

Electrons Dancing with Photons in the Ocean of Digits

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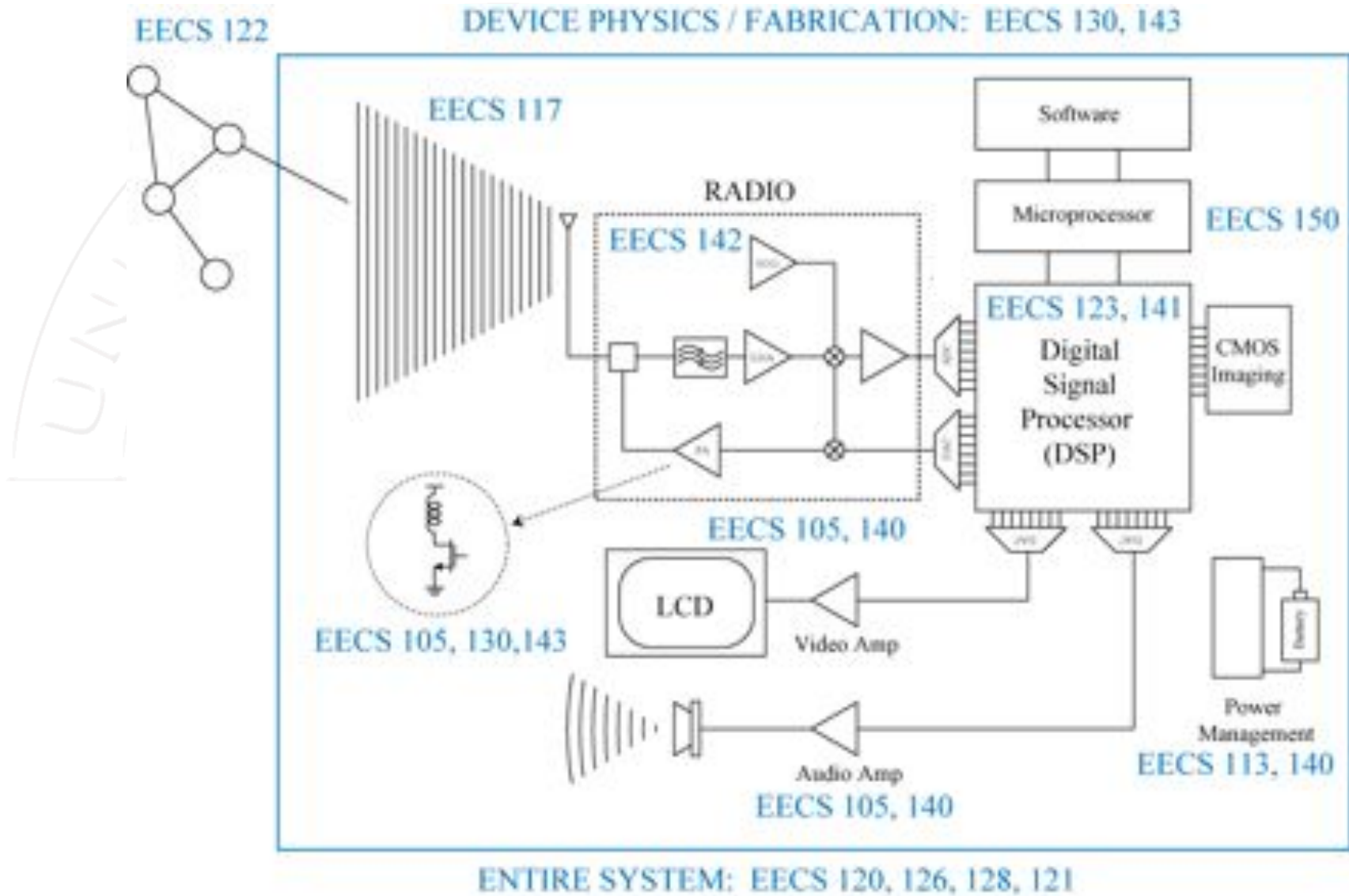


Peek inside of a cell phone...



- Lot's of “chips” (Integrated Circuits)
- What's inside of these chips?

Cell Phone by EE Courses



Hybrid Technology (Prius)

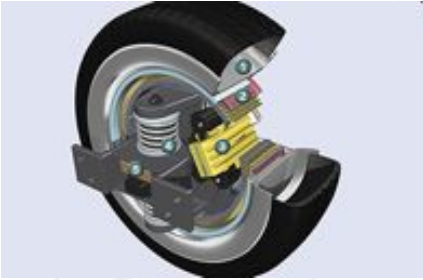


Solar Cells

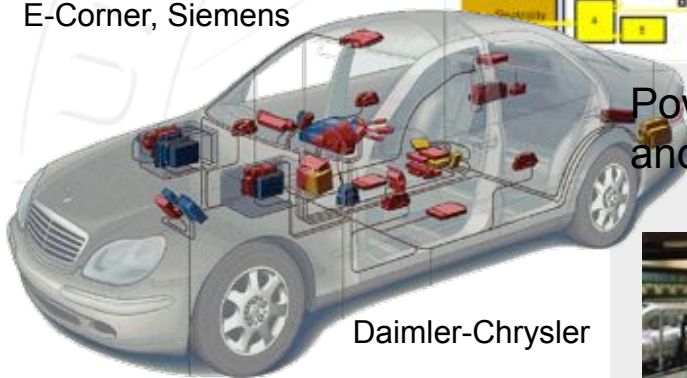


Cyber-Physical Systems (CPS): Orchestrating networked computational resources with physical systems

Automotive



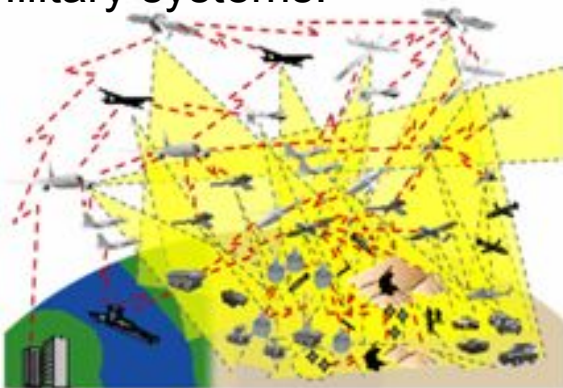
E-Corner, Siemens



Power generation
and distribution

Daimler-Chrysler

Military systems:



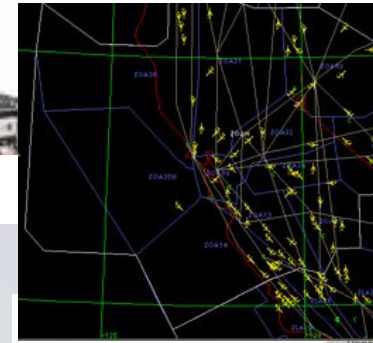
Building Systems



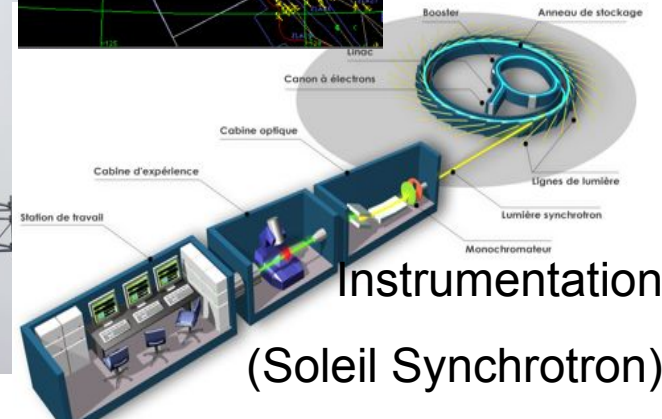
Avionics



Telecommunications



Transportation
(Air traffic control at SFO)



Instrumentation
(Soleil Synchrotron)

Factory



Courtesy of Kuka Robotics Corp.

EE Trichotomy

- Devices

- You can “touch and feel” devices
- Semiconductors are materials of choice, properties can be engineered
- Information is ultimately represented by electrons (and ‘holes’) and/or photons

- Circuits

- Any interconnection of devices that performs a useful function
- Digital circuits, analog circuits, “RF” and microwave

- Systems

- The theory behind EE systems. A model for the system that includes noise, non-linearity, feedback, and dynamics.
- Most often digital signal processing algorithms used.



Some EE History

Telegraphy

- First there was telegraphy – use “Vail” (Morse) code to send messages over long distances.
- Patented in the US in 1837 by Morse and Vail.
- West coast connected by 1861 → end of Pony Express.
- Telegraph cables run along train tracks moving both information, people, and goods rapidly along the country



Transatlantic Cable



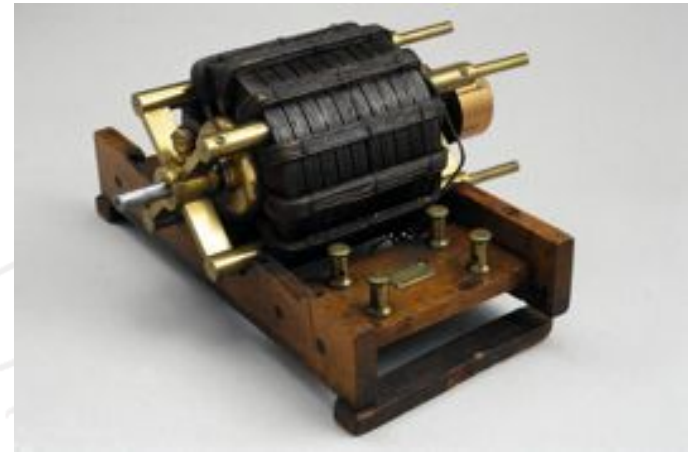
- Transatlantic cable completed by 1866 (worked only a few days before it failed). → Led to the advancement in the theory of transmission lines.

Bell

- Alexander Graham Bell was the first to be awarded a patent for the electric telephone by the United States Patent and Trademark Office (USPTO) in March 1876.
- 10 March 1876 — The first successful telephone transmission of clear speech using a liquid transmitter when Bell spoke into his device, “Mr. Watson, come here, I want to see you.” and Watson heard each word distinctly.



Tesla



The induction motor, another Tesla invention.

- In 1891 Nikola Tesla demonstrate wireless transmission of signals and he suggested wireless telegraphy as an application.

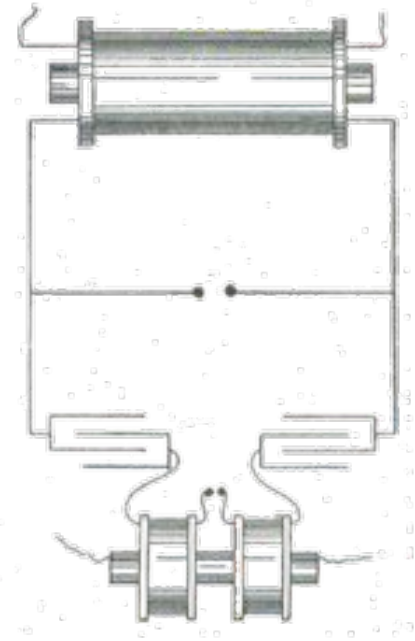
Bose

- In November 1894, the Bengali Indian physicist, Jagadish Chandra Bose, demonstrated publicly the use of radio waves in Calcutta (did not file for a patent).



Wireless / Radio

- Started as wireless telegraphy. The history of the invention of the radio is very disputed.
- Marconi widely recognized as an early inventor although he played a more important role in commercializing the radio. In 1895 he sent signals 1.5 km. Transatlantic in 1902.



Titanic Boost in Radio

- In 1912, the RMS Titanic sank in the northern Atlantic Ocean.
- Wireless radio transmissions (telegraph) were used to report the ship's location.
- Britain's postmaster-general summed up, referring to the *Titanic* disaster, “Those who have been saved, have been saved through one man, Mr. Marconi...and his marvellous invention.”



Early “Ultra Wideband” Radio



- In the beginning these sparks generated “ultrawideband” interference which represented “Vail” code.
- The systems were essentially passive (vacuum tubes and transistors were not yet invented) and just realized with *LC* tanks and transformers.

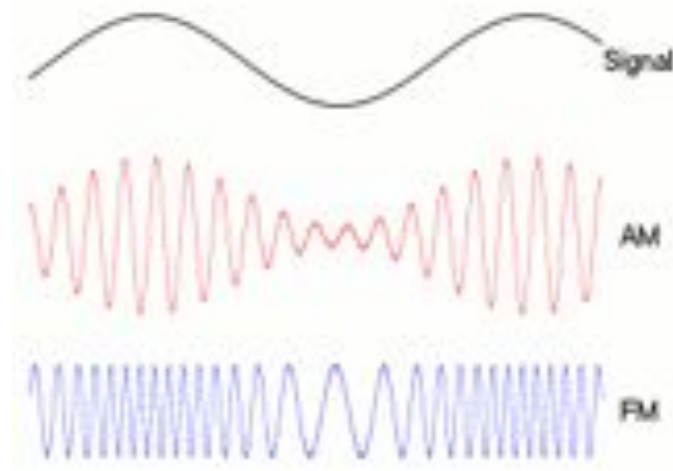
First Audio Transmissions

- Reginald Fessenden: Invented amplitude-modulated (AM) radio, so that more than one station can send signals (as opposed to spark-gap radio, where one transmitter covers the entire bandwidth of the spectrum).
- On Christmas Eve 1906, Reginald Fessenden made the first radio audio broadcast, from Brant Rock, MA. Ships at sea heard a broadcast that included Fessenden playing O Holy Night on the violin and reading a passage from the Bible.



