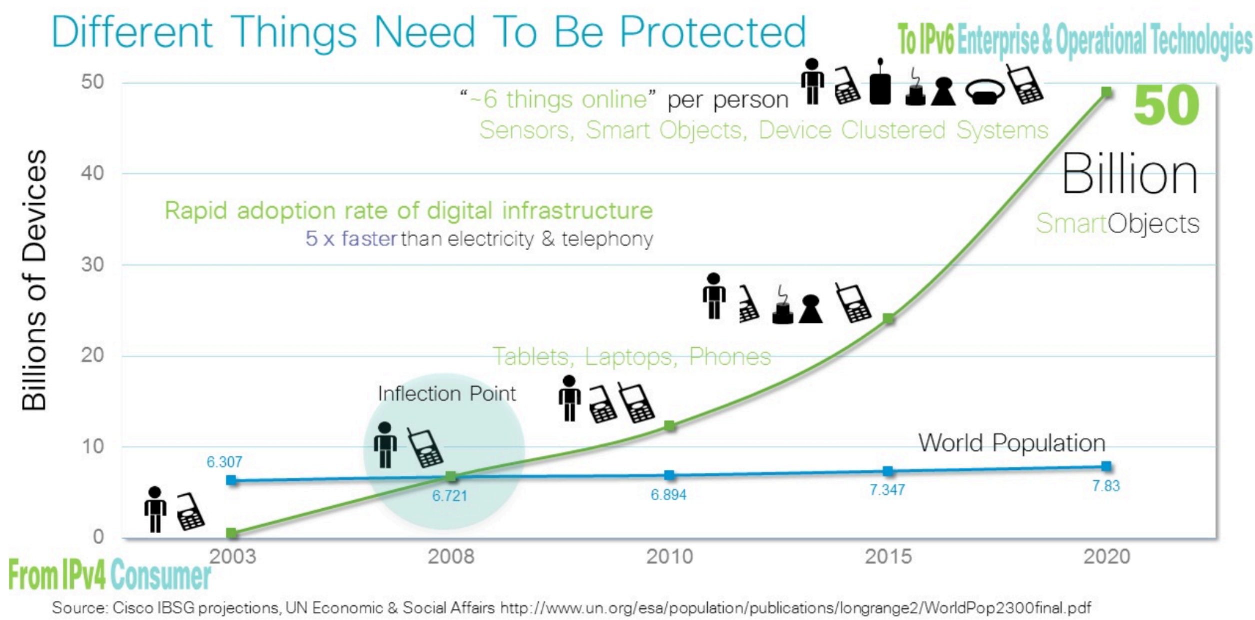




- MEMS technology, pioneered here (Berkeley Sensor and Actuator Center, *BSAC*), uses the same process to fabricate silicon ICs to build low cost sensors
- Mechanical signals can be coupled readily into the electronical domain
  - Accelerometers, pressure, chemical, gyroscopes, microphones, resonators and filters…

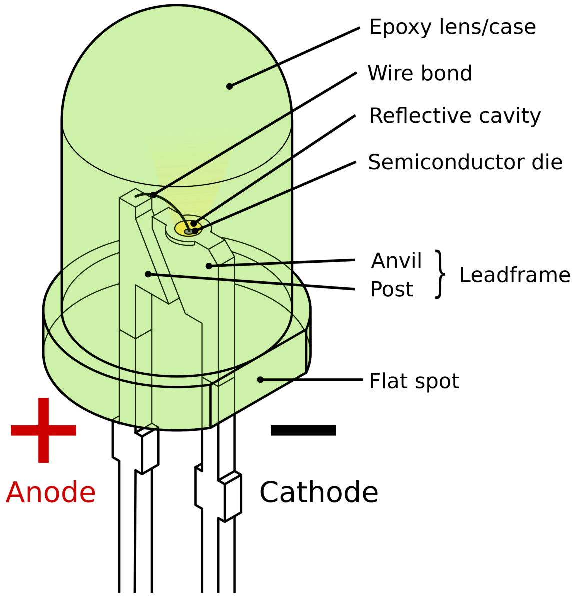
IoT

https://www.linkedin.com/topic/internet-of-things



- The *Internet of Things* (IoT) revolution is happening today
- Sensors can be placed everywhere and wireless connectivity allows intelligent buildings, factories, cars, and even toasters

Diode -- LED



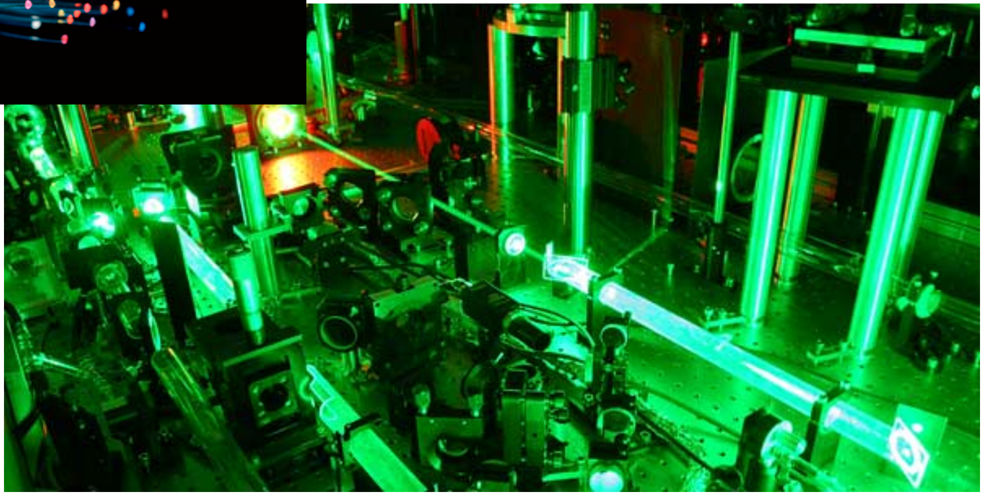
- A light emitting diode (LED) converts electrical energy into photons of light
  - Extremely efficient … revolutionizing lighting
- Runs off DC current

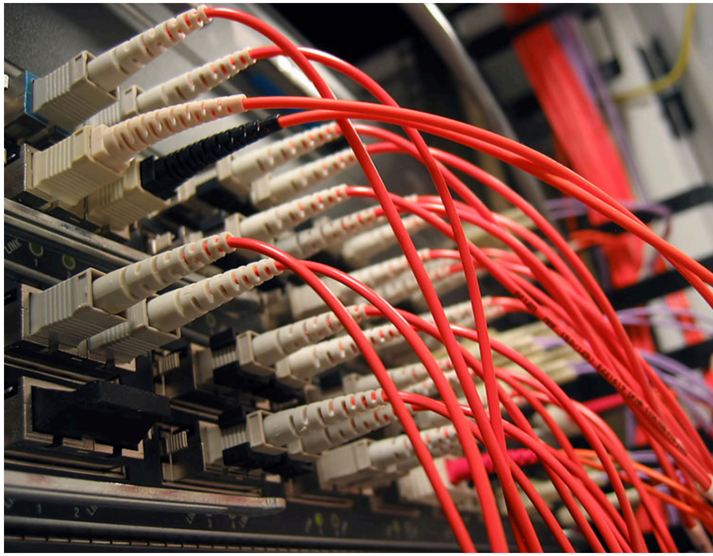
LED Efficiency

Energy Efficiency & Energy Costs	 Light Emitting Diodes (LEDs)	 Incandescent Light Bulbs	 Compact Fluorescents (CFLs)
Life Span (average)	**50,000 hours**	**1,200 hours**	**8,000 hours**
Watts of electricity used (equivalent to 60 watt bulb). LEDs use less power (watts) per unit of light generated (lumens). LEDs help reduce greenhouse gas emissions from power plants and lower electric bills	**6 - 8 watts**	**60 watts**	**13-15 watts**
Kilo-watts of Electricity used (30 Incandescent Bulbs per year equivalent)	**329 KWh/yr.**	**3285 KWh/yr.**	**767 KWh/yr.**
Annual Operating Cost (30 Incandescent Bulbs per year equivalent)	**$32.85/year**	**$328.59/year**	**$76.65/year**

http://www.designrecycleinc.com/led%20comp%20chart.html

Photonics





- Laser diodes can create coherent light and modulate the amplitude to carry information
- Our good friend the diode can also respond very quickly to light if biased correctly (not as a solar cell)
- Signals can be transported across the ocean with low loss … Fiber optic communication is the most efficient way to send information across a long distance

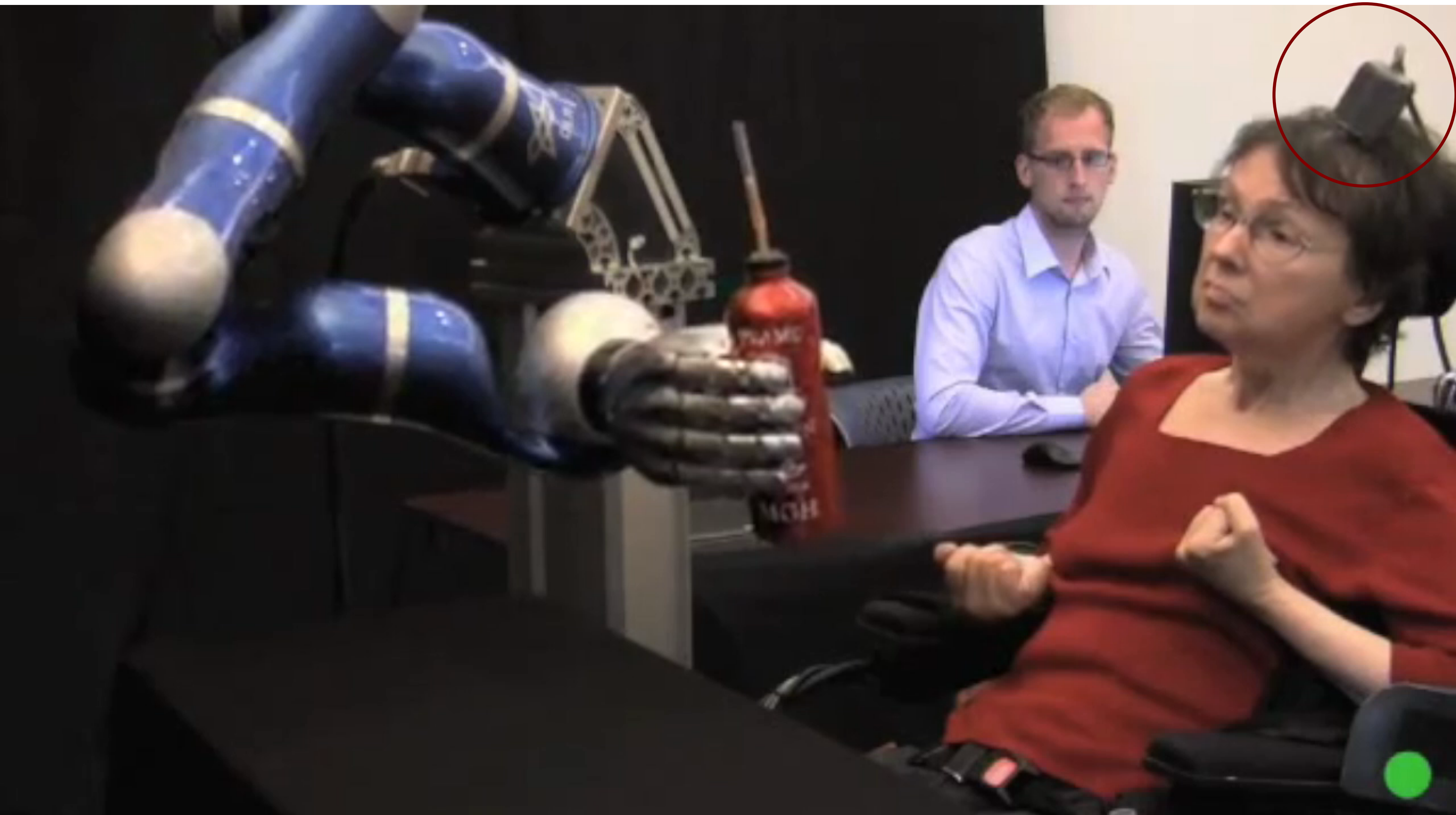
Medical Electronics

- Inside every medical device, you will find a range of sensors and interface electronics

ECG / SpO2

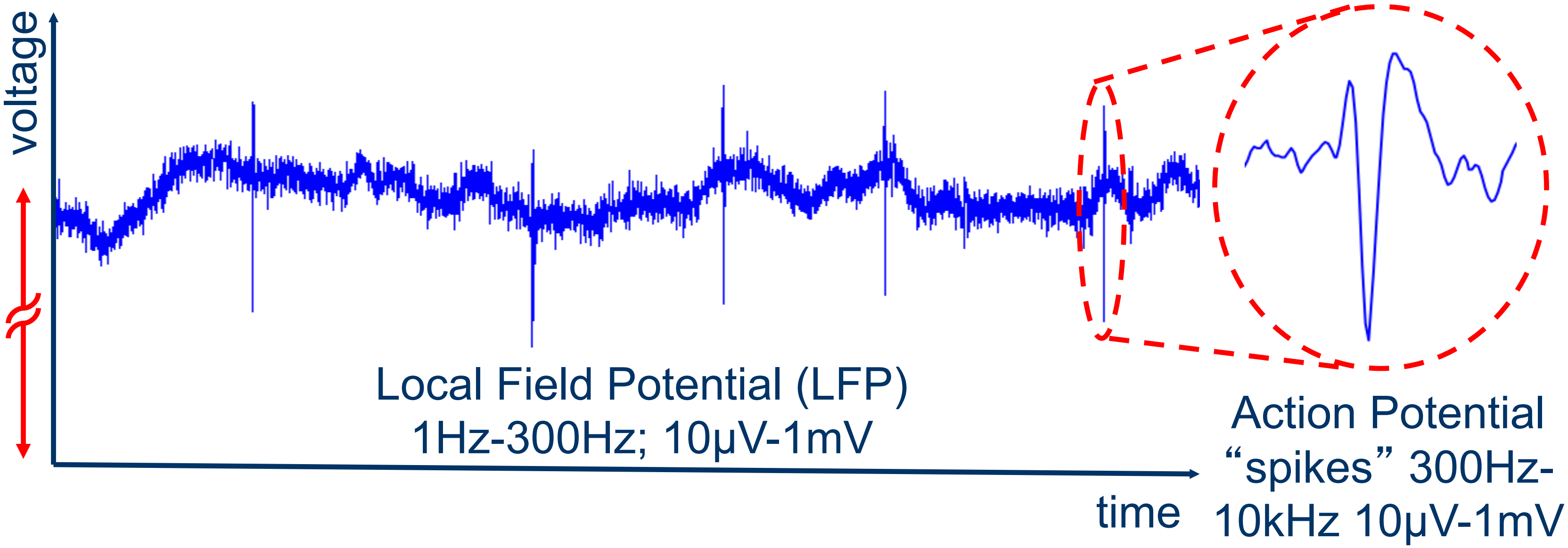
- Two commonly used devices to monitor patient health are Electrocardiogram (ECG) and Blood Oximetry (SpO2) sensors
- ECG uses a bunch of op-amps to amplify a weak signal that can be used to diagnose the health of the heart
- SpO2 uses light / infrared diodes and photosensors + interface electronics to measure blood oxygen levels

Brain-Machine Interfaces



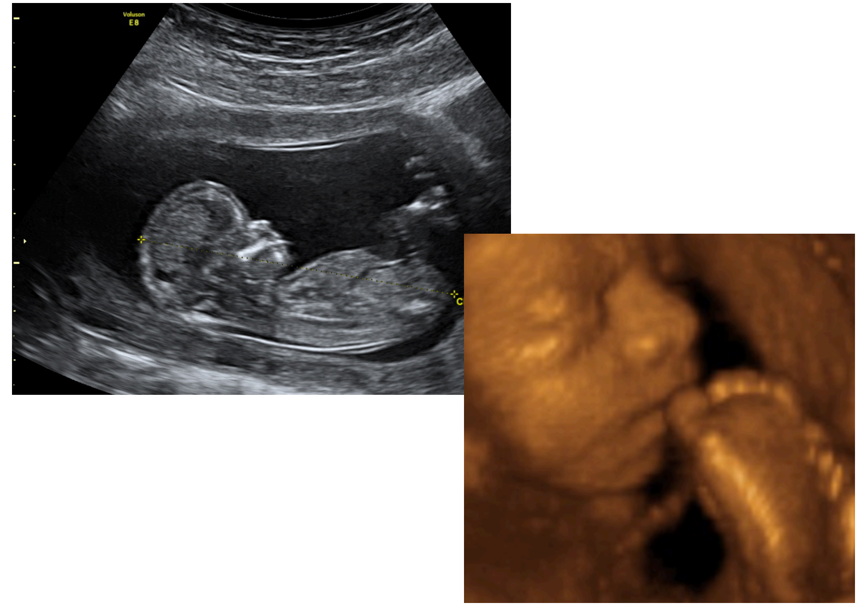
Source: Hochberg et al., *Nature* '12

Brain-Machine Interfaces



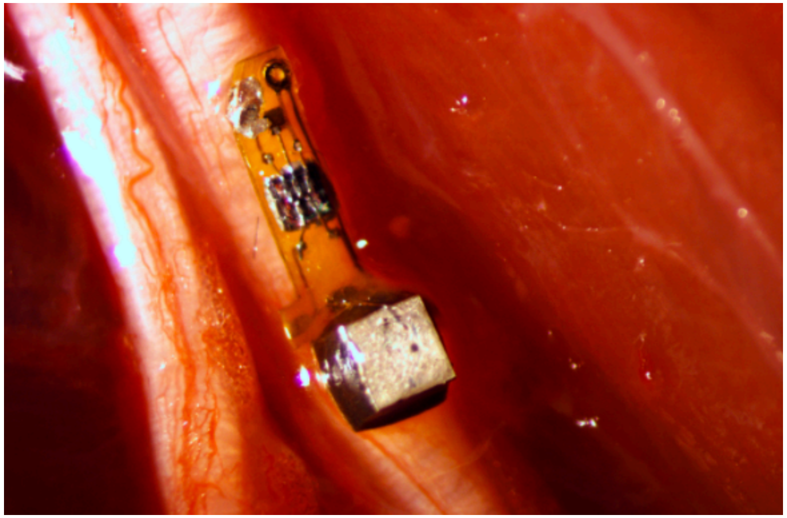
- Similar to ECG, the goal of a brain-machine interface is to record the small-amplitude neural signals and pick out the meaningful signals from the “noise”.
- These signals are then decoded to create trajectories, movements, and speeds for controlling prostheses, computers, etc.

Sonogram or Ultrasound

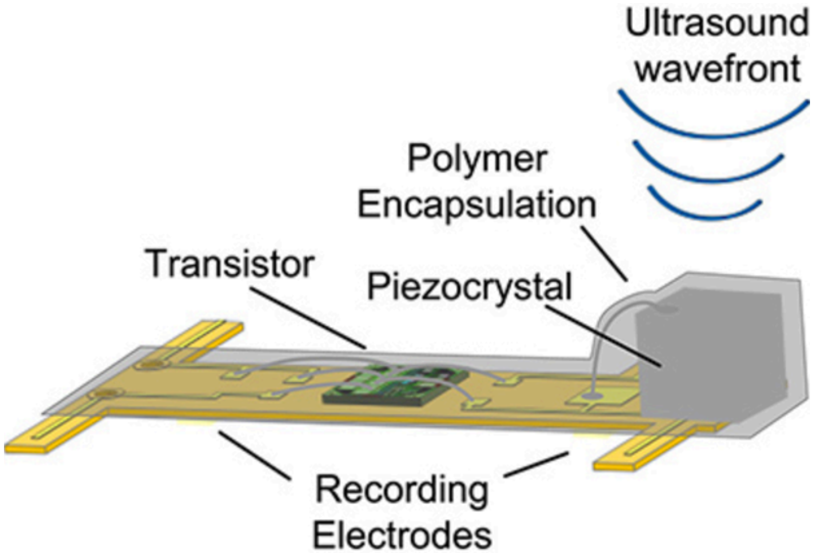


- Sound waves are transmitted inside the body … echos, or reflections, off different parts of your body are used to reconstruct a 2D or 3D image
  - Echo-cardiogram can be used to "see" heart in action
- Integrated circuits and MEMS has revolutionized the scale of these devices ... Handheld devices are now available

Ultrasound – Powering Tomorrow's Devices

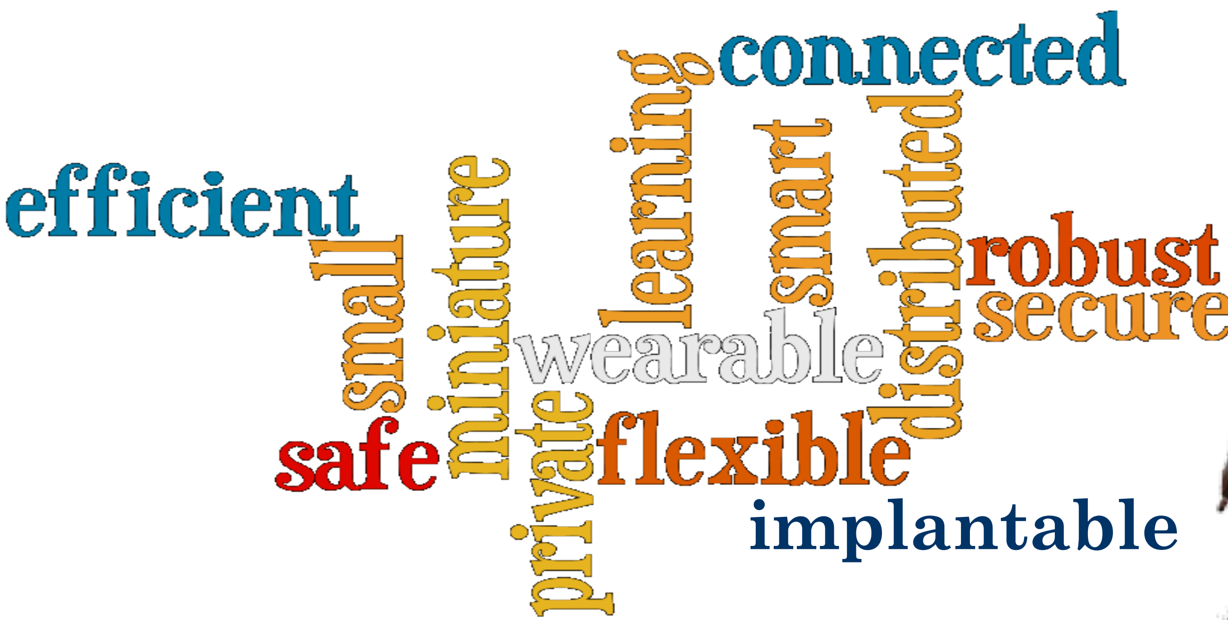


Seo, et al. Neuron 2016

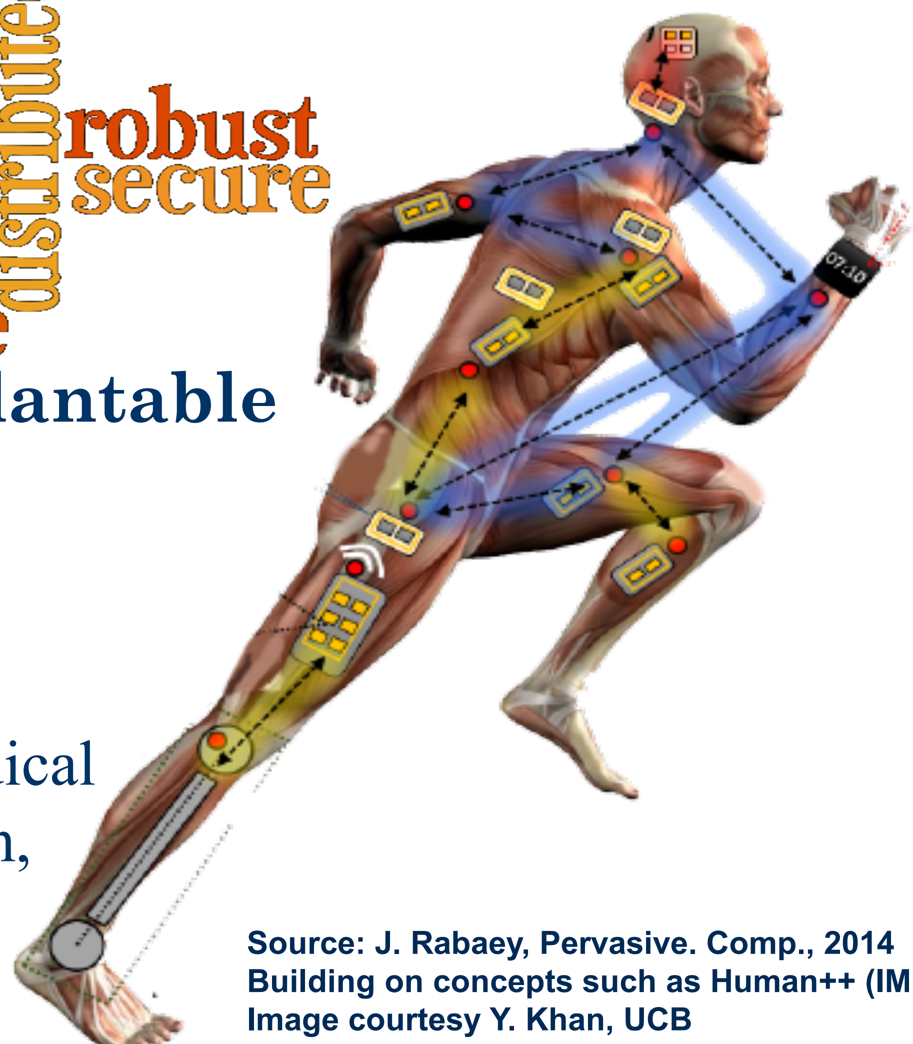


- Ultrasound can also be transformed into electrical power
- It's efficient propagation through tissue can be used to power and communicate with tiny implantable sensors that monitor nerves, organs, body temperature and more!
- Neural dust: Invented at Berkeley!

The Future



- Soon we will have access to wearable and implantable medical devices that will monitor, learn, diagnose and treat disease.



Source: J. Rabaey, Pervasive. Comp., 2014
Building on concepts such as Human++ (IMEC)
Image courtesy Y. Khan, UCB

5G Revolution

- Berkeley Wireless Research Center (BWRC) played an important role in demonstrating that mm-wave frequencies (60 GHz) can be used for communication and low cost CMOS technology was a viable option (research started in 2000, early demonstrations by 2004)
- Today mm-wave frequencies are one of the key aspects of next generation 5G communication systems
  - Several Gigabit/second per user
  - Low latency
  - Less interference due to spatial multi-plexing

Perspective

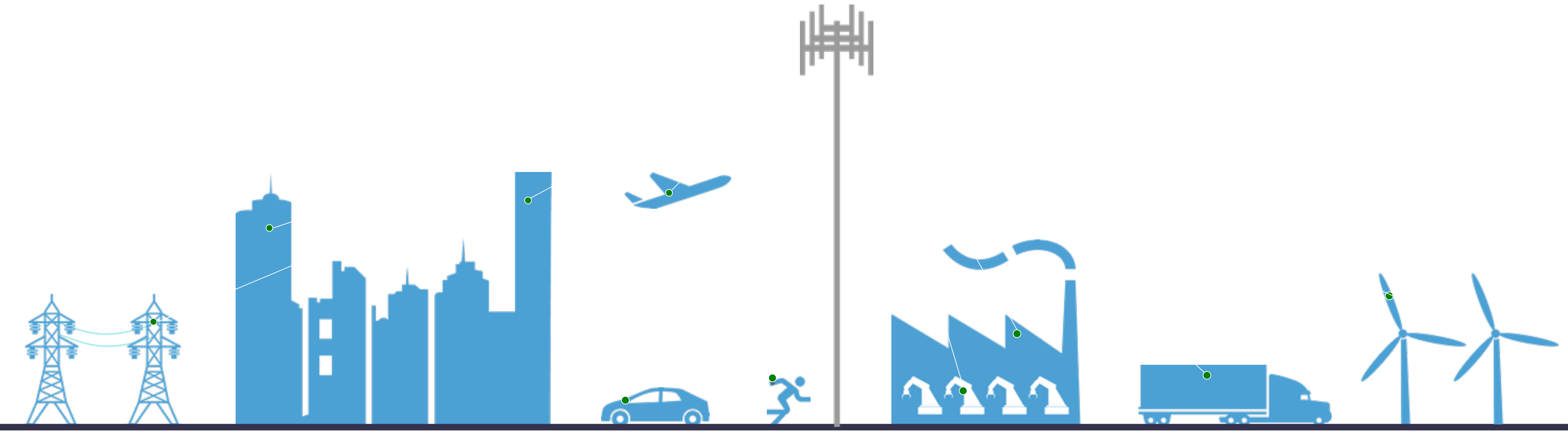
Papal Conclave 2005

Papal Conclave 2013

James Kimery

Director of RF Research and SDR Marketing at NI

Hyper Connected Everything



Data rate

Capacity

Power Consumption

Coexistence

Security

Monitoring

James Kimery

Director of RF Research and SDR Marketing at NI

5G + IoT

IOT WILL IMPACT
75% ENGINEERS
IN 3 YEARS
- VDC

50 BILLION
DEVICES CONNECTED BY 2020

7 THINGS
FOR EVERY
1 HUMAN
- GARTNER

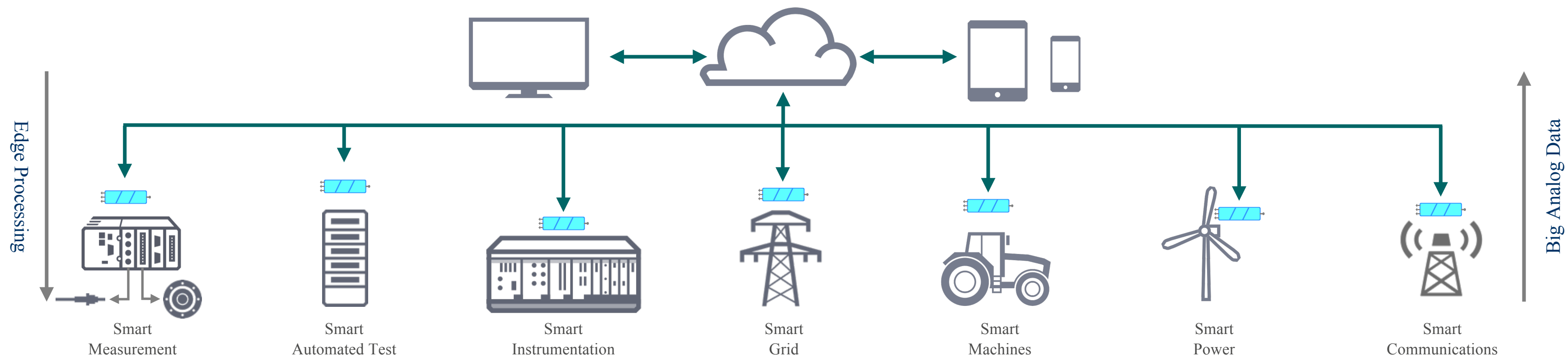
1.9 BILLION
SMARTPHONES

BY 2025
45%
OF THE IOT WILL BE
INDUSTRIAL
- IHS

$19
TRILLION
OPPORTUNITY

James Kimery
Director of RF Research and SDR Marketing at NI

The Industrial Internet of Things



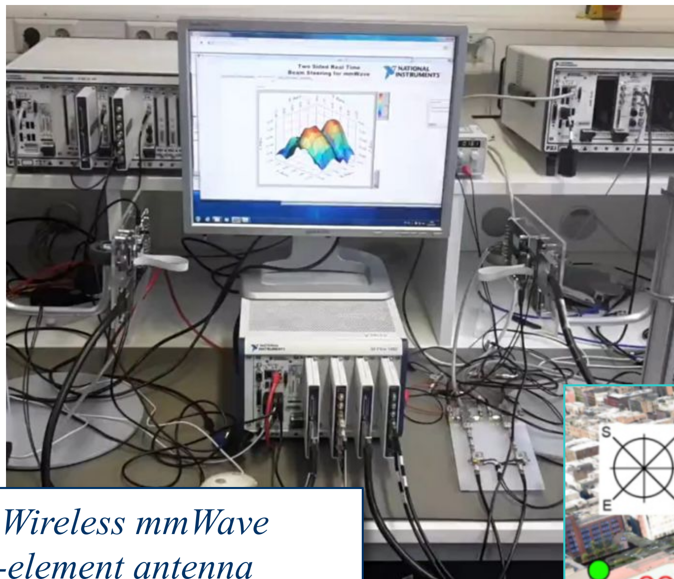
Enhanced Requirements for the IIoT

Reliability | Latency | Security | Upgradeability

James Kimery

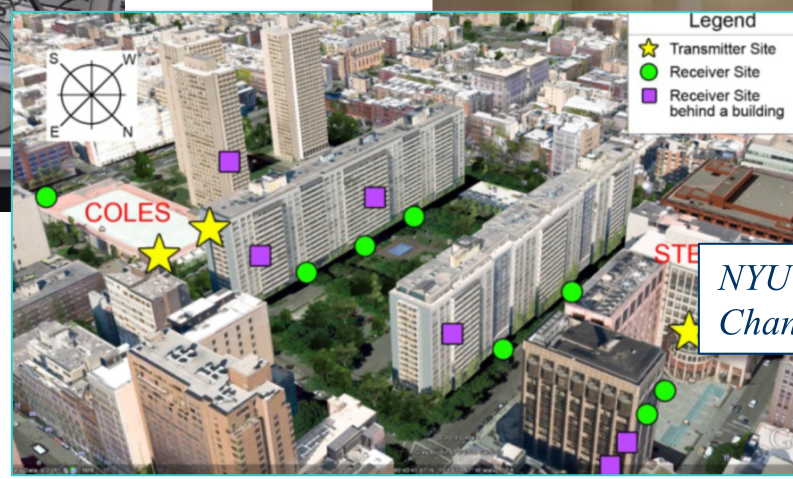
Director of RF Research and SDR Marketing at NI

mm-Wave and Massive MIMO Testbeds



NYU Wireless mmWave multi-element antenna beamforming

Rutgers Orbit Lab



NYU Wireless mmWave Channel Measurements

James Kimery
Director of RF Research and SDR Marketing at NI

Are you ready?

- There are tons of opportunities and challenges in designing the next generation systems
- The goal of 105 is to give you enough background in the circuits, device, and system aspects so that you can get involved now !