E40M

MOS Transistors, CMOS Logic Circuits, and Cheap, Powerful Computers

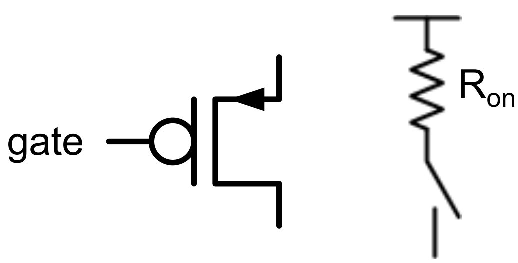
Reading

- Chapter 4 in the reader
- For more details look at
  - A&L 5.1 Digital Signals
    (goes in much more detail than we need)
  - A&L 6-6.3 MOS Devices

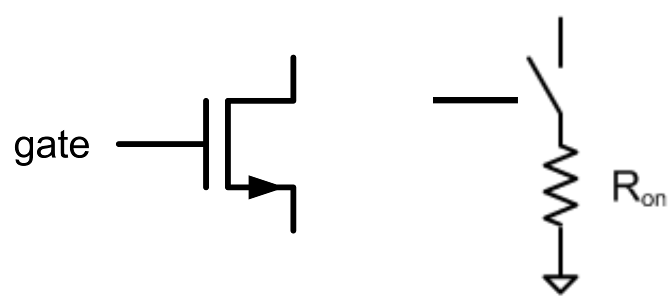
MOSFET a.k.a. MOS Transistor

- Are very interesting devices
  - Come in two “flavors” – pMOS and nMOS
  - Symbols and equivalent circuits shown below

- Gate terminal takes no current (at least no DC current)
  - The gate voltage* controls whether the “switch” is ON or OFF



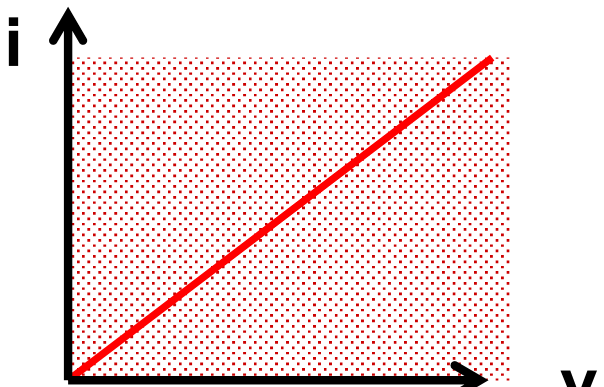
pMOS



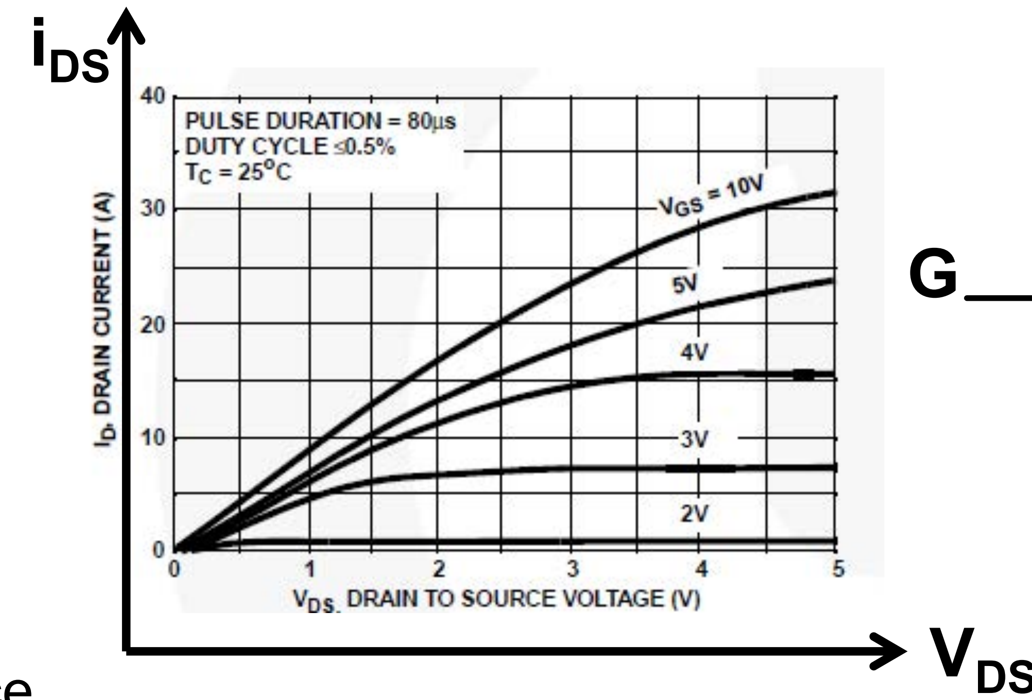
nMOS

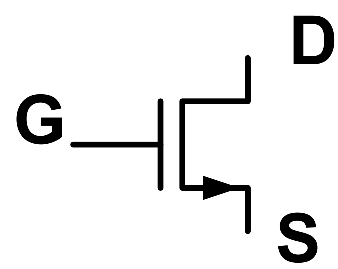
* actually, the gate – to – source voltage, V_{GS}

nMOS i-V Characteristics



Remember the resistor?





- nMOS is still a device
  - Defined by its relationship between current and voltage
  - But it has 3 terminals!
    - Current only flows between the source and drain
    - No current flows into the gate terminal!

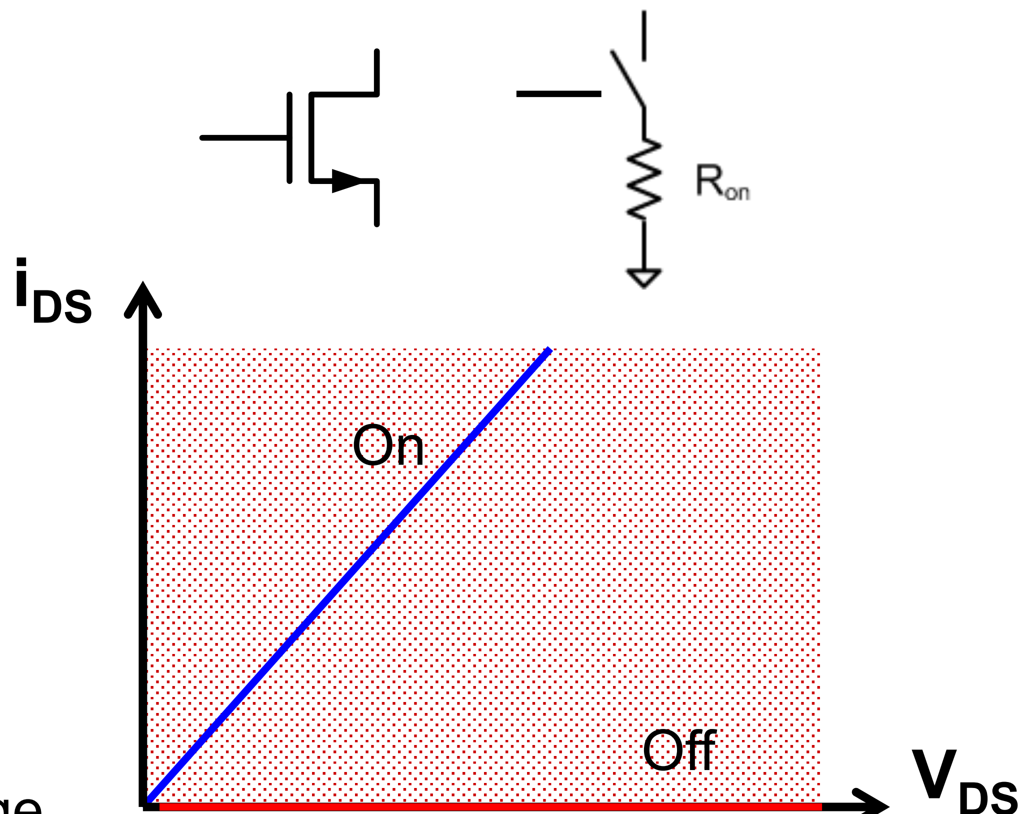
Simple Model of an nMOS Device

- We will model an nMOS device by components we know
  - Resistor
  - Switch
- NMOS