AM/FM Wireless Radio

- The dominant telegraph company of the time was Western Union. They had a monopoly on telegraphy and they dismissed telephony and radio.
- Telegraph gave way to audio transmission, mainly phone lines and broadcast radio.
- Frequency modulation (FM) was invented by Armstrong in 1935. FM has greater noise immunity than AM but requires more bandwidth.



Digital Communications

- By sampling a signal and quantizing it (turning it into finite precision numbers), we can easily store it using digital technology and we can also transmit it digitally.
- Audio signals, for example, need to be sampled at about 20,000 times per second and with a resolution of around 18-bits to completely retain the fidelity of the signal (for the human ear)
- Today information is still transmitted with AM and FM, but the amplitude and phase of the signal are mapped into a finite alphabet. These digital signals are more noise immune and can be coded (guarded) to prevent, correct, and detect errors in transmission.

A large, faint watermark of the University of Qom is visible in the background. It features a semi-circular arch with the text 'UNIVERSITY OF QOM' and 'QOM' on the right side. Inside the arch is a stylized sunburst or starburst design.

Devices

Devices

- Devices: Physical stuff you can “touch and feel”
 - Manufacturing driven largely by integrated circuit (IC) fabrication
 - The building block of ICs: Transistors
 - Transistors used to make:
 - Logic gates, memory, amplifiers
- Devices include electronic devices and optical devices
 - Electron (and “hole”) transport through metals and semiconductors
 - Semiconductors can be engineered to have specific properties (conductivity). The junction between two semiconducting materials is where the magic happens
 - Photons (light) used to carry information through waveguides (fiber optics) or through electromagnetic radiation (radios, wireless).
 - Semiconductor junctions can generate photons or detect photons (optical receivers, solar cells)

The Transistor



- Invented at Bell Laboratories on December 16, 1947 by William Shockley (seated at Brattain's laboratory bench), John Bardeen (left) and Walter Brattain (right)
- Inventors awarded Nobel Prize
- Probably the most important even in EE history

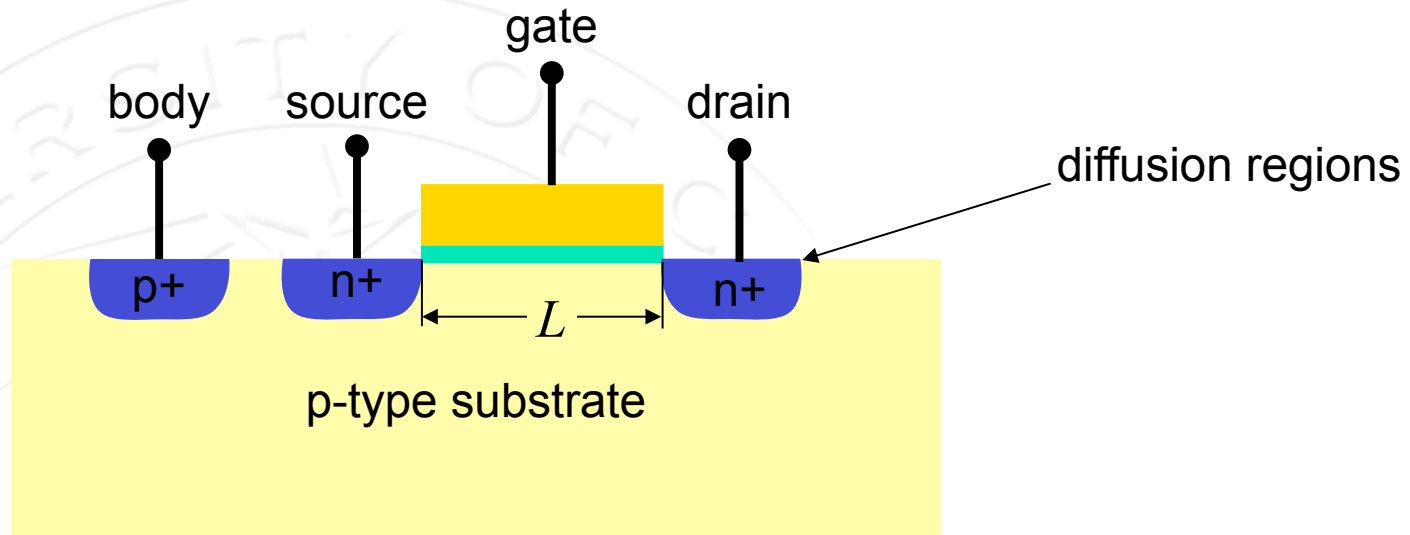
Early Transistors

- Bell labs was the research lab of a telephone company. As such the importance of the transistor was not recognized by many of the business folks at AT&T.
- Device was flaky and low power compared to vacuum tubes, the workhorse device of the time (for sig amplification)
- In 1952 first transistorized radios appear. Compared to vacuum tube, transistors were compact.
- Transistor radio was a revolutionary battery operated device.



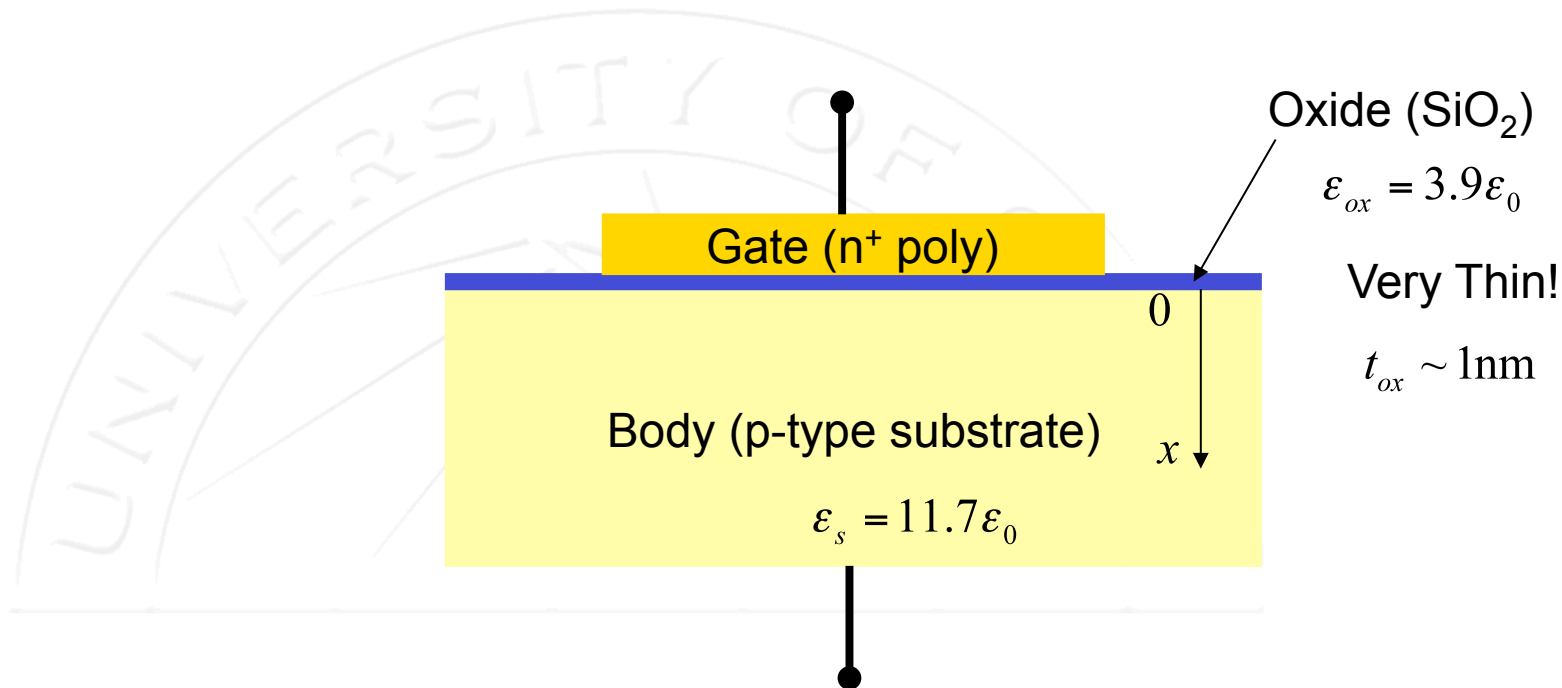
http://en.wikipedia.org/wiki/File:Sanyo_Transistor.jpg

How does a transistor work?



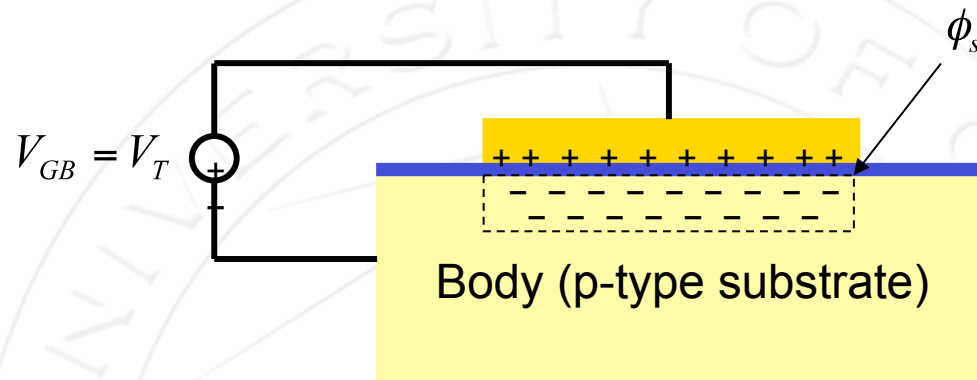
- Metal-Oxide-Semiconductor sandwich. Usual structure is actually polysilicon, silicon dioxide, silicon. (Note that the original transistor fabricated was not an MOS device.)
- A “channel” for current flow can be setup between the drain/source.
- The channel conduction (between drain and source) is controlled by the gate voltage.

Basic Structure: MOS Capacitor

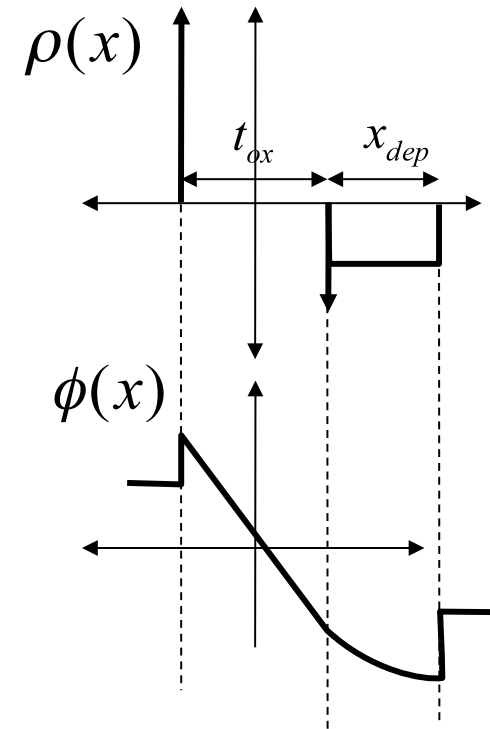


- MOS = Metal Oxide Silicon
- Sandwich of conductors separated by an insulator
- “Metal” is more commonly a heavily doped polysilicon layer n⁺ or p⁺ layer
- NMOS → p-type substrate, PMOS → n-type substrate

