# EE3: Introduction to Electrical Engineering

# Lecture 6: Devices to Embedded Systems

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# Outline

- p-n junctions
- Diodes
- Transistors
- Op amp construction
- Logic gates
- Embedded systems architecture

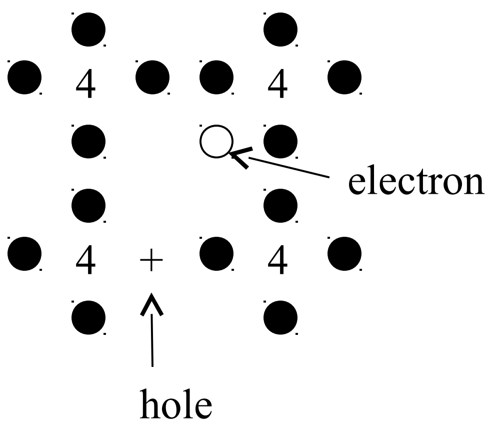
# Conduction in Solids

Thermal energy results in some electrons being displaced from bonds in the lattice comprising the solid. In conductors, there are many free electrons, in semiconductors few, and in insulators, almost none.

With an electric field, the motion of these electrons is still random, but has a drift with average velocity that depends on the strength of the field and a mobility constant

In conductors, the current is due to free electrons only; in semiconductors it is due to both electrons and “holes” in the covalent bonds, which move in opposite directions. The holes are like positive charge, and so both contribute to the current.

# Holes and Doping



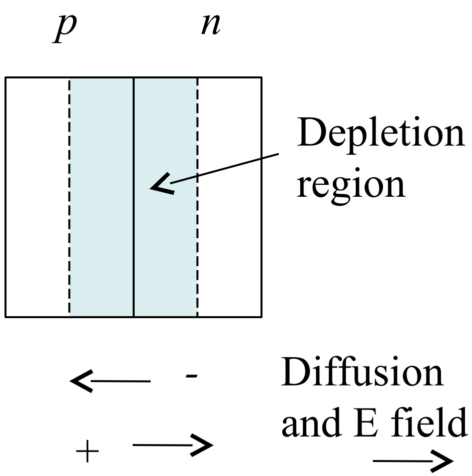

In a pure semiconductor such as silicon, the number of holes $p$ and electrons $n$ balance, and are equal to the intrinsic concentration $n_i$.

Doped semiconductors include small concentrations of other elements that disrupt the lattice.

In a $p$-doped semiconductor, there are many unfilled bonds so that $p>n$, but $pn=n_i^2$

In a $n$-doped semiconductor, there are many free electrons so that $n>p$, but $pn=n_i^2$

# $p$-$n$ Junctions




With two materials, joined together, majority carriers will diffuse across the boundary and recombine, creating a "depletion" region of fewer carriers

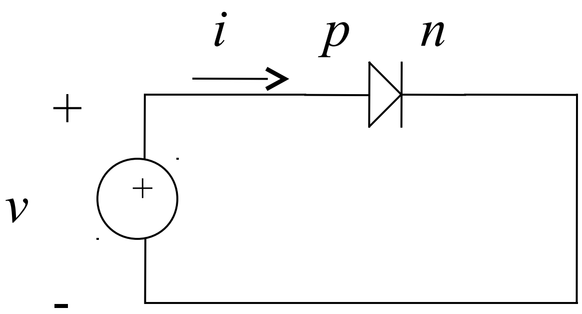
When an electric field is applied, it can either reinforce or counteract this diffusion current.

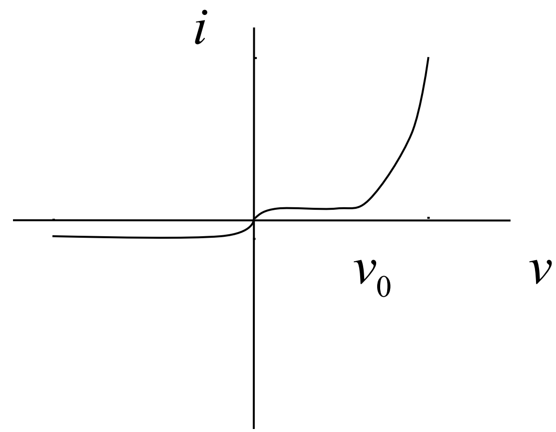
At the point the two effects balance, $v_0$, usually a few tenths of a volt, it is as if there is an open circuit.