  Source = Gnd

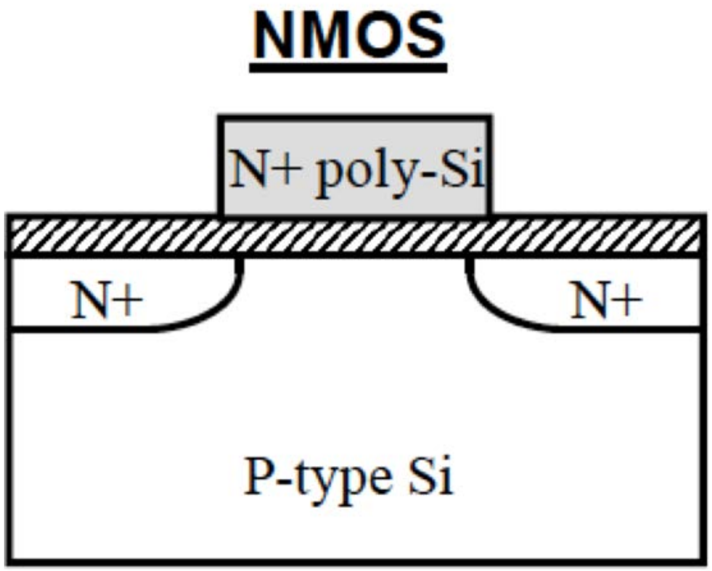
  Gate = Gnd => Off

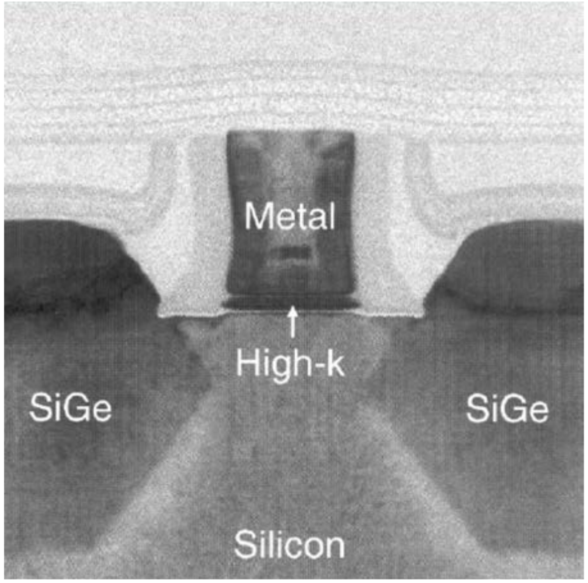
  Gate = Vdd => On

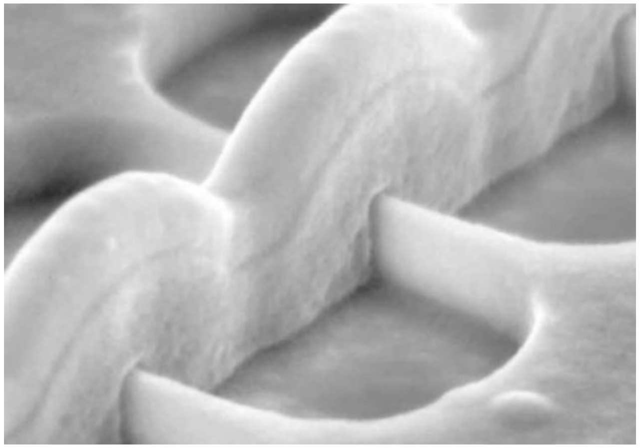


- This really simple model is suitable for applications where there's one value of "On" voltage.

How Does an nMOS Transistor Actually Work?
(FYI – not essential for this course)



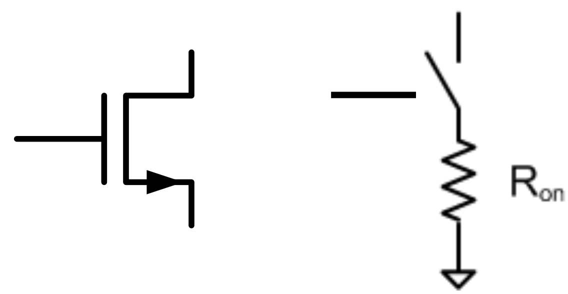




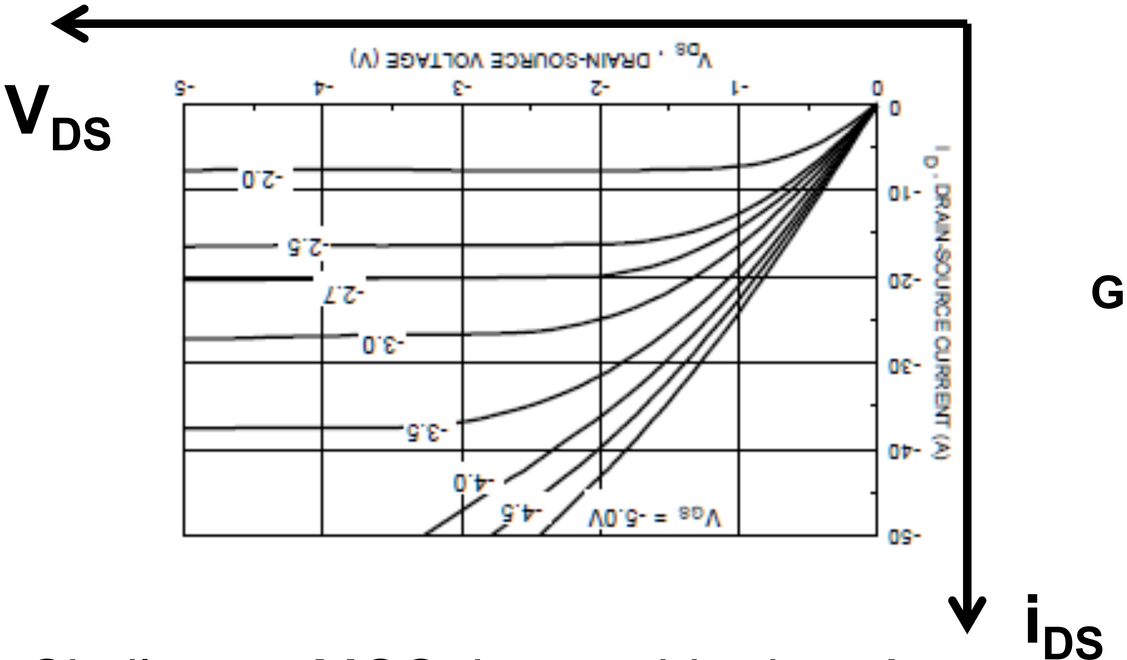
http://www.extremetech.com/wp-content/uploads/2014/09/close+finfet.jpg

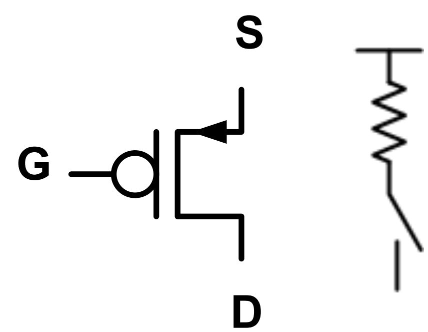
Problem With nMOS Device

- While an nMOS device makes a great switch to Gnd
- It doesn't work that well if we want to connect to Vdd
  - To turn transistor on
    - Gate needs to be higher than source
  - But we want the source to be at Vdd
    - Oops …



pMOS i_{DS} vs. V_{DS} Characteristics

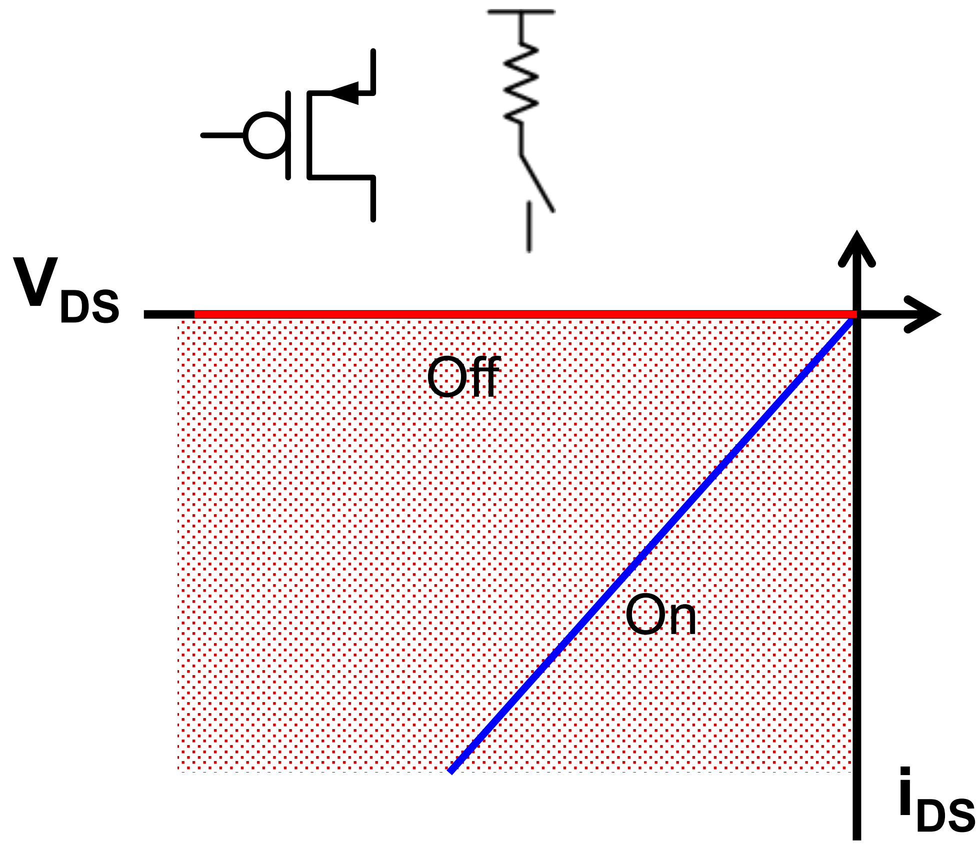




- Similar to nMOS, but upside down!
  - Turns on when the gate-to-source voltage is < -1 V
  - And the drain-to-source voltage should be negative
    - Source should be the terminal with the higher voltage!

Simple Model of a pMOS Device

- We will model an pMOS device by components we know
  - Resistor
  - Switch



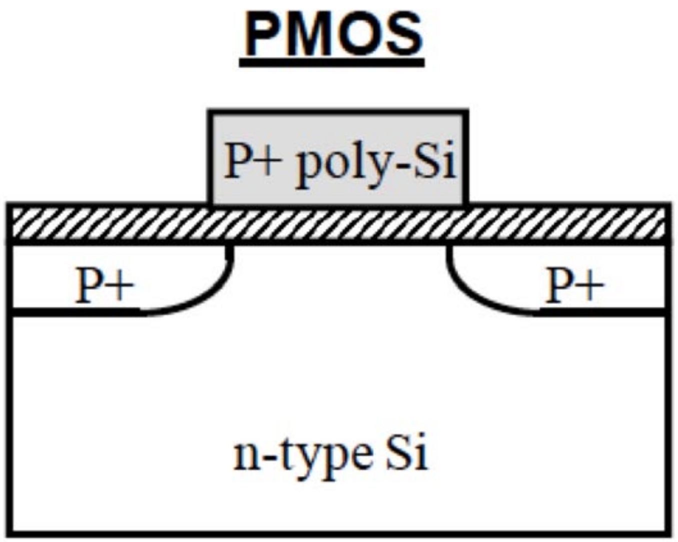
- NMOS

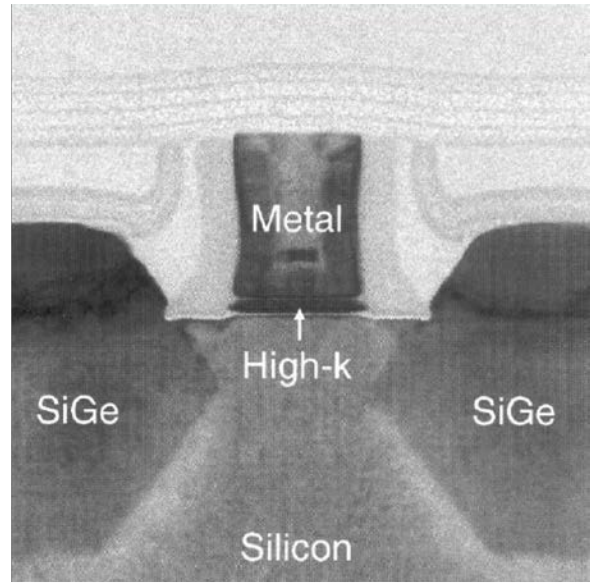
  Source = Vdd

  Gate = Gnd => On

  Gate = Vdd => Off

How Does a pMOS Transistor Actually Work?
(FYI – not part of this course)





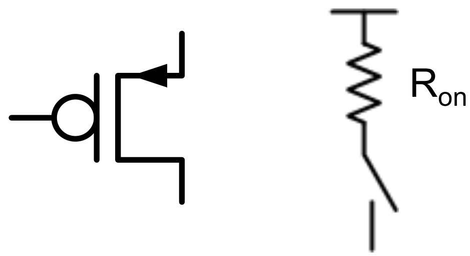
nMOS and pMOS Devices “Complement” Each Other – Complementary MOS or CMOS

- PMOS

  Source = Vdd (+ supply)

  Gate = Gnd => On

  Gate = Vdd => Off

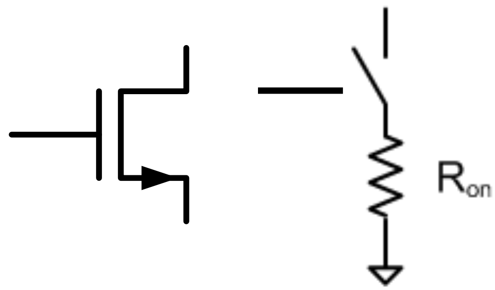


- NMOS

  Source = Gnd

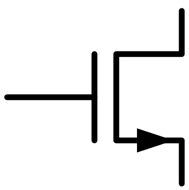
  Gate = Gnd => Off

  Gate = Vdd => On

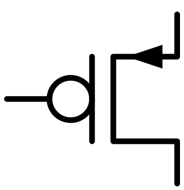


MOS Transistor Summary

- MOS transistors are *extremely* useful devices
  - Almost all of your electronics uses them on the inside
  - Including your phone, laptop, WiFi and Bluetooth, and your Arduino
- Come in two "flavors"
  - nMOS



    - It is a switch which connects source to drain
    - If the gate-to-source voltage is greater than V_{th} (around 1 V)
      - Positive gate-to-source voltages turn the device on.
  - pMOS



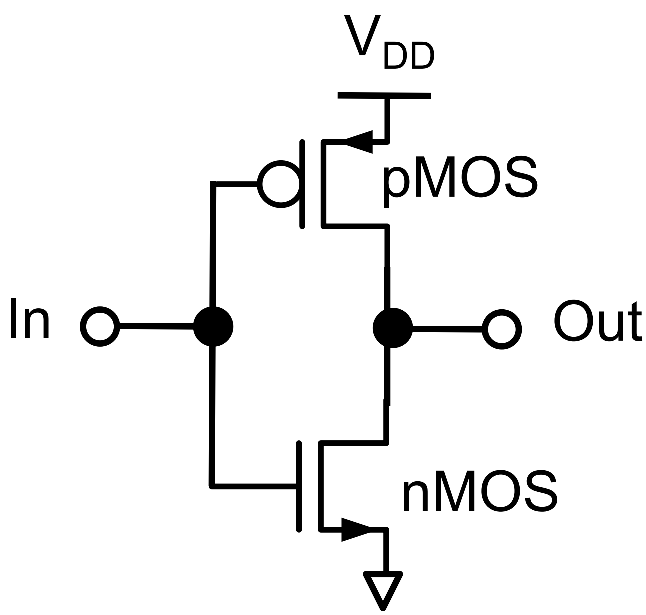
    - It is a switch which connects source to drain
    - If the gate-to-source voltage is less than V_{th} (around -1 V)
      - Negative gate-to-source voltages turn the device on

… and there's zero current into the gate!