Creating a Channel: Inversion

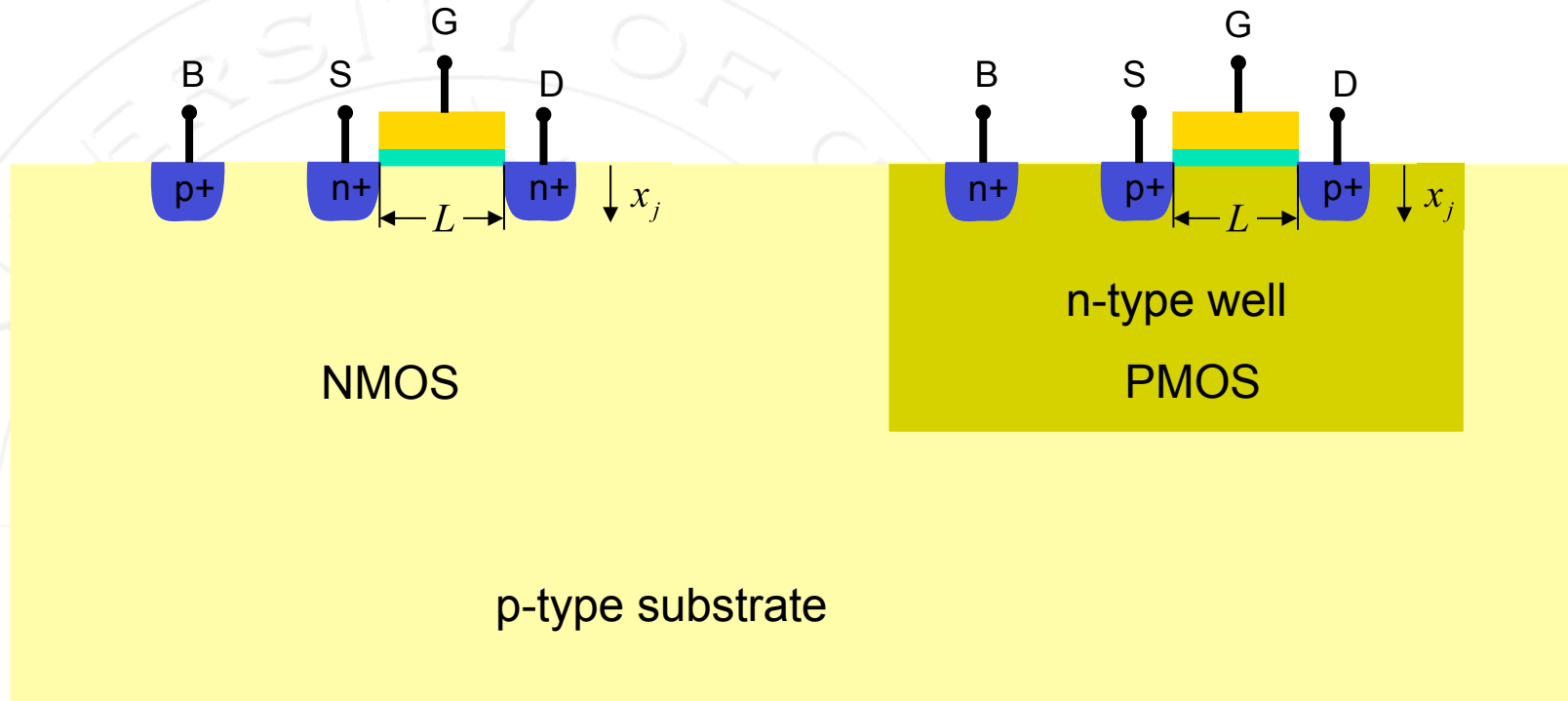


$$n_s = n_i e^{\frac{q\phi_s}{kT}} = N_a$$



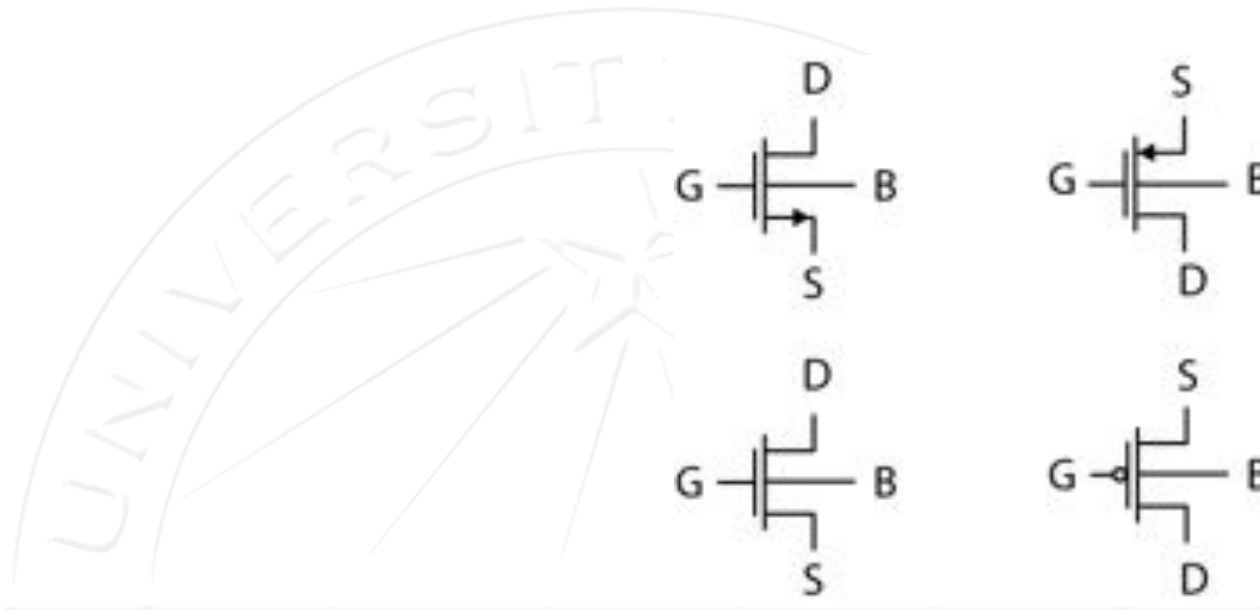
- The surface potential increases to a point where the electron density at the surface equals the background ion density
- At this point, the depletion region stops growing and the extra charge is provided by the inversion charge at surface

CMOS



- Complementary MOS: Both P and N type devices
- Create a n-type body in a p-type substrate through compensation. This new region is called a “well”.
- To isolate the PMOS from the NMOS, the well must be reverse biased (pn junction)

Circuit Symbols



- The symbols with the arrows are typically used in analog applications
- The body contact is often not shown
- The source/drain can switch depending on how the device is biased (the device has inherent symmetry)

Logic Gates



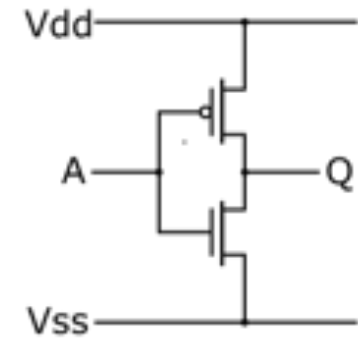
AND



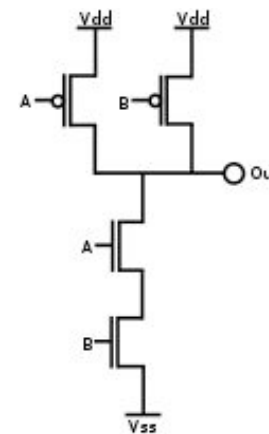
OR



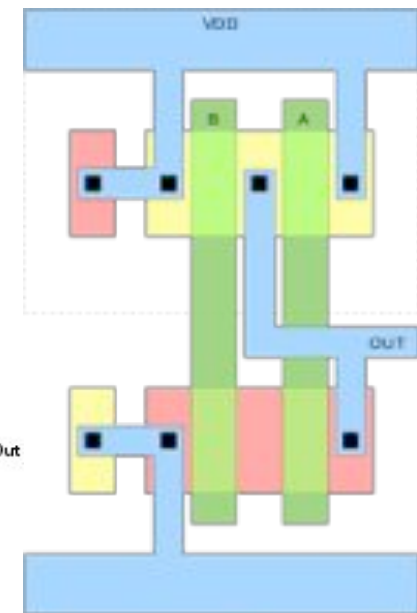
NOT



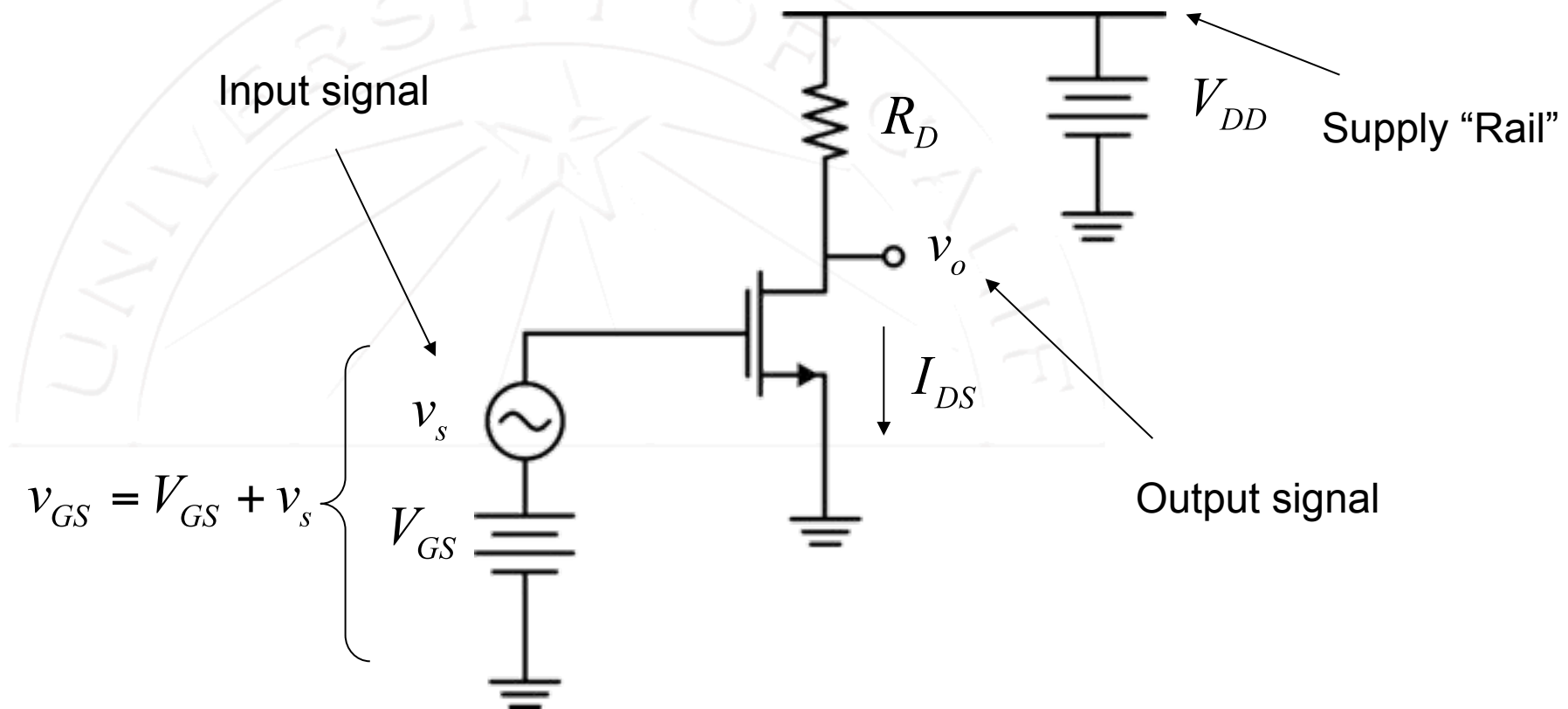
- Logic gates perform Boolean algebra. Any logical operation on bits can be written as expressions involving these basic operators.
- Examples: A 20-bit adder can be reduced to a circuit involving a bunch of logic gates.
- CMOS transistors easily implement these functions. Note that the function to the right is a NAND, or a AND followed by a NOT.