Below $v_0$, little current flows. Above it, there is very little resistance, and high currents can flow.

# Diodes

A single p-n junction can be used to make a diode

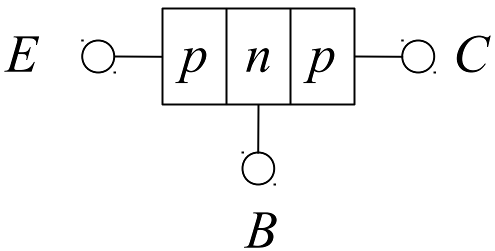


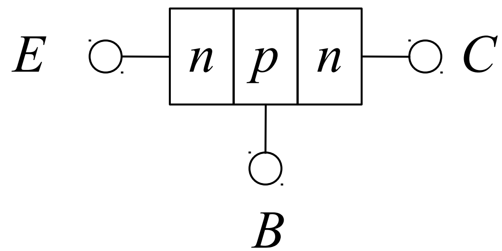



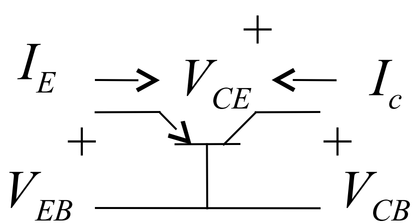

This is often approximated as being zero current below the cutoff voltage and an open circuit above; for large signals, we further approximate the cutoff voltage as zero.

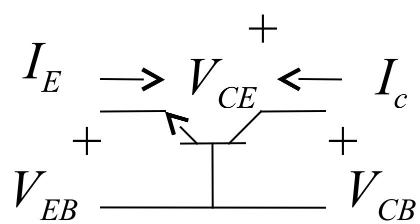
# Bipolar Junction Transistor

Although MOSFETs (used in CMOS) are far more common, BJT’s are easier to explain. Two possible structures are:



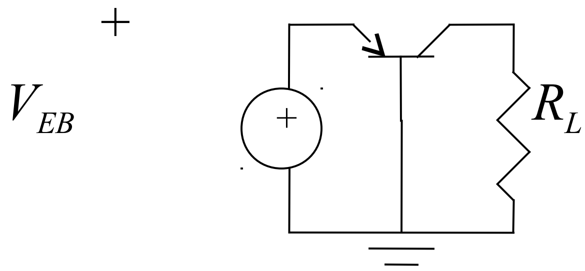



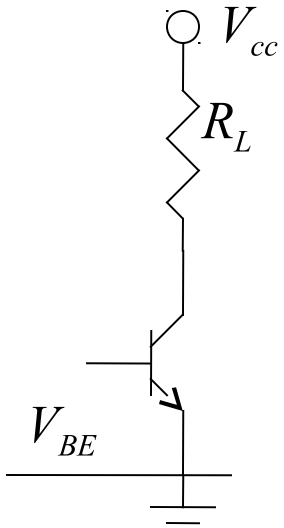

With no external bias currents, no current flows.

# *pnp* BJT



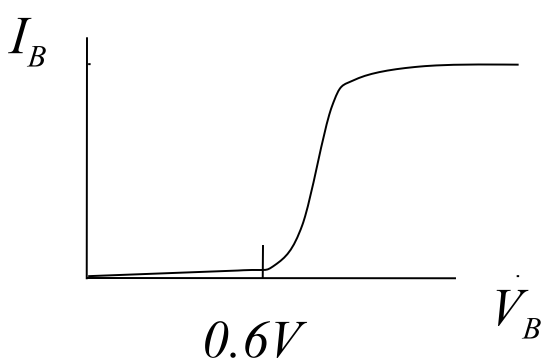

The bias in the emitter-base junction causes holes to flow into the base; thus electrons flow into the emitter. The holes diffuse across the *n*—type base where *E*=0. At the collector junction, the field is positive and large, and so they are accelerated across the junction.