MOS Logic Gates

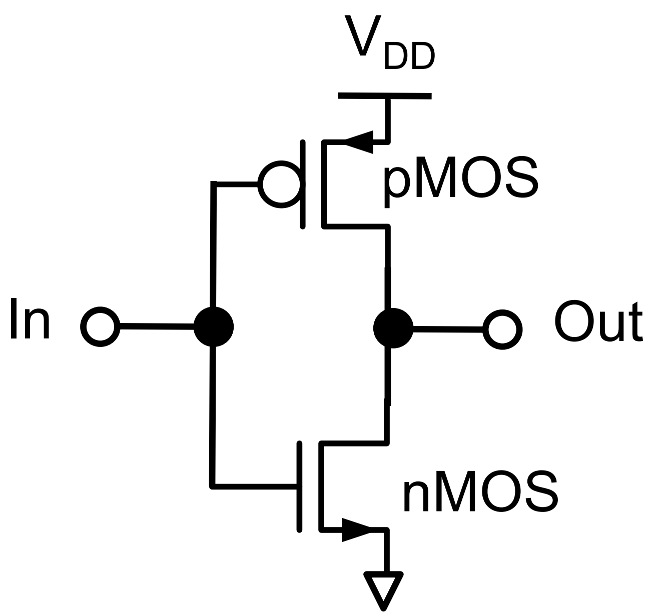
What Does This Circuit Do?

- Is the output a logic function of the input? Consider V_{in} = GND



What Does This Circuit Do?

- Now consider $V_{in} = V_{DD}$



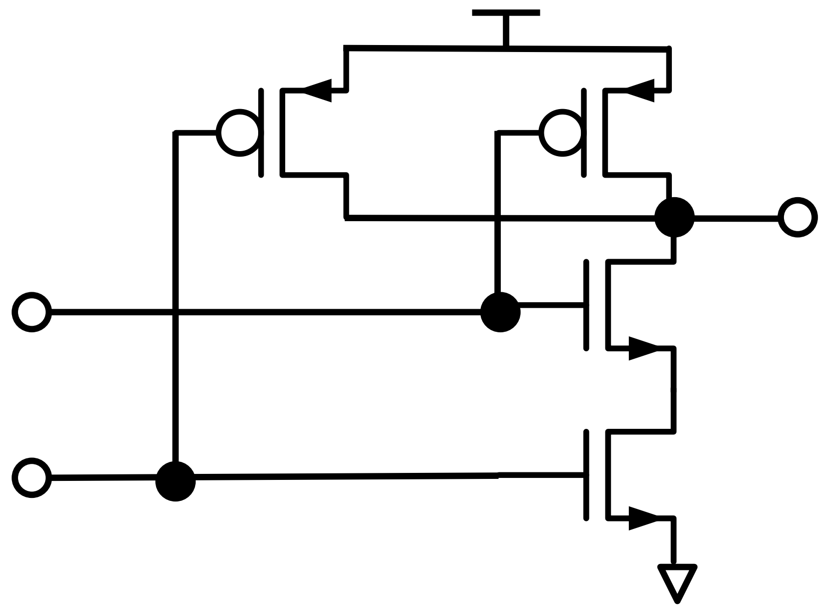
Building Logic Gates from MOS Transistors

- Remember Boolean Logic?
  - AND, OR
  - NAND = Not-AND = AND followed by Inverter
    - Output is only low when A and B are true (high)
  - NOR = Not-OR = OR followed by Inverter
    - Output is low when either A or B is true (high)

- You can make them from MOS devices
  - But only the inverting gates (NOR and NAND)

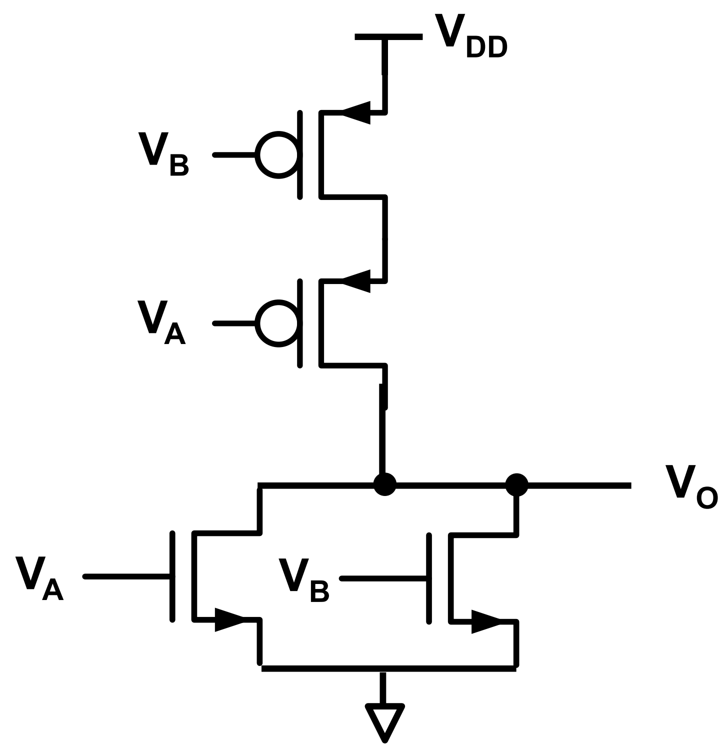
Building a CMOS NAND Gate

- Output should be low if both input are high (true)
- Output should be high if either input is low (false)

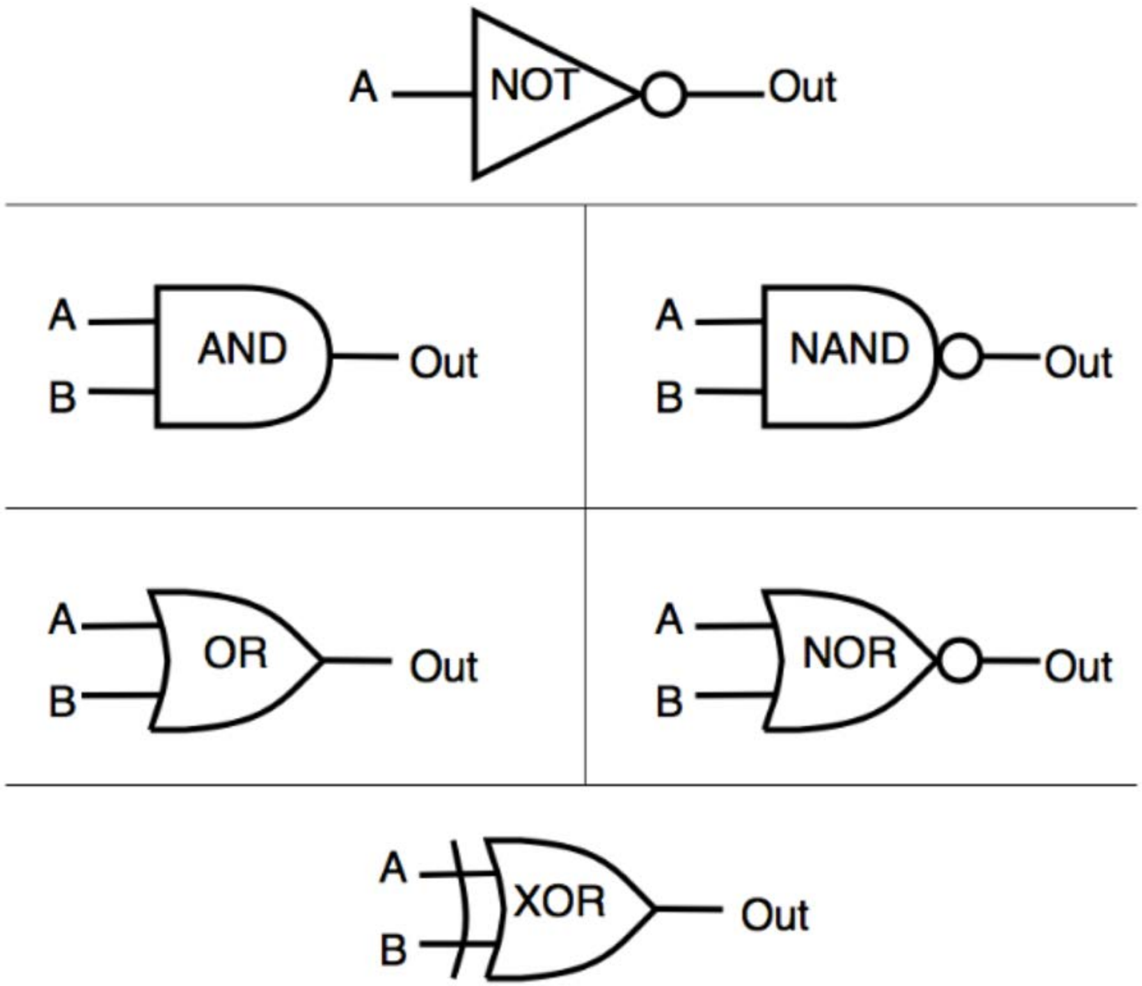


Building a CMOS NOR Gate

- Output should be low if either input is high (true)
- Output should be high if both inputs are low (false)

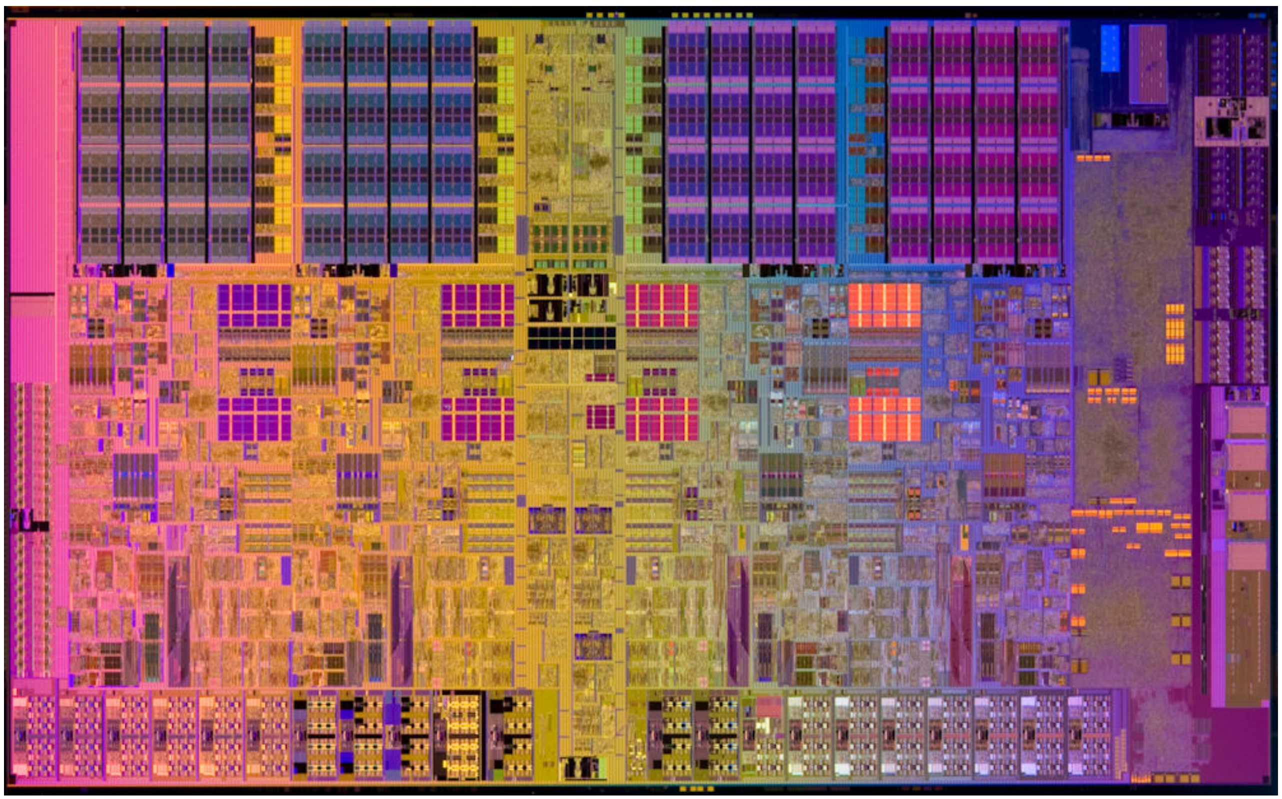


Logic Symbols



If You Look At Your Computer Chip

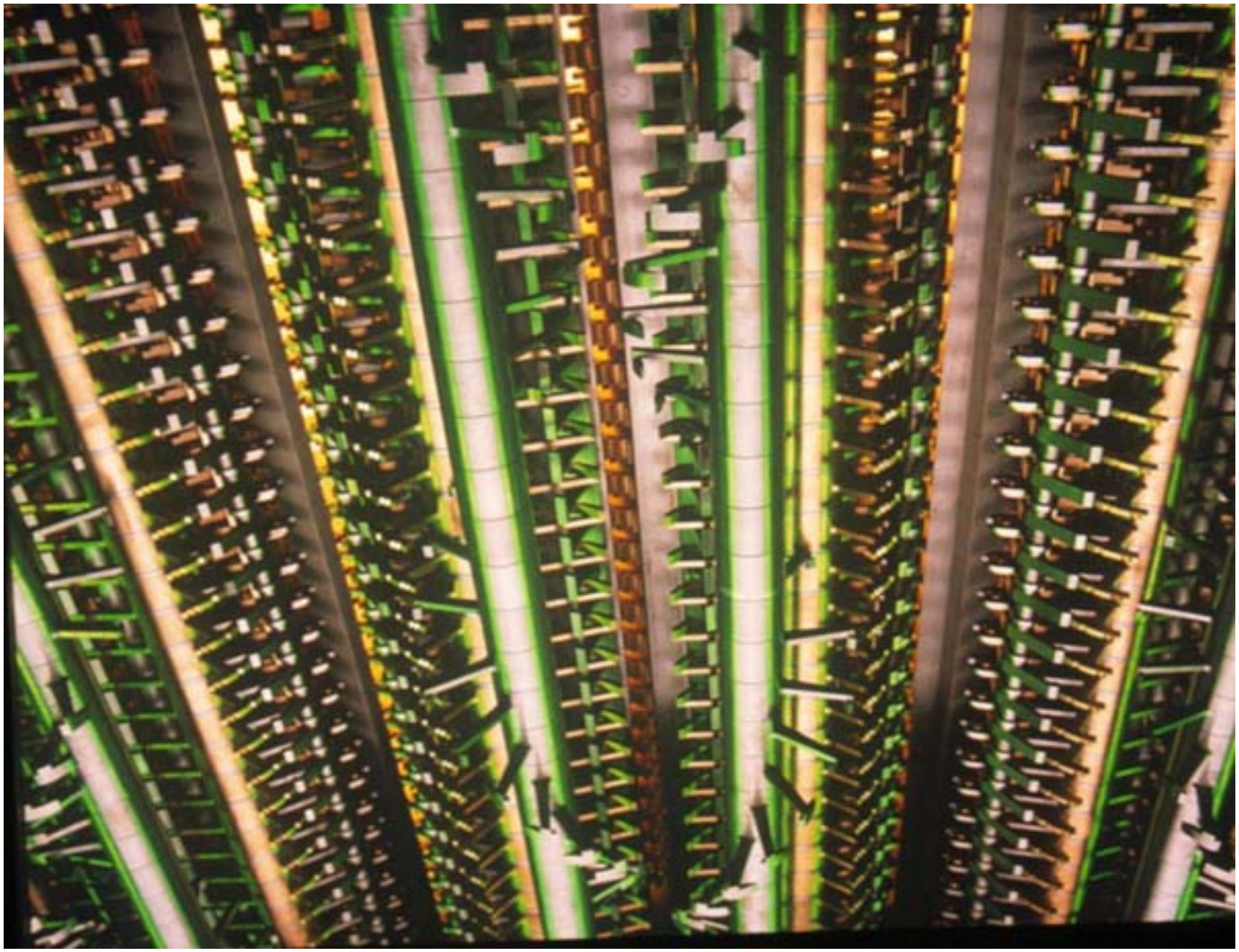
- It is just billions of transistors
  - Creating many logic gates, and memory



- Take EE108A if you want know how we do that …

HOW THE MOS TRANSISTOR CHANGED THE WORLD …

First Computing Machines Were Mechanical



Picture of a version of the Babbage difference engine built by the Museum of Science, UK

"The calculating section of Difference Engine No. 2, has 4,000 moving parts (excluding the printing mechanism) and weighs 2.6 tons. It is seven feet high, eleven feet long and eighteen inches in depth"

Moving Electrons is Easier than Moving Metal

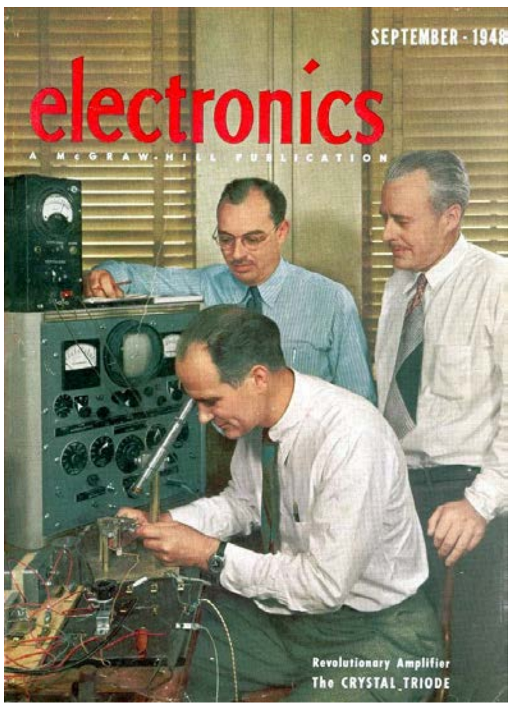
- Building electronics:
  - Started with tubes, then miniature tubes
  - Transistors, then miniature transistors
  - Components were getting cheaper, more reliable but:
    - There is a minimum cost of a component (storage, handling …)
    - Total system cost was proportional to complexity

- Integrated circuits changed that
  - Printed a circuit, like you print a picture,
    - Create components in parallel
    - Cost no longer depended on # of devices

A Little History

1st (Bipolar Junction) Transistor
Christmas Eve 1947

By Bardeen, Brattain, and Shockley,
Nobel Laureates in Physics 1956



(http://www.bellsystemmemorial.com/belllabs_transistor.html)

1st Integrated Circuit

Jack Kilby, Nobel Laureate in Physics 2000
Bob Noyce

(Courtesy of TI and Huff, SEMATECH)

What is an Integrated Circuit?

- A device having multiple electrical components and their interconnects manufactured on a single substrate.

- First IC 1958
  - Jack Kilby at TI
  - Germanium
  - A hack
    - Wax support
  - Made history
- Planar Process 1961
  - Bob Noyce at Fairchild
  - Silicon

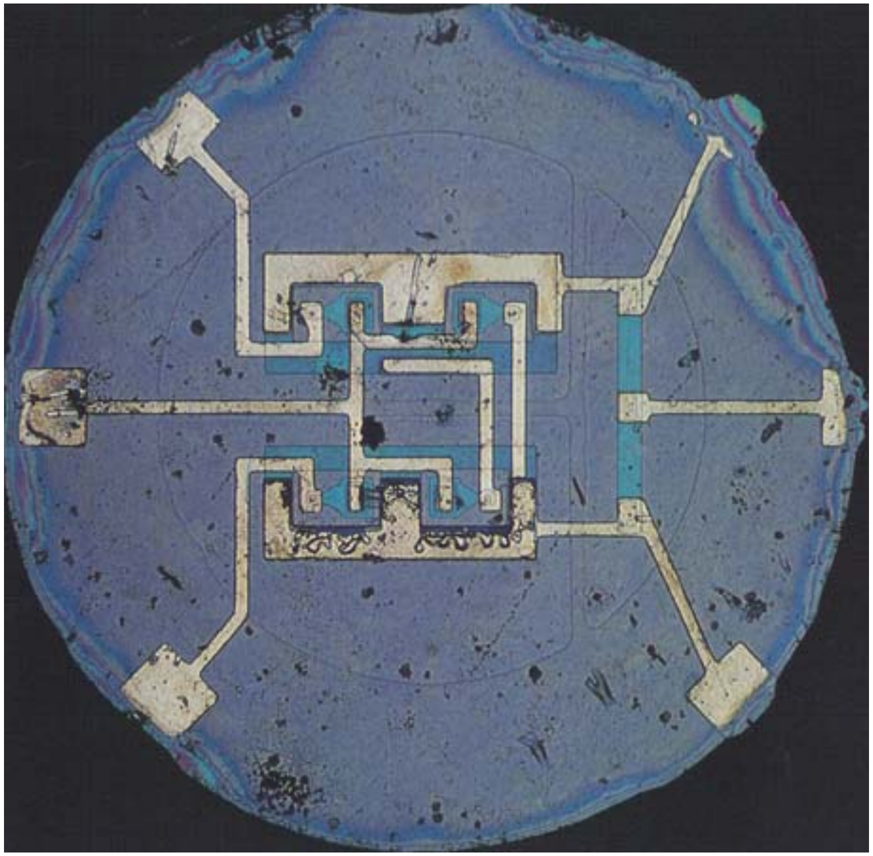
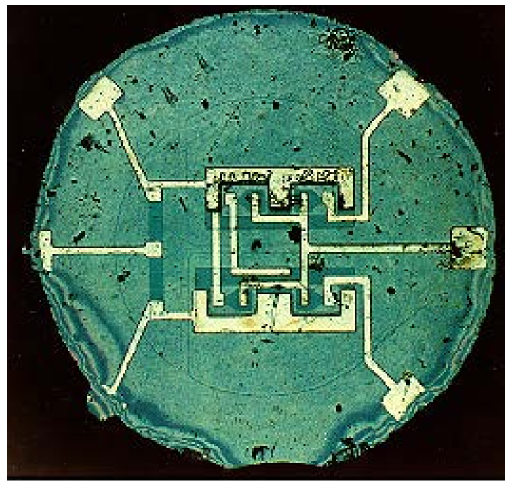
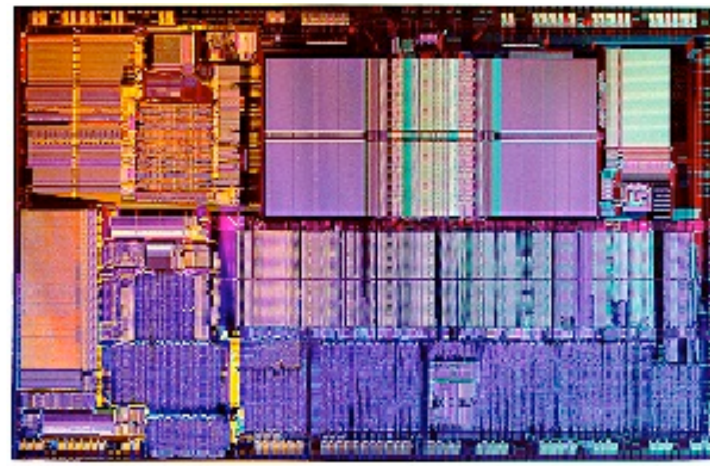


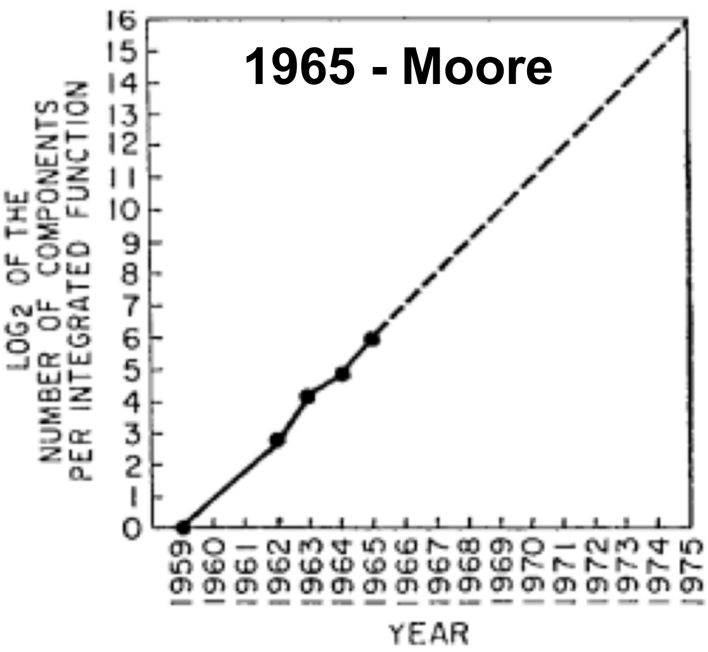
Image from State of the Art © Stan Augarten

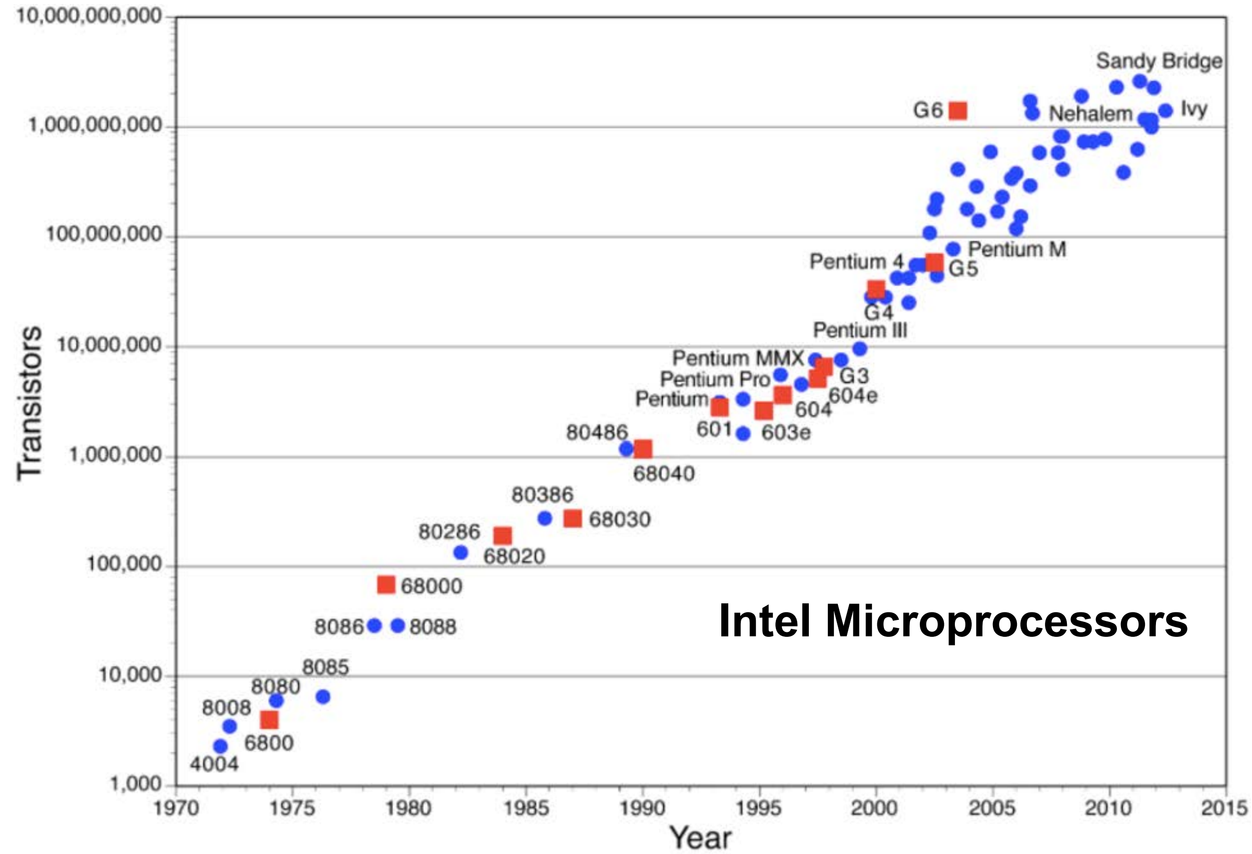
Miniaturization Progress Over 50 Years

From This	To This	To This
		
Point Contact Transistor	First Integrated Circuit	Modern Microprocessor

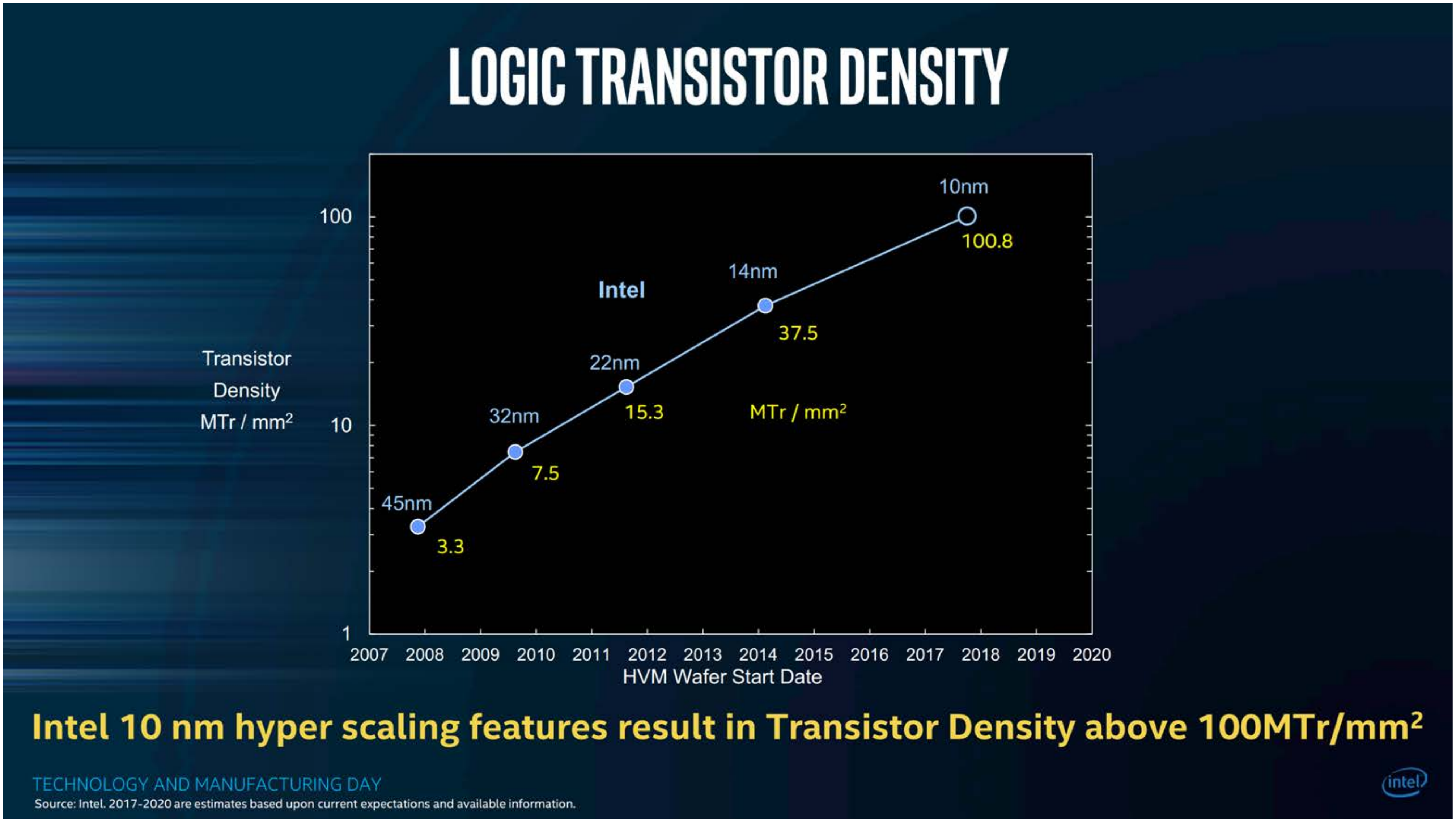
- Modern silicon chips have > 10^9 components in 1 cm^2 area.

Moore's "Law"



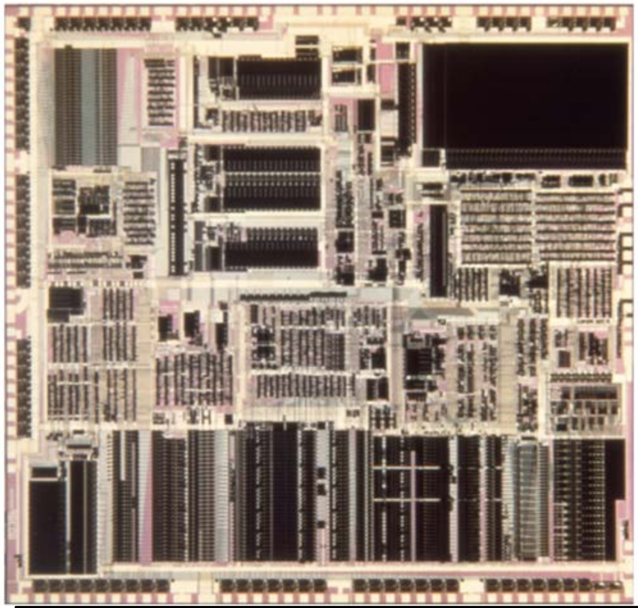


- "The complexity for minimum component costs has increased at a rate of roughly a factor of 2 per year." Gordon Moore, 1965

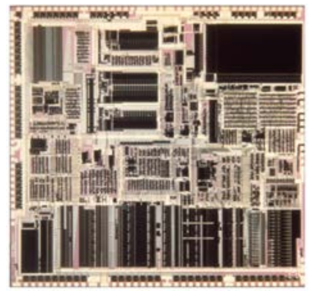


Kaizad Mistry, Intel Technology and Manufacturing Day, March 28, 2017

What This Means



80386 chip area
shrinks to 17 mm^2



80386 die size
shrinks to 0.05 mm^2

Chip edge is only twice the
diameter of a human hair!

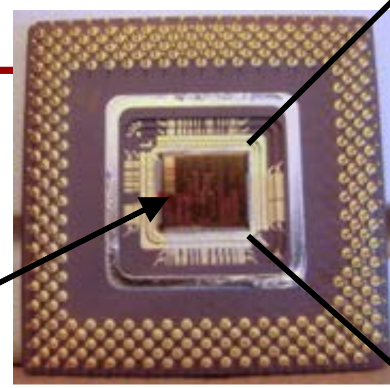
1985 (Intel 80386)	**1989** (Intel 80486)	Intel 10 nm CMOS* circa 2019
275,000 transistors	1,180,235 transistors	
104 mm^2; 2640 Tr/mm^2	16,170 Tr/mm^2	100,000,000 Tr/mm^2

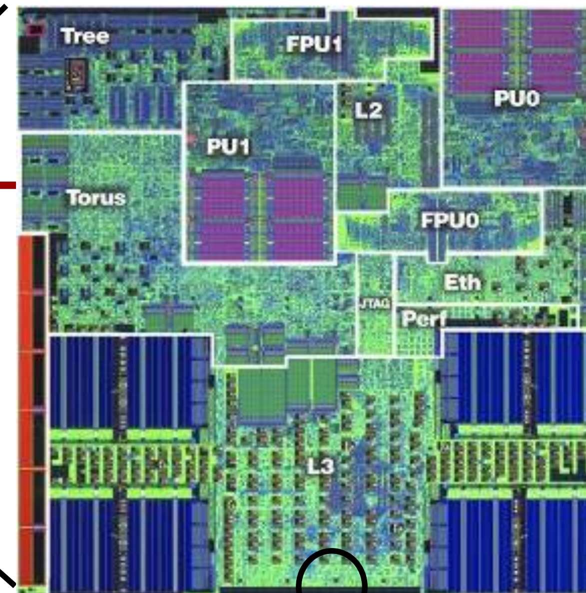
… or the original chip area could contain > 10 billion transistors!

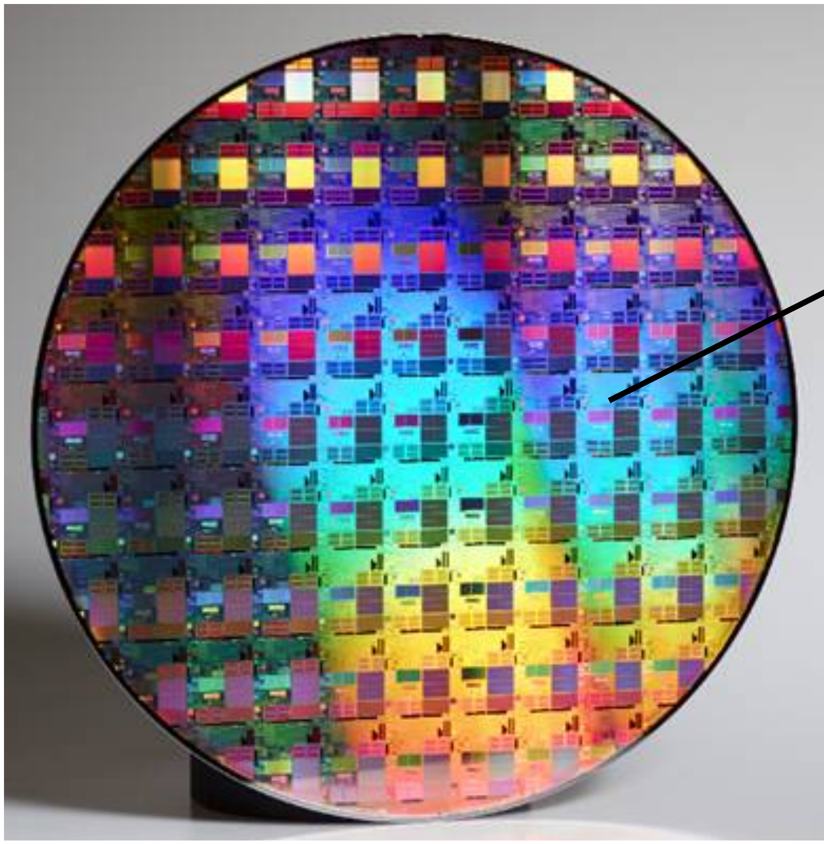
*Kaizad Mistry, Intel Technology and Manufacturing Day, March 28, 2017

Take The Cover Off A Microprocessor

Packaged die



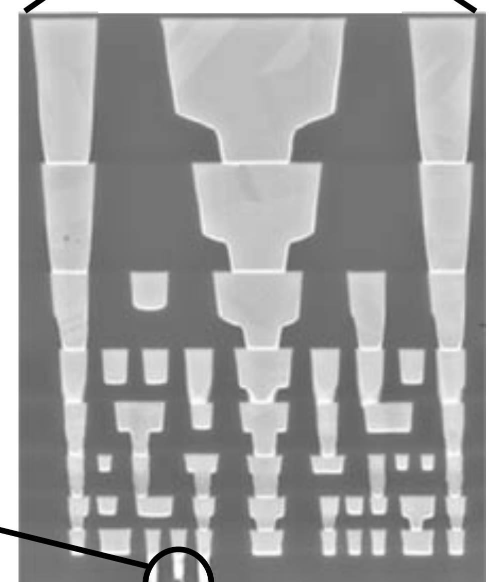




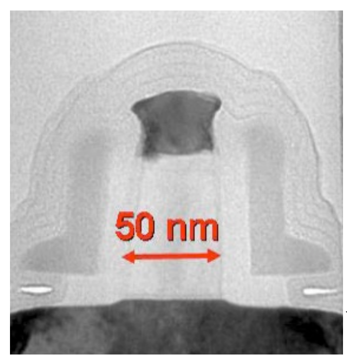
Full wafer (100s of dies)

modern wafers: 200-300 mm diameter (8-12 inches)

Cross-section



Single transistor



Learning Objectives

- Understand how nMOS and pMOS transistor work
  - Voltage controlled switch, the gate voltage controls whether the switch is ON of OFF
  - nMOS devices connect output to Gnd
  - pMOS devices connect the output to Vdd

- Be able to create MOS NAND, NOR and Inverter circuits
  - Using pMOS and nMOS devices