NAND

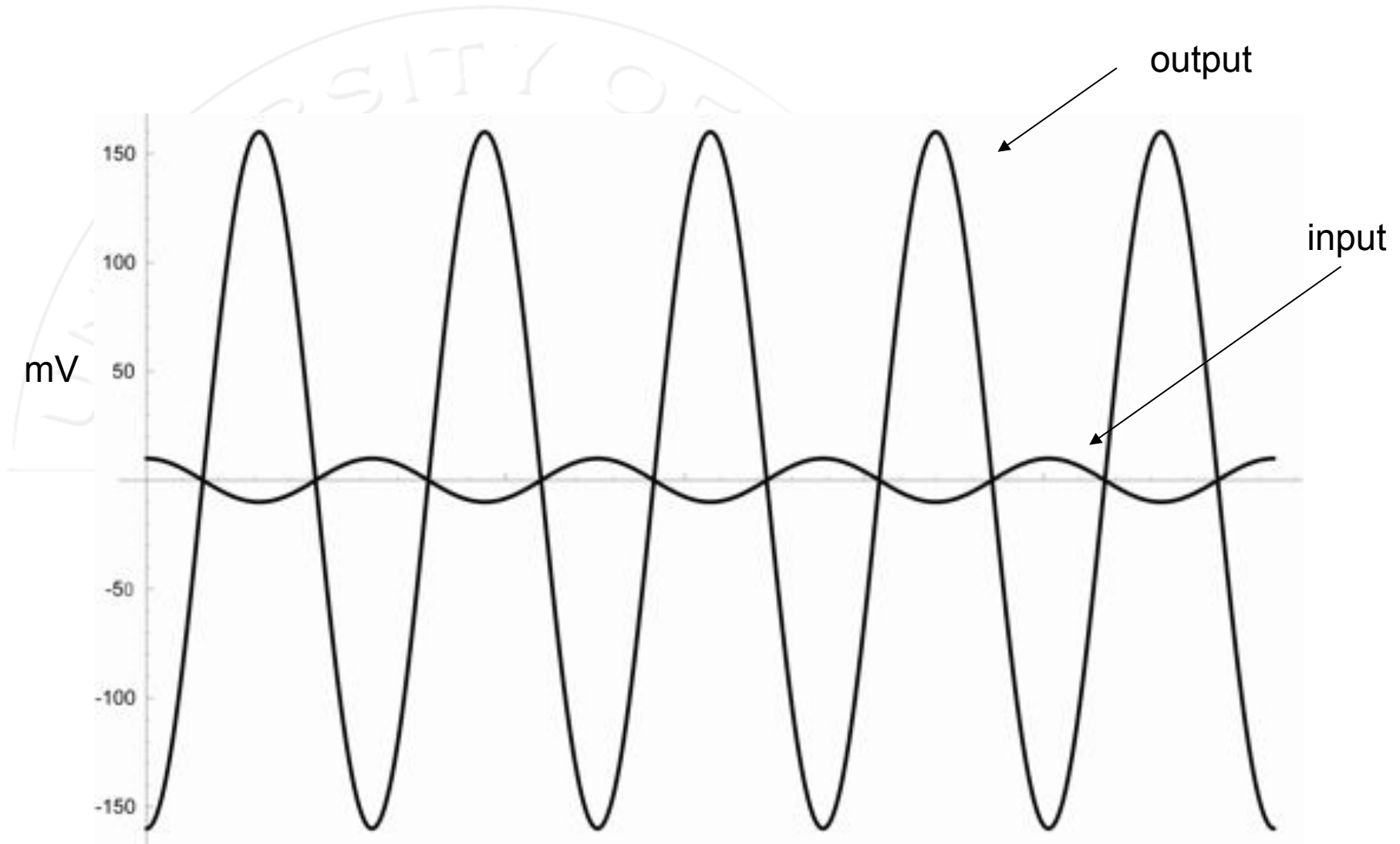


Amplifiers

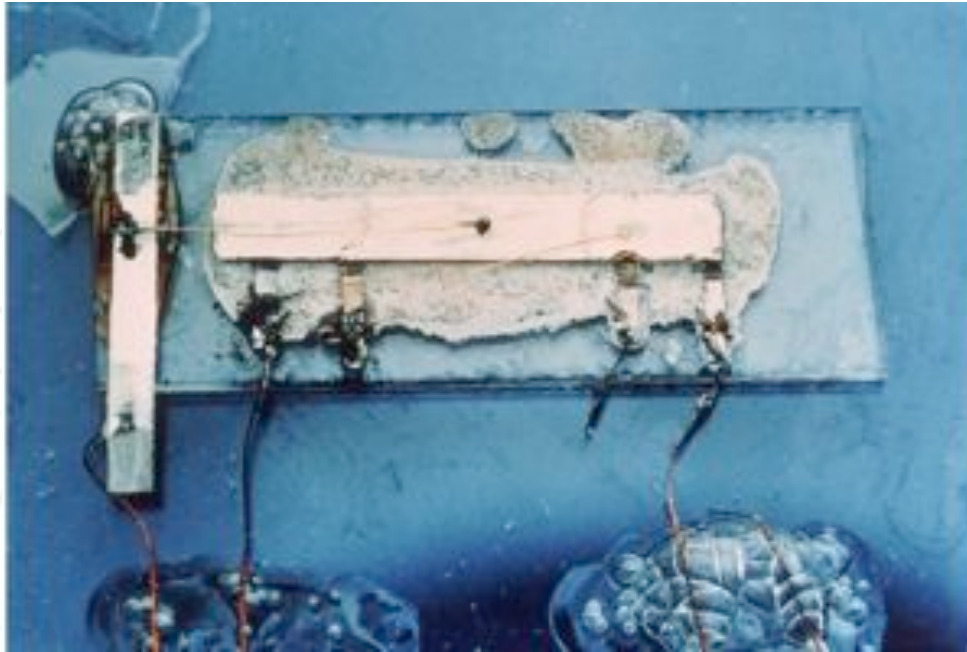


- A signal with virtually no power can control the gate conductance and thus modulate the larger output signal.

Voltage Amplification



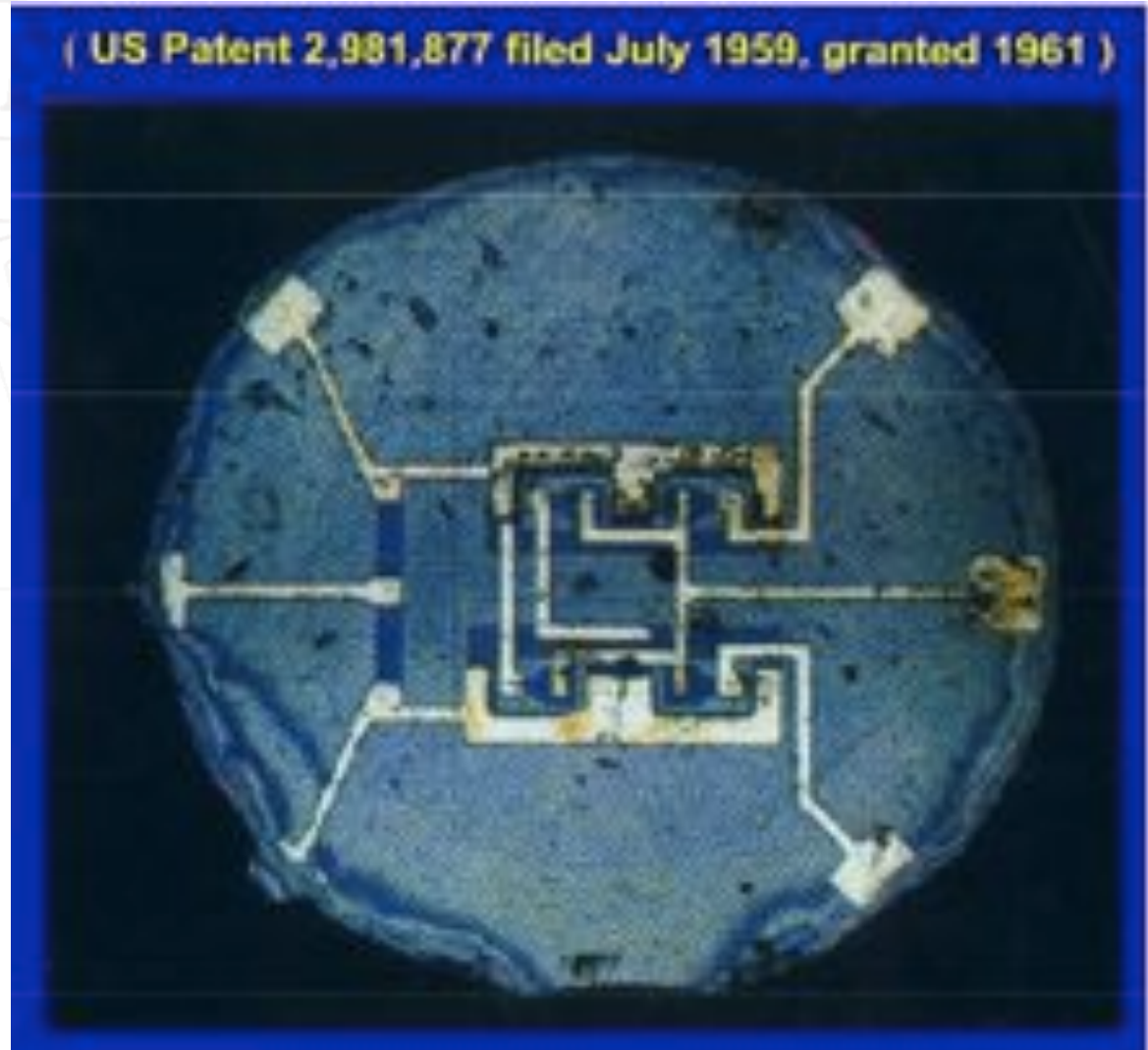
The Integrated Circuit



- First IC is invented by Jack Kilby of Texas Instruments and Robert Noyce of Fairchild Semiconductor (later founded Intel)
- In his patent application of February 6, 1959, Kilby described his new device as “a body of semiconductor material ... wherein all the components of the electronic circuit are completely integrated.” (2000 Nobel Prize in Physics)

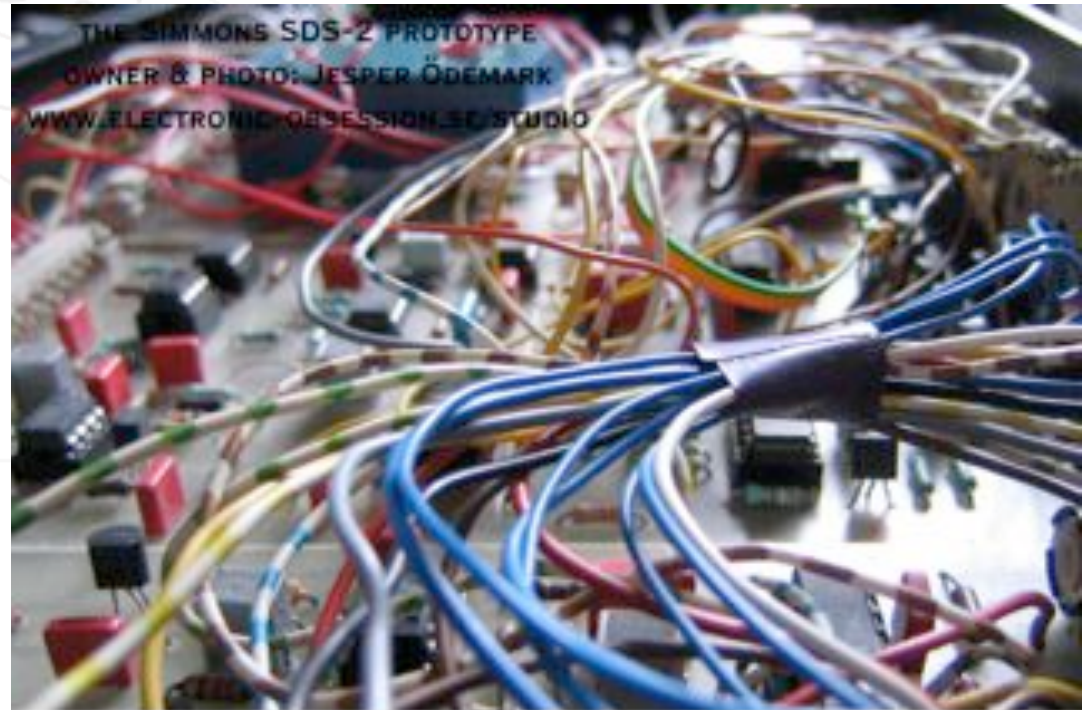
Noyce's IC Invention

- Silicon oxidation, Photolithographic patterning of SiO_2 , Selective doping through openings in SiO_2
- A complete materials processing recipe for integrated circuits, CCD's, memory, etc., (the full set of electronic signal processing functions.)



Why IC's were revolutionary:

- When building a complex circuit, most of the failures occur in the wiring and connections
→ spaghetti of wires
- Printed circuit boards help improve reliability but they are physically large and discrete components are fairly expensive
- ICs: Low cost mass production, monolithic, includes transistors and interconnect.



IC's Today

- Easily integrate millions to *billions* of transistors on a single chip.
- Patterns printed once and can be used again and again to make copies of IC.
- High yields through careful manufacturing tolerances.
- Dimensions have gone from sub mm to sub micron. Today the gate length and oxide of a transistor is ~ 10 nm (about ten layers of atoms)

Photolithography

- Silicon is a semiconductor. The electrical properties change drastically when the material is exposed to minute quantities of dopants.
- Silicon is the starting material for most IC fabrication. It is grown in a very pure state as a silicon ingot and then sliced into thin *wafers*.



IC Fabrication: Si Substrate

- Pure Si crystal is starting material (wafer)
- The Si wafer is extremely pure (~1 part in a billion impurities)
- Why so pure?
 - Si density is about 5×10^{22} atoms/cm³
 - Desire intentional doping from 10^{14} – 10^{18}
 - Want unintentional dopants to be about 1-2 orders of magnitude less dense $\sim 10^{12}$
- Si wafers are polished to about 700 μm thick (mirror finish)
- The Si forms the substrate for the IC

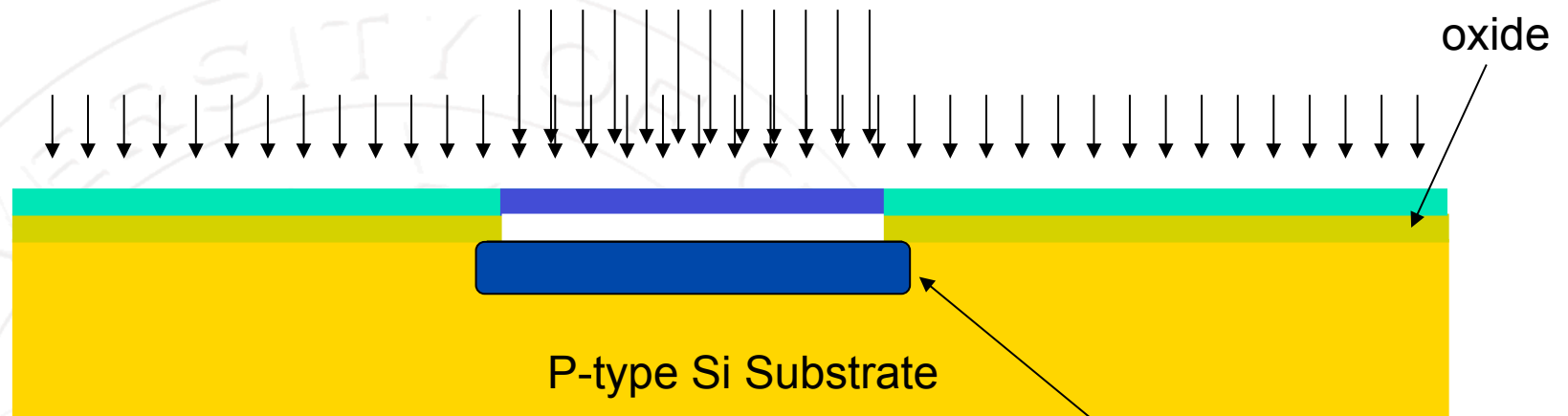
IC Fabrication: Oxide

- Si has a native oxide: SiO_2
- SiO_2 (Quartz) is extremely stable and very convenient for fabrication
- It's an insulators so it can be used for house interconnection
- It can also be used for selective doping
- SiO_2 windows are etched using photolithography
- These openings allow ion implantation into selected regions
- SiO_2 can block ion implantation in other areas

Dopants

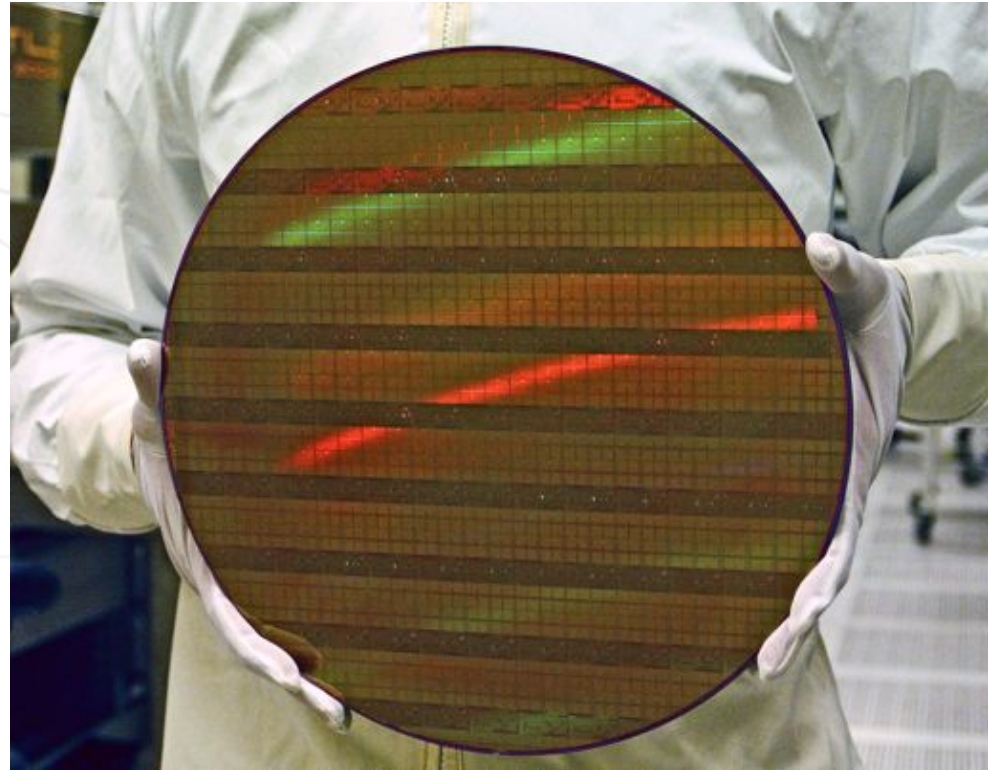
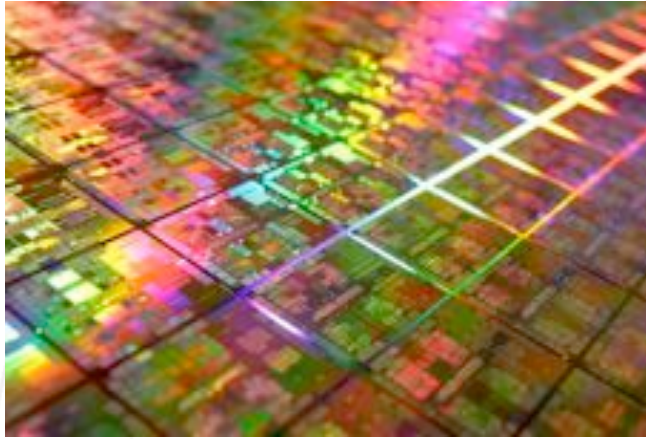
- Dopants introduced into material in specific locations using photolithography patterning and etching.
- Insulators are grown on top of layers to provide interconnect and to form devices.
- A transistor is just a junction of a few different pieces of doped silicon regions.

Ion Implantation



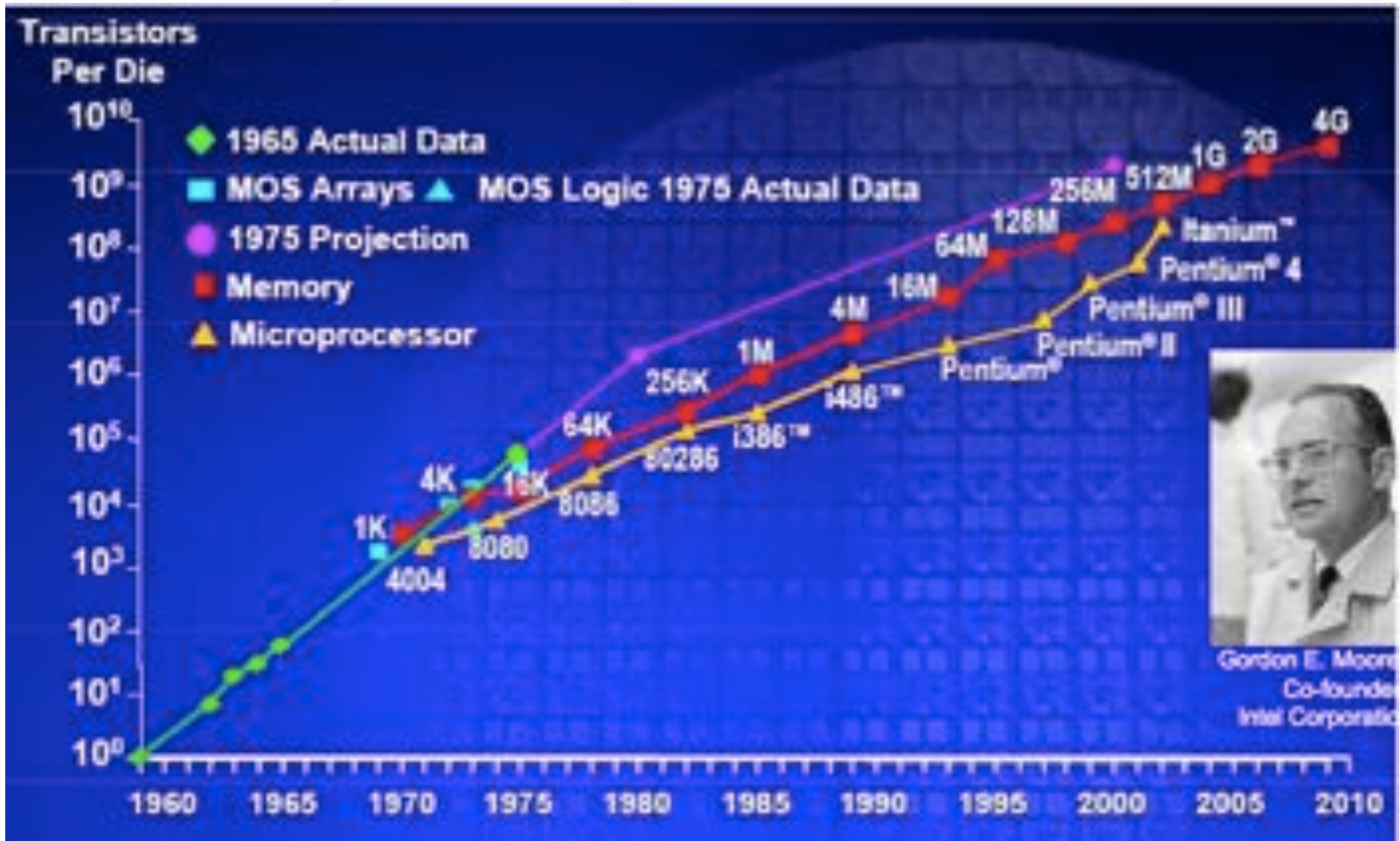
- Si substrate (p-type)
- Grow oxide (thermally)
- Add photoresist
- Expose (visible or UV source)
- Etch (chemical such as HF)
- Ion implantation (inject dopants)
- Diffuse (increase temperature and allow dopants to diffuse)

Wafers



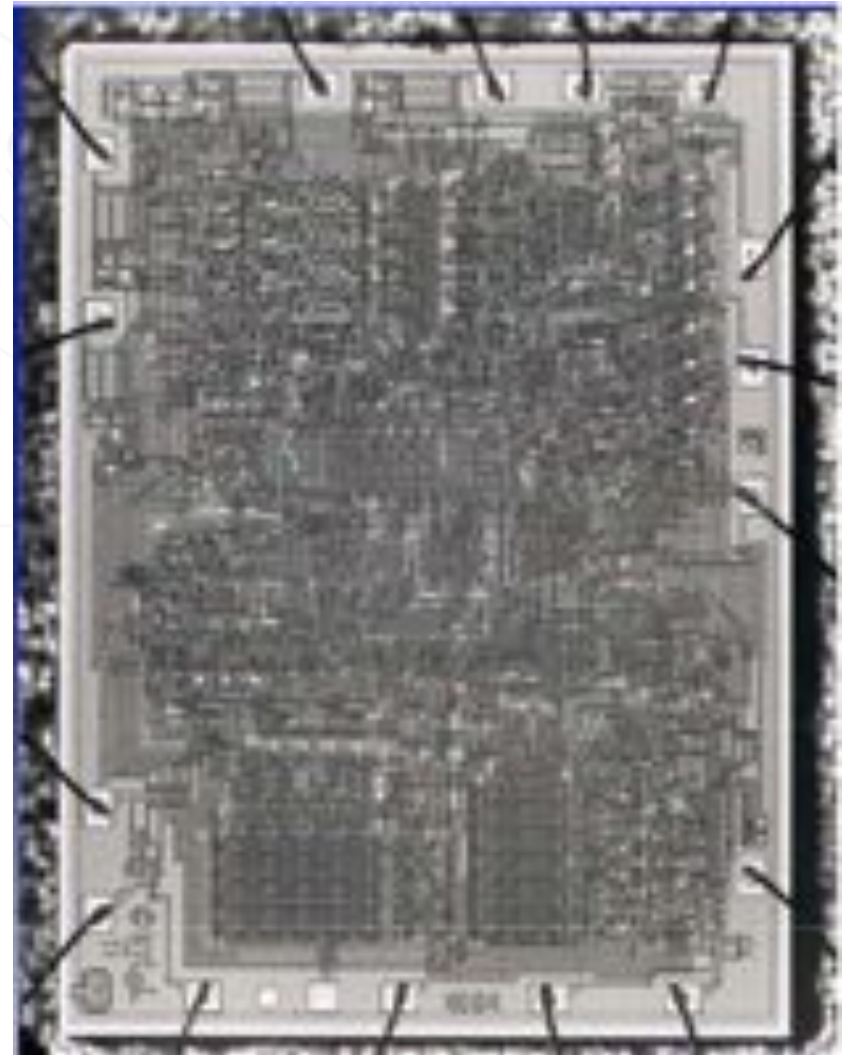
- The IC pattern can be “stepped” across the wafer and many copies of the same circuit are fabricated. The bigger the wafer, the more circuits!

Moore's Law



First Microprocessor

- First general purpose “programmable” processor packaged into a single die
- 2300 transistors
- 60 kHz clock speed

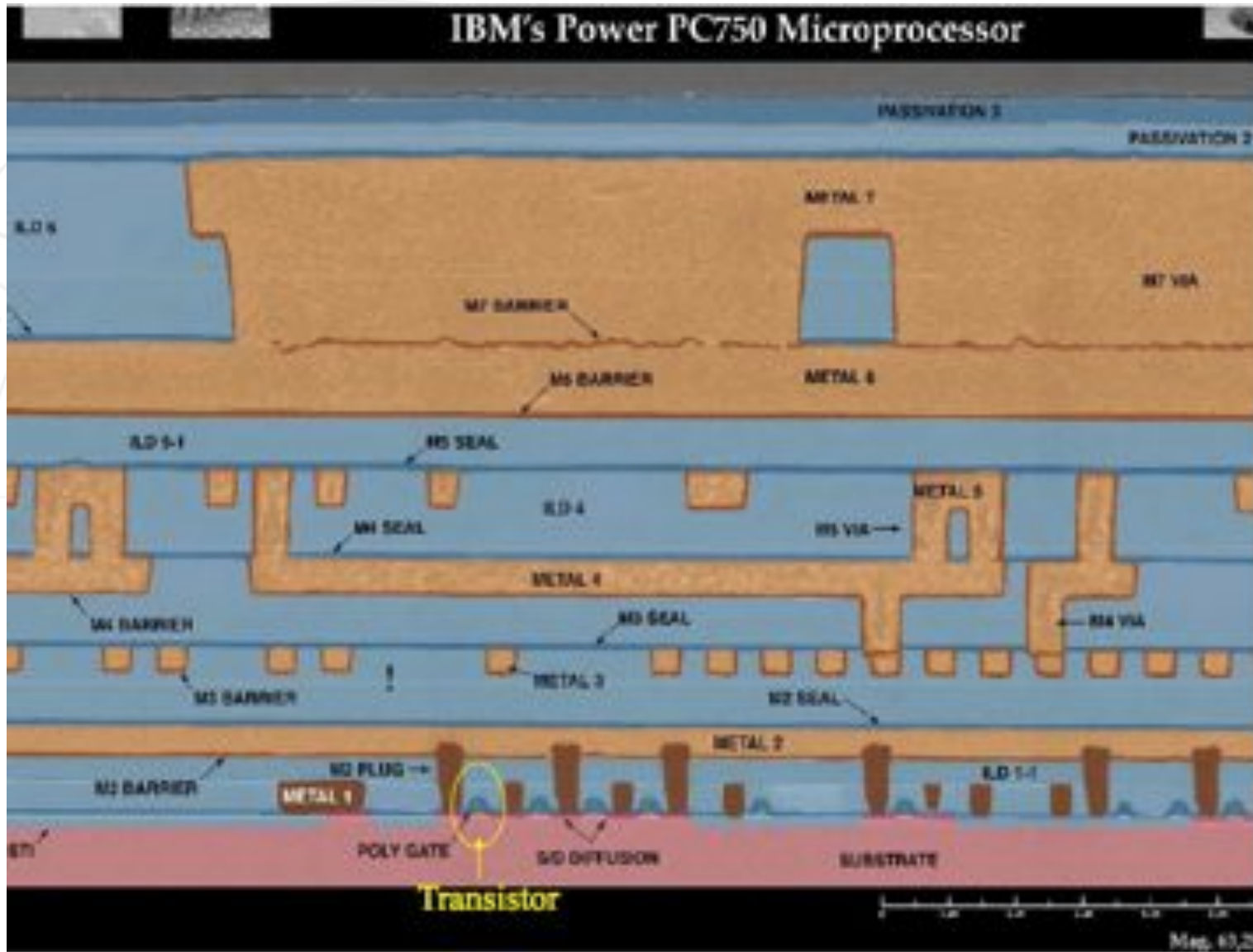


Pentium 4

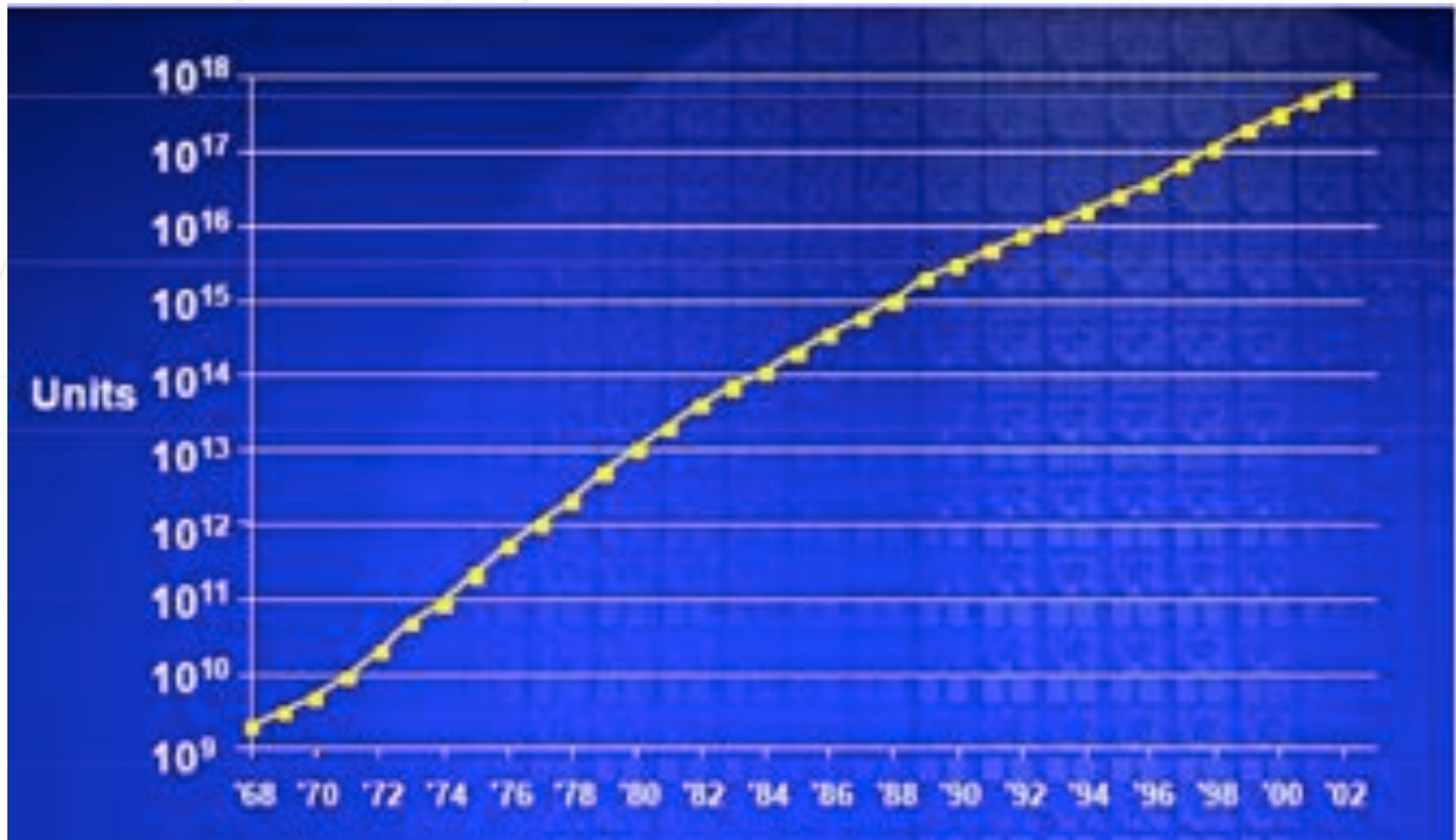
- 42 million components
- 1.7 GHz
- 0.18um Technology



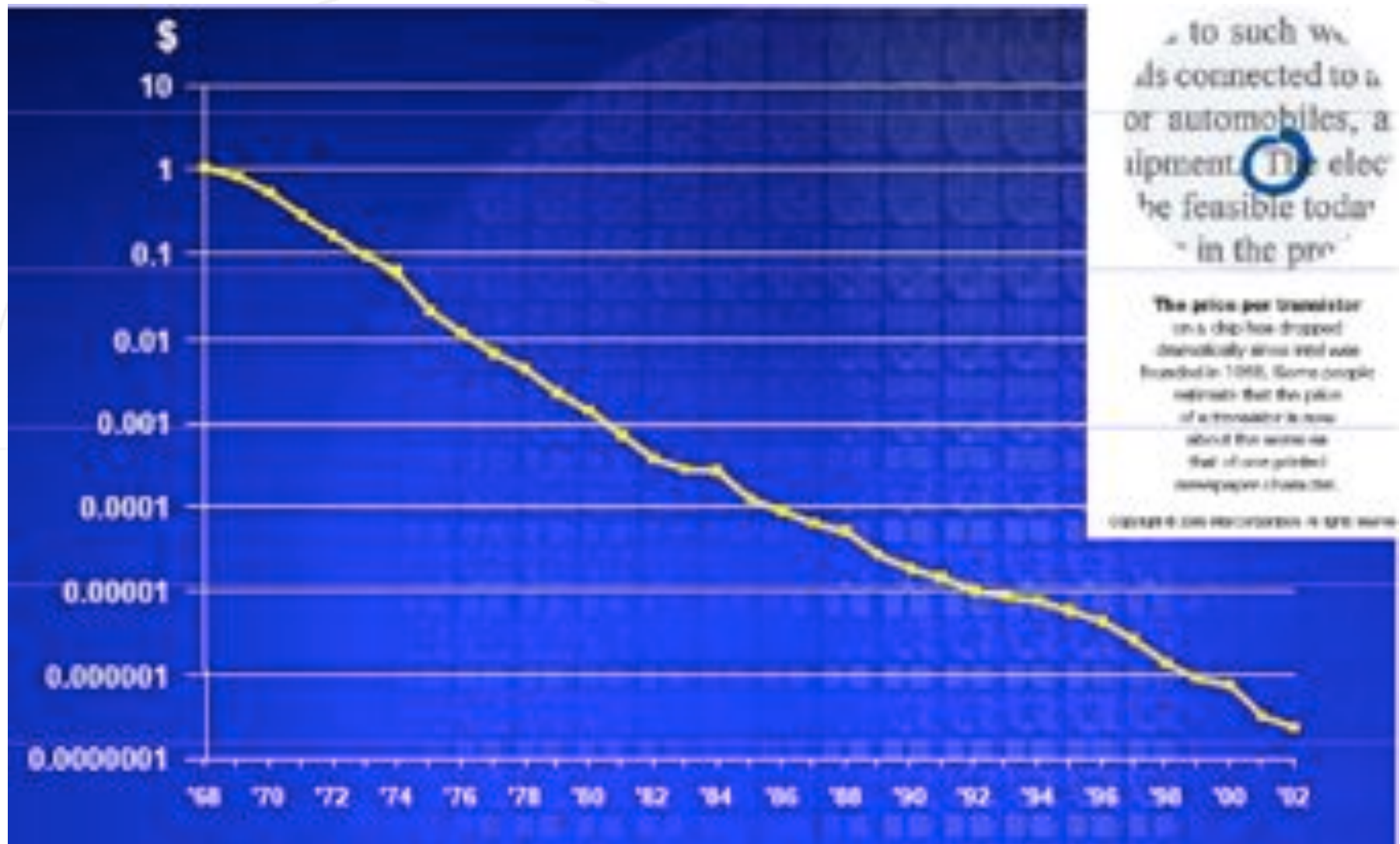
IC Cross Section



Transistors Shipped Per Year



Transistor Price Per Year



Year	1961	2004	Improvement Ratio
Minimum critical dimension	25 μm	0.09 μm	277
Area per feature	625 μm^2	8100 nm^2	80,000
Wafer Diameter	5mm	300mm	60
Wafer Area	25 mm^2	900 cm^2	3600
Working Voltage	5Volts	1.25Volts	4
Transistors per chip	6	10^9	10^8
Transistors shipped per year	10^6	10^{19}	10^{13}
Average Transistor Price	\$10	\$0.000000005	5×10^{-10}
Size of Industry (\$/year)	\$ 5×10^8	\$ 2.5×10^{11}	500

MEMS

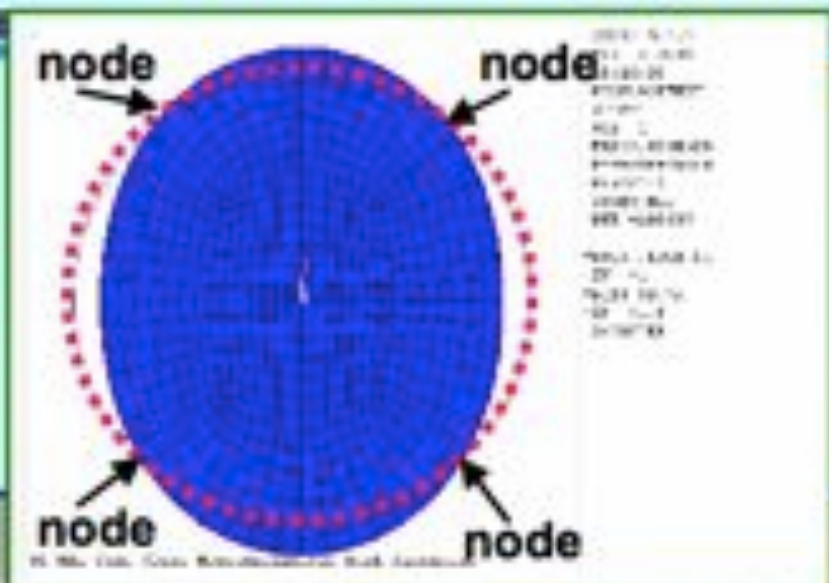
- Micro Electro-Mechanic Systems
- Use the same technology for building chips but now build mechanical structures!
- Often older process nodes can be used which brings the cost down.
- Common MEMS devices include accelerometers for automobile airbags and for devices such as the cell phone. (iPhone popularized the the tilt function using an accelerometer.)
- Active research on building high Q resonators with MEMS technology for radio applications.



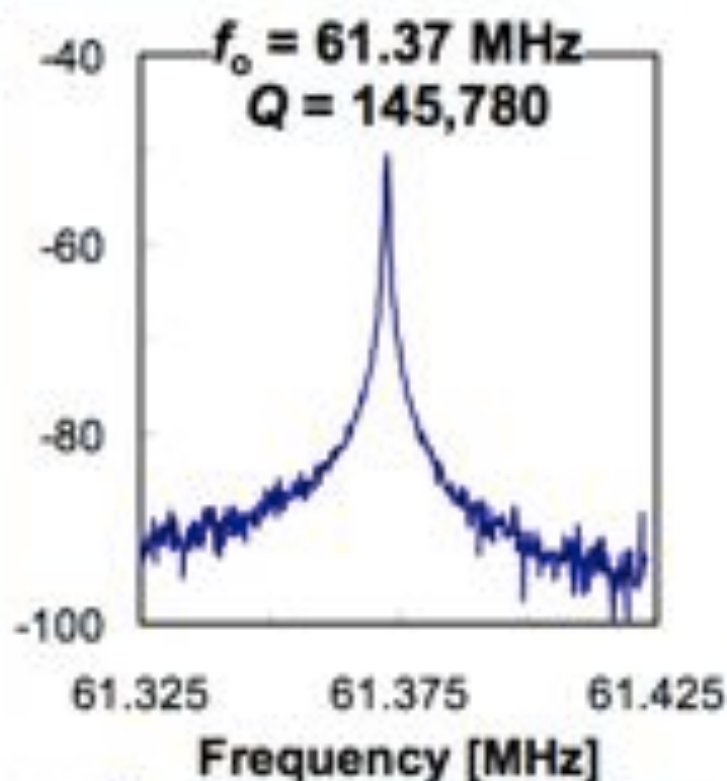
Michigan

Wine-Glass Disk Resonator

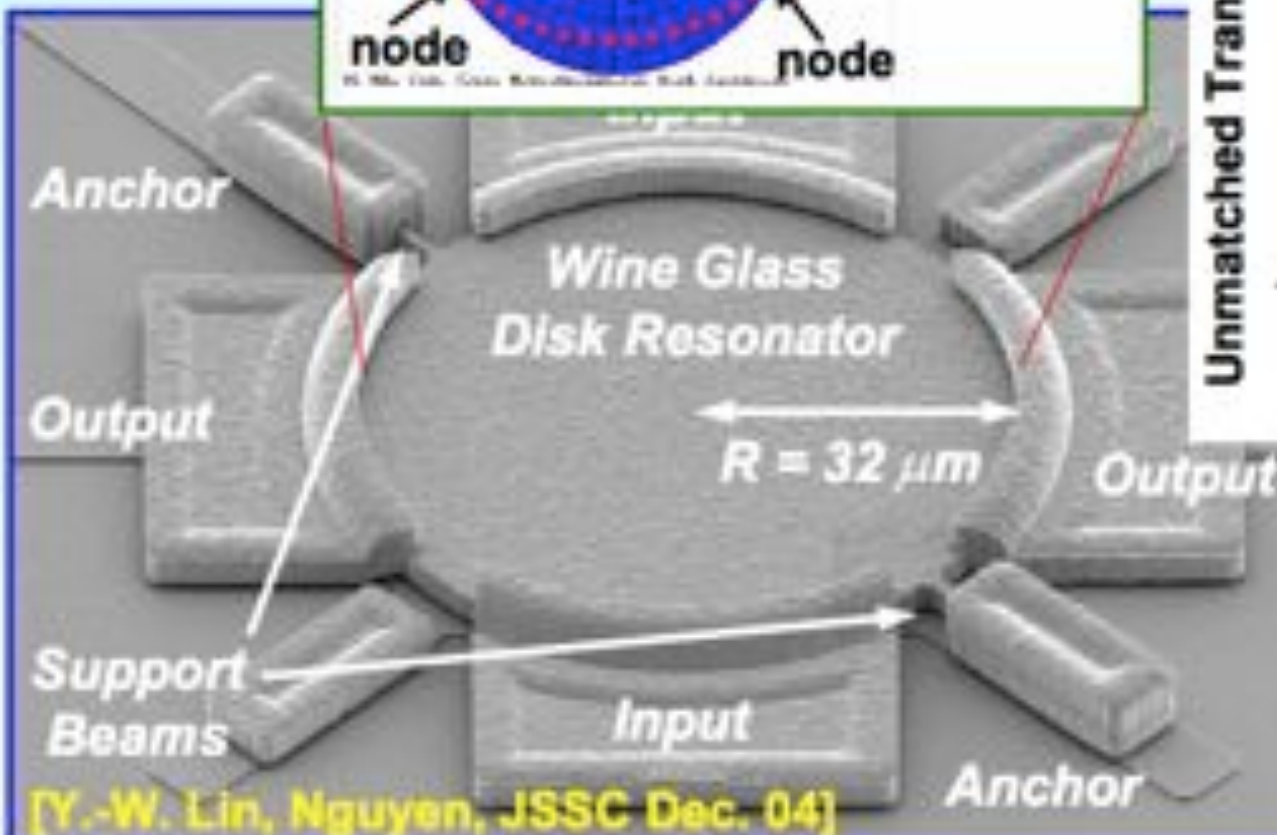
Compound Mode (2,1)



Unmatched Transmission [dB]



Resonator Data
 $R = 32 \mu\text{m}$, $h = 3 \mu\text{m}$
 $d = 80 \text{ nm}$, $V_p = 3 \text{ V}$



[Y.-W. Lin, Nguyen, JSSC Dec. 04]

“Green” IC Technology: Solar PV

- The sun shines about 1kW of energy per square meter
- A solar or photovoltaic cell converts light into electricity (no pollution!)
- The junction of two semiconducting regions can be used to capture photons and convert them into electricity (photoelectric effect). The photon energy must be larger than the band gap.



A large, faint watermark of the University of Qom is visible in the background. It features a semi-circular arch with the text 'UNIVERSITY OF QOM' and 'QOM' on the right side. Inside the arch is a stylized star or sunburst design.

Circuits

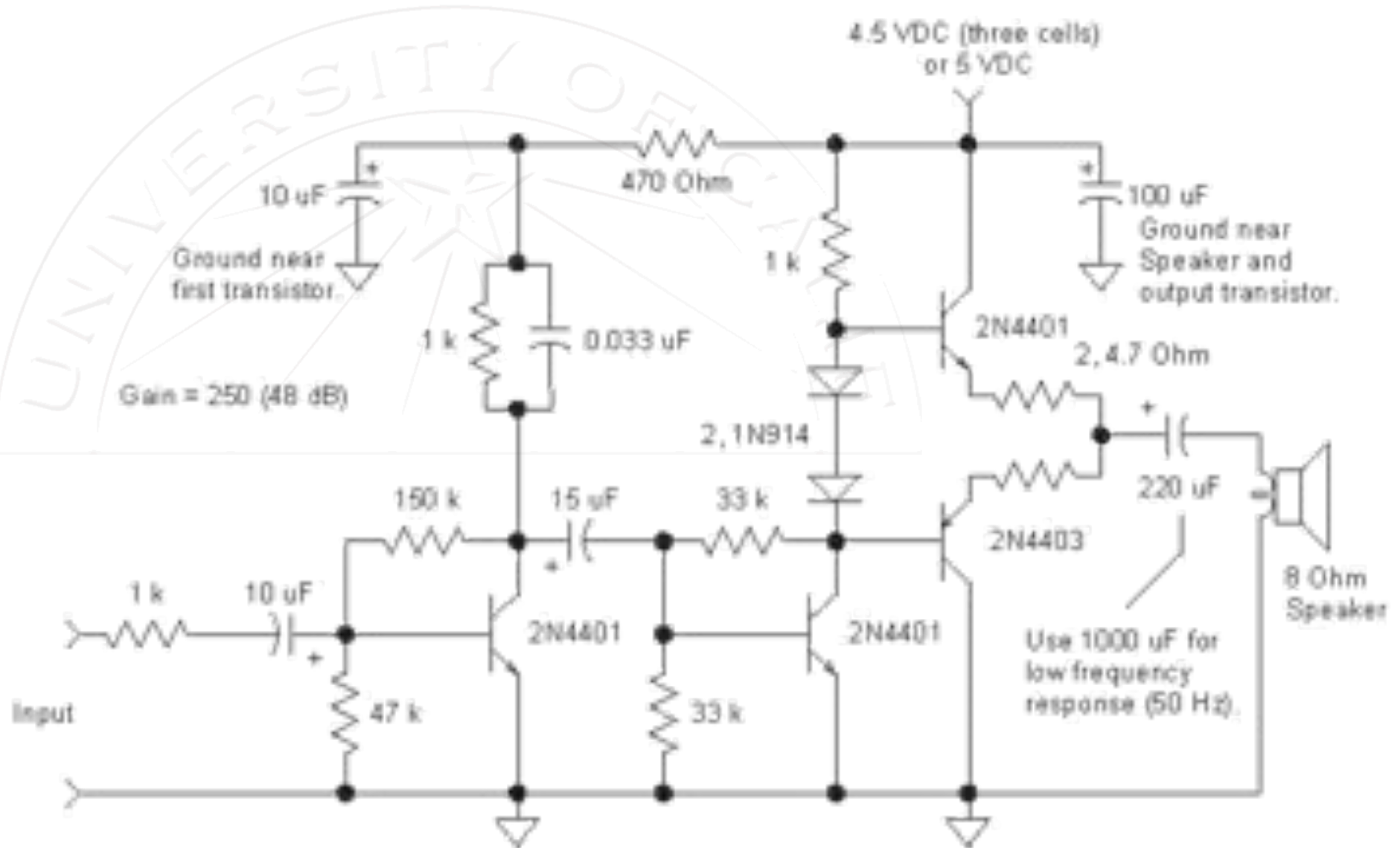
Circuits

- When devices are interconnected to perform some useful function, we say that thing is a circuit
- Examples:
 - A light bulb/switch, spark generator in internal combustion engine, a radio, a cell phone, a computer
- A typical “circuit” may contain millions of devices. How do we deal with this level of complexity?
 - Hierarchy: Divide and conquer
 - A large circuit is broken up into my sub-blocks
 - Sub-blocks are broken up into sub-blocks ...

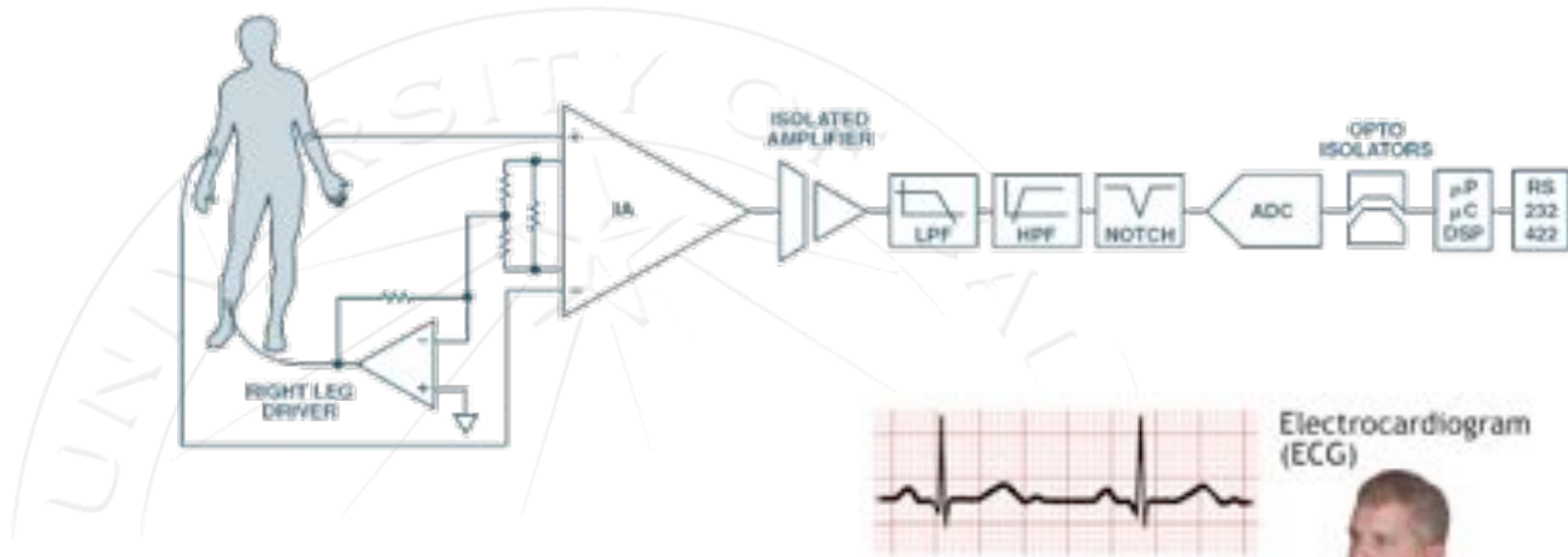
Analog Circuits

- Analog circuit represent the signal as an electrical current/voltage
- Typical analog circuits:
 - Amplify signals (weak signal picked up by microphone)
 - Filter signals (remove unwanted components, interference, noise)
 - Perform mathematical operations on waveform
 - Multiplication, differentiation, integration
- Circuits very susceptible to noise and distortion
- Analog circuits are “hand crafted” by analog “designers”
- Attempts to automate analog design (Computer Aided Design or CAD) have largely failed

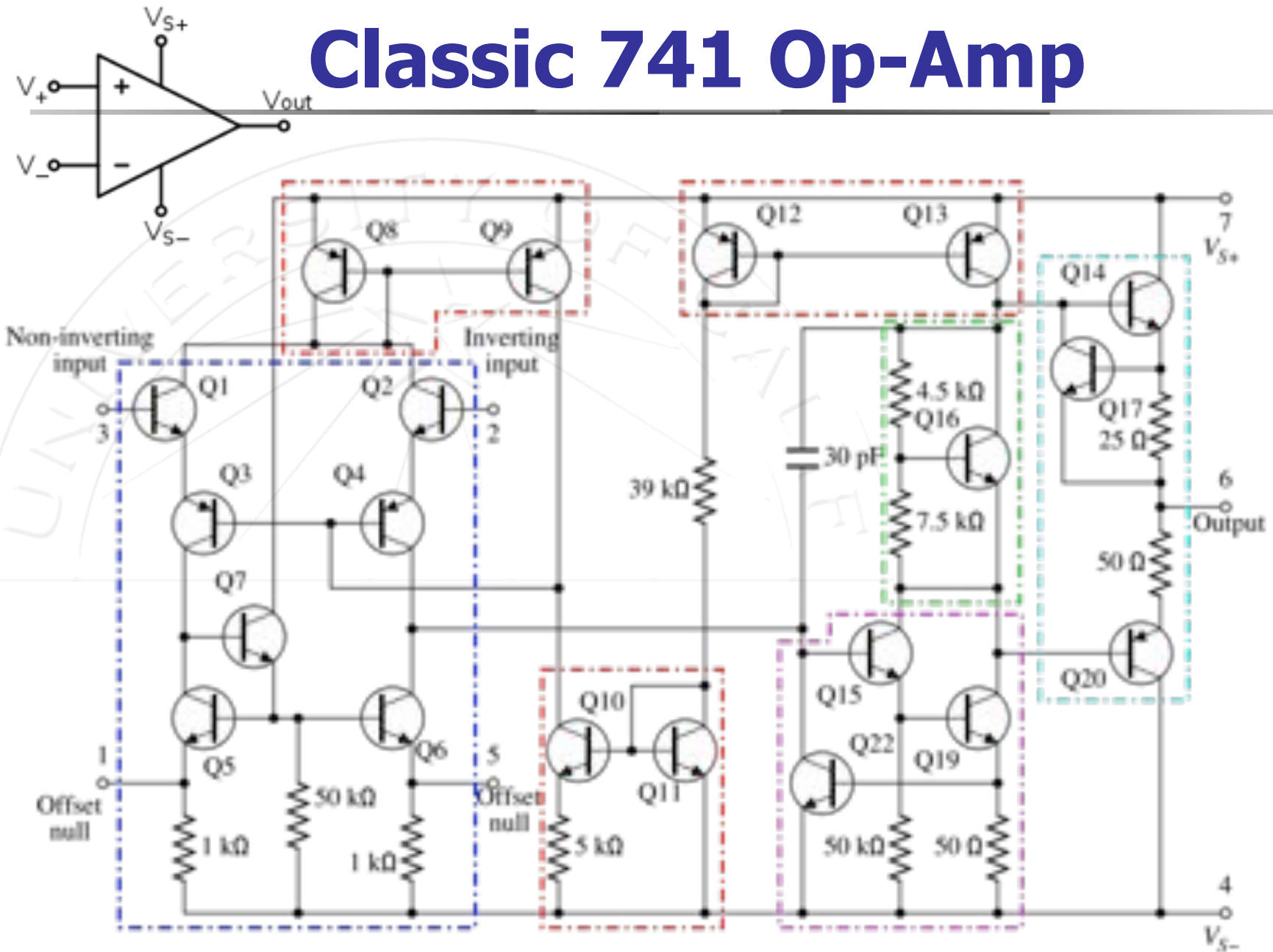
An Audio Amplifier



An ECG Front-End



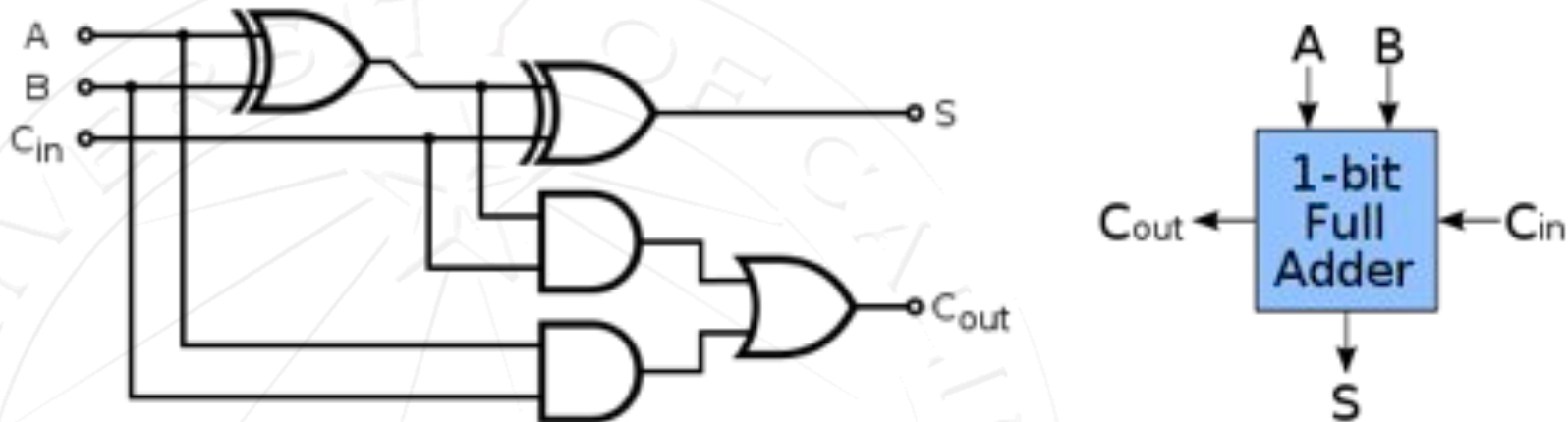
Classic 741 Op-Amp



Digital Circuits

- Represent quantities by discrete voltages, “1” and “0” (e.g. 1V and 0V) – “bits”
- Digital circuits perform “logic” operations on the signals (AND, OR, XOR) – “combinatorial logic”
- Mathematical operations can be performed using logic operations (XOR is a 1-bit adder)
- Digital memory created using capacitors (dynamic memory) or through latches/flip-flops (regenerative circuits)
- Digital circuits are robust against noise (signal levels are regenerated to “0” and “1” after digital functions)
- Digital circuits often “clocked” to simplify design

Ripple Carry Adder



- The above circuit is a full adder. The input bits are A, B, and C_{in} (carry in). The output is the sum S and C_{out} (carry out).
- By chaining together many of these elements, we can produce an adder of any desired precision.

Computers

- ENIAC was the first general purpose computer
- Used by Army to calculate artillery firing tables. Later used for calculations related to the hydrogen bomb.
- Early computers filled up entire rooms and were very unreliable.
- First “bug” was a moth causing a circuit fault.
- First programmer was Ada Lovelace (~ 1840!!!)

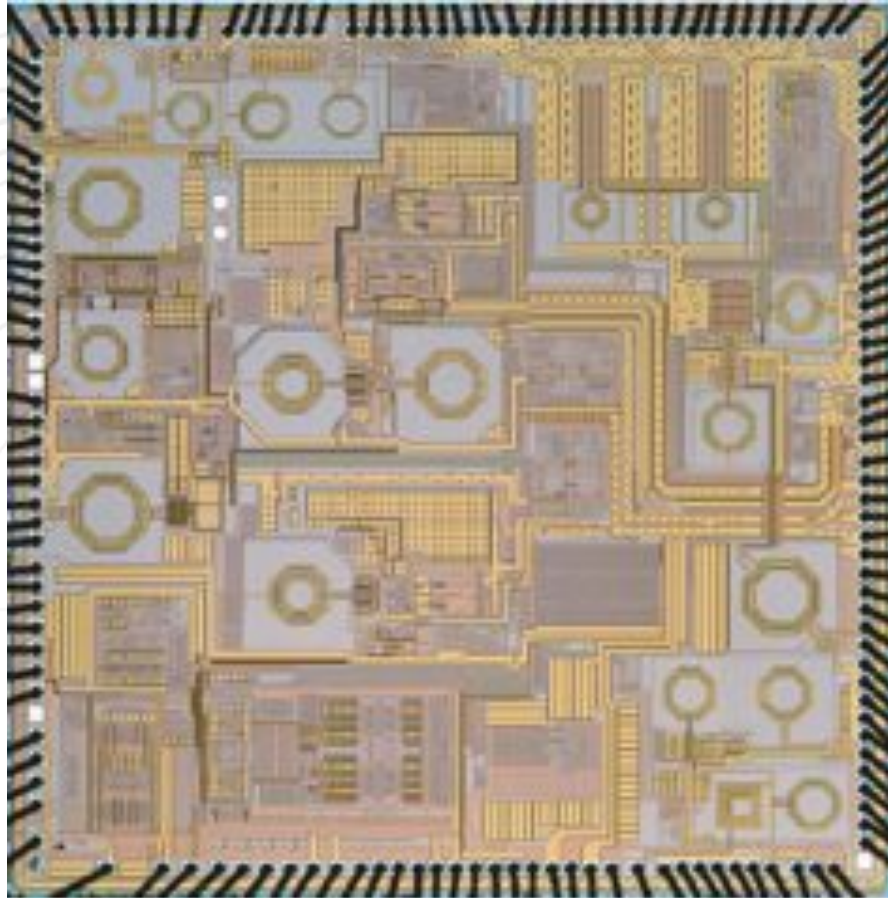


Programmers Betty Jean Jennings (left) and Fran Bilas (right) operate the ENIAC's main control panel at the Moore School of Electrical Engineering. (U.S. Army photo from the archives of the ARL Technical Library) [Wikipedia]

High Frequency Circuits

- A special class of analog circuits (and sometimes digital) operate at very high frequencies: $\sim 1 \text{ GHz} - 100 \text{ GHz}$
- These circuits are specially designed to send / receive signals outside of the IC
 - Wireless radio propagation, fiber optic drivers, line drivers
- Circuit theory has to be modified in order to correctly describe the behavior of these circuits
 - Often the circuit dimensions are comparable with the wavelength of the signals – distributed effects become important!
- Antennas, transmission lines, waveguides, directional couplers, power combiners ...

A Radio Front-End



- Includes a complete WLAN transceiver
 - Big circular (spiral) objects are inductors
 - Transistors too small to see

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Systems

Systems

- There is a strong theoretical foundation in EE that helps engineers understand and improve electronic systems
 - What is the correct stochastic representation of signals?
 - How fast do you need to sample a signal in order to preserve its content so you can process it digitally (Nyquist Sampling Theorem)?
 - How much information can be transmitted (without error) in a given bandwidth (say your telephone cables) when we assume the channel is corrupted by additive white Gaussian noise? → Shannon's Famous Capacity Theorem
 - Modems: 300-9600 baud, 28.8k, 56k
 - Today: 1-10 Mbps+
 - How do you design a wireless system to contend with multipath propagation? What are the performance limits?

Digital Signal Processing

- A continuous time band limited signal (audio, video, radio signal) can be sampled at a rate of twice the highest frequency of interest without any information loss.
- The discrete time representation of the signal can be quantized (information loss) and stored in a computer.
- These signals can be manipulated using very Digital Signal Processors (DSP) or custom IC's to perform complex mathematical operations.
- Examples include echo cancellation, channel equalization, compression, filtering.
- DSP allows extremely complex communication systems to be realized using low cost hardware.

Image Compression

- A digital image contains redundancy. Simple *lossless* compression schemes include run-length coding. More sophisticated compression schemes try to use only a few bits for signals that occur often and many bits for signals that occur rarely. This process is automatically done using Huffman coding.
- Lossy compression throws away information, but in a way so as to minimize the impact on the quality of the signal.
- Images contain a lot of high frequency spatial data that can be discarded (JPEG compression).



MP3 Audio Files

- MP3 files take advantage of the psychoacoustic properties of the human ear/mind to compress audio files by an order of magnitude (An entire uncompressed CD contains 700MB of data, or about 80 minutes of music. You can get about 800 minutes after compression).
- The signal is chopped up in the frequency domain into bins. Each bin is coded with the number of bits commensurate with the required resolution based on our hearing ability.
- Examples: A strong tone can “jam” nearby tones. You can’t hear a weak tone next to a strong tone.
- Early computers could not decompress MP3 in real time!

MPEG Movies

- Video has a lot of bandwidth: $1024 \times 1024 \times 32 \times 60 \sim 2 \text{ Gb/s}$
- MPEG is a video compression algorithm that not only compresses each still frame of video (spatial), but also uses information from previous frames to reduce the information coded in a new frame (temporal).
- From frame to frame, very little changes (imagine a scene showing two people talking). If we divide up the screen into blocks and examine how each block changes, then we can see maybe in the sky a bird flying but nothing else changes.
- Motion estimation (“motion vectors”) is used to predict how blocks of images move around the screen, to further reduce the information content.
- Digital video broadcasting needs video compression.

Medical Imaging

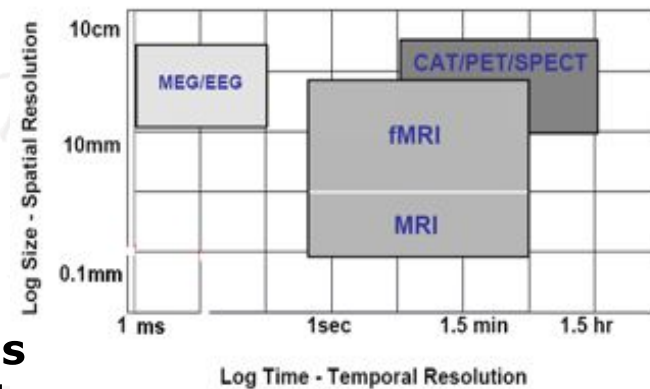
- Create images of organs for clinical and scientific purposes
- Data of human anatomy or physiology
- Often solving an inverse problem to find the properties of tissue inferred from observed signals
- Steady 10% of hospital costs



Imaging Modalities

- **X-Ray** **Attenuation based on tissue density and form, “sees” dense structures**
- **Ultrasound** **Acoustic Impedance measurement, motion sensing from Doppler**
- **PET** **Distribution of particle emitting radioactive drugs or tracers, maps metabolism**
- **MRI/fMRI** **Maps hydrogen containing structures, water content measurements**
- **Electro-Magnetic Tomography** **Multi-channel recorder reads EEG/MEG signals, inverse EM problem to find current density distribution**
- **Optical Imaging** **Measures optical properties, enables spectroscopy**

Imaging Method Comparisons
Darker color - more invasive



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