# Common Emitter Configuration



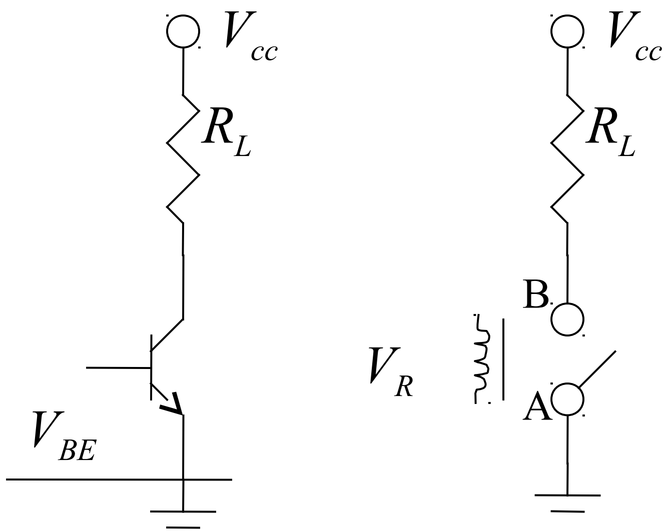

This is a more typical way to bias an npn transistor. When $V_{BE}>V_0$, the cutoff voltage, electrons nearly freely flow from emitter to collector. Below this, there is negligible current.

When on, $I_C>>I_B$, and so the transistor acts as an amplifier.




Relatively small additional voltage causes saturation, and so the transistor can also be used as a switch, with the voltage depending on the supply and load resistor.

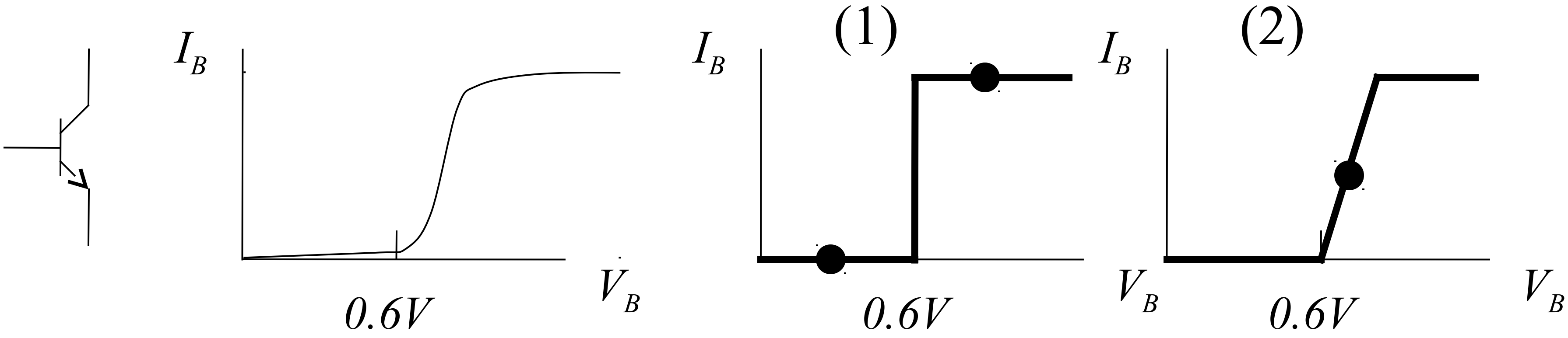
# EFTS




How are transistors and relays similar and different in their functionality?

Solution: Both transistors and relays transition from zero current to a short circuit based on a control voltage. They differ in how they must be biased for this control voltage to open and close the switch, and because the transistor can also be biased to be an amplifier. The transistor has higher parasitic resistance as well, but can flip states far faster.

# Approximate Models



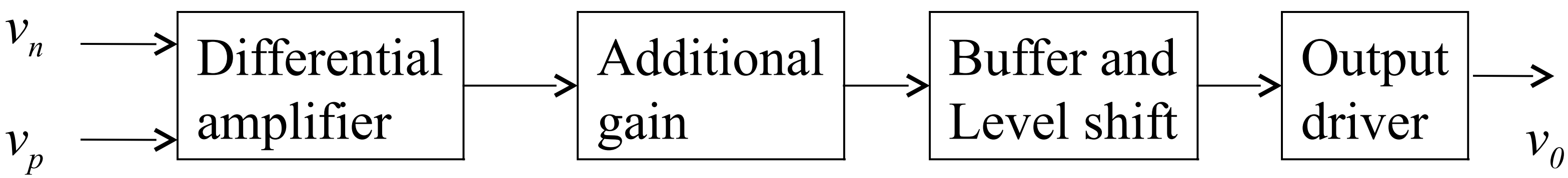

Depending upon how the transistor is to be used, various piece-wise linear approximations are employed for analysis

(1) In this approximation, once $V_B > V_0$ the C-E path strongly conducts with a voltage drop of $V_0$; otherwise it is essentially off. This is used for digital logic applications, among others.

(2) In the small signal approximation, at the indicated bias point the transistor can act as an amplifier, with the amplification depending on supply voltages and resistances.

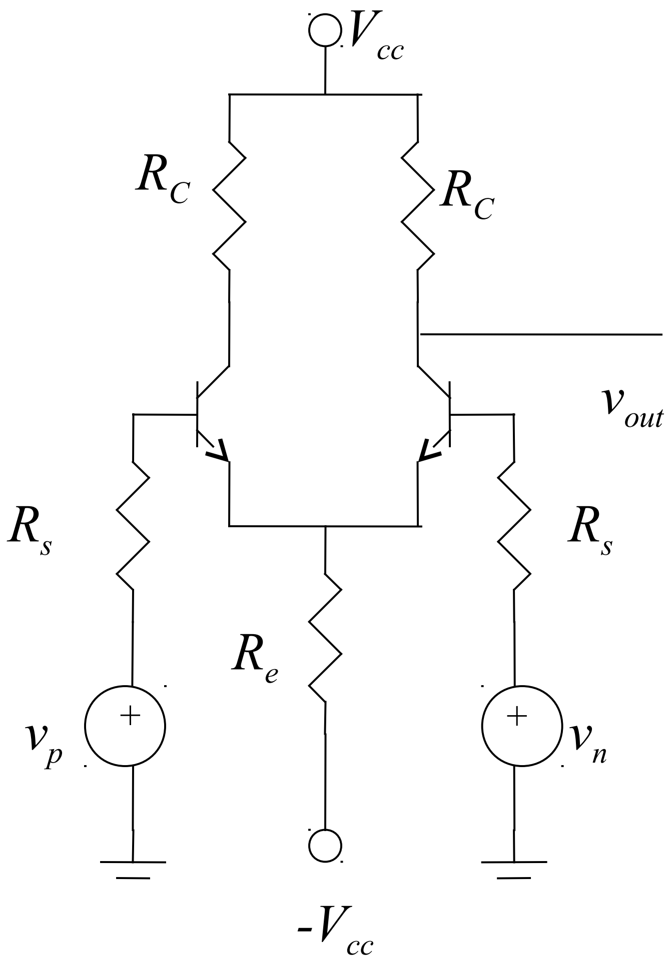
# Application: Op Amp Construction

An op amp includes multiple transistors in the following blocks

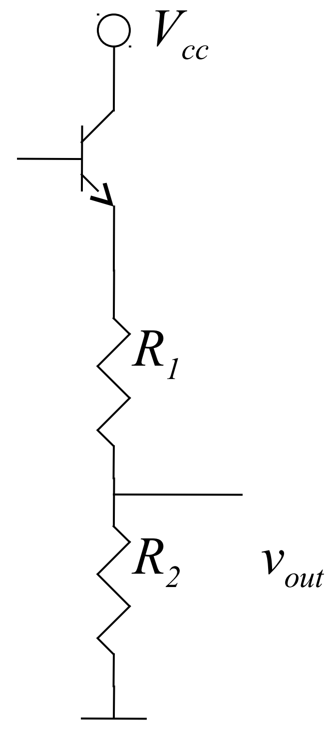



These stages collectively provide the high input resistance, large amplification, and low output resistance

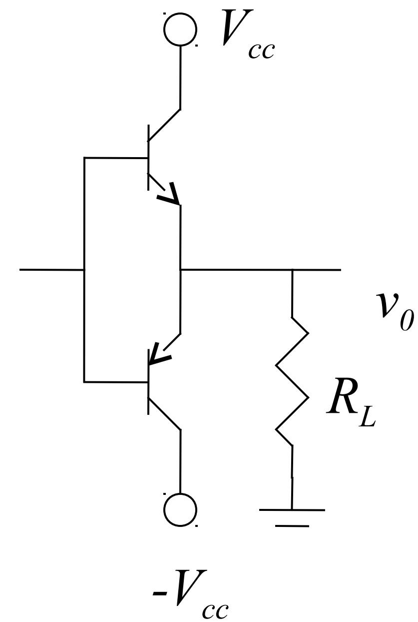
# Op Amp Components




Differential
amplifier

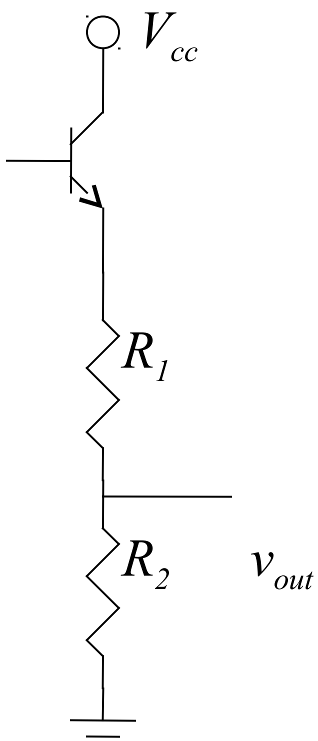



Buffer and
Level shift




Output
driver

# EFTS




Buffer and
Level shift

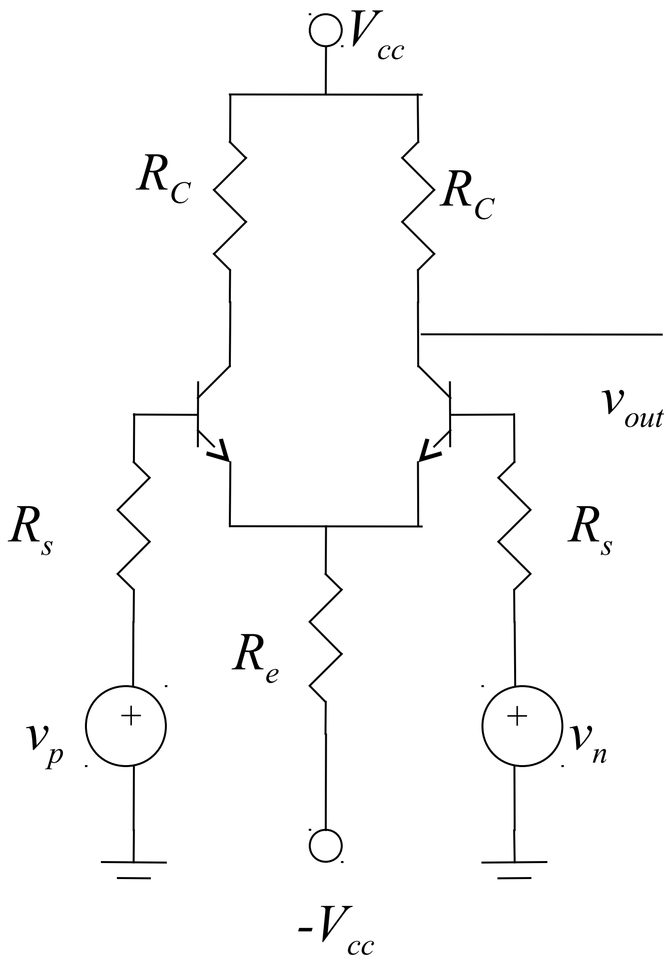
If $V_B$=10.6, $R_1$=500, $R_2$=500, what is $v_{out}$?

Solution: With the transistor on, the voltage drop across BE is roughly 0.6 V. Thus $V_E$=10.

$V_{out}$=10(500/(500+500))=5 V.

The circuit acts as a buffer for the preceding stages because little current enters the base.

# Differential Amplifier




Trick: decompose input voltages into common and difference parts.

Here $R_e$ is assumed large so that the current through it is near zero. Define $v_s=(v_p+v_n)/2$

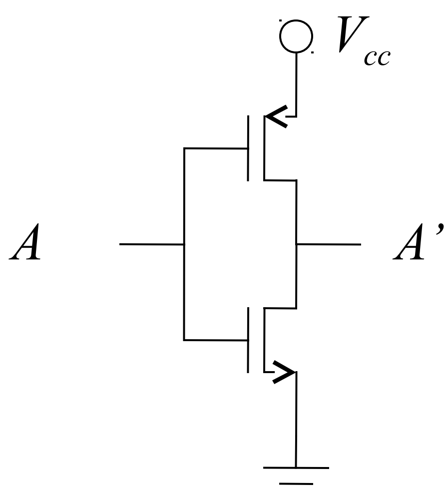
If $v_s=v_p=v_n$, by symmetry the currents into the collectors are also near zero and $v_{out}=0$. So the common part of the voltage has no effect on the output.

If now we consider $v_p=-v_n$, then by symmetry these currents are also negatives of each other, and sum so that the emitter current is zero. $v_{out}$ thus depends on the difference voltage and a model such as (2).

# CMOS Logic Gates

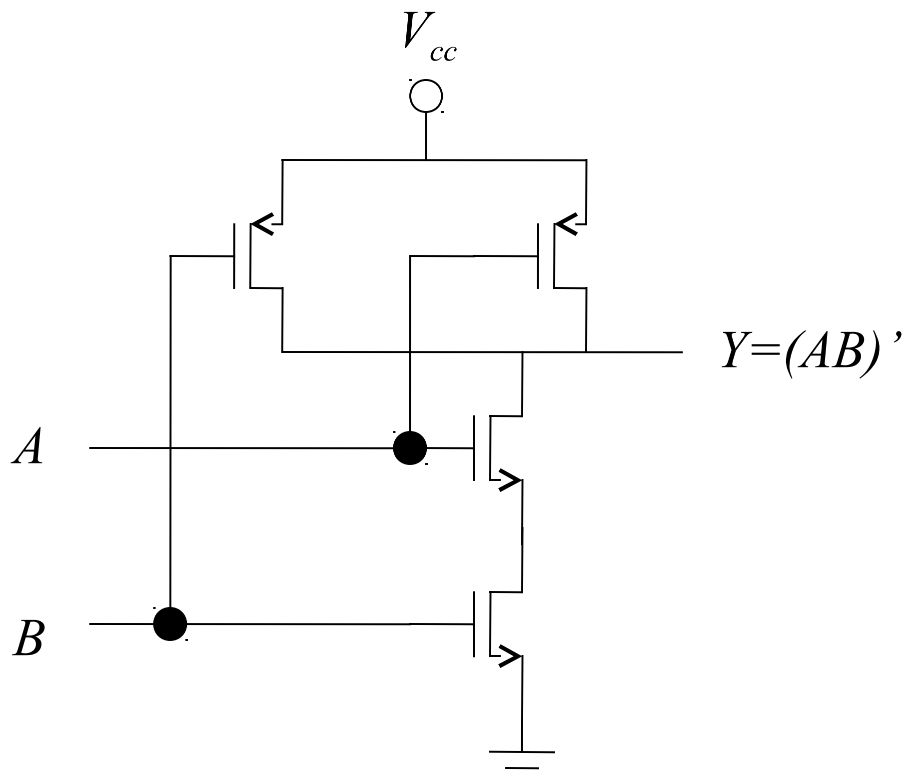
Most digital logic is based on CMOS technology, which stands for complementary metal on silicon, i.e., pairs of MOS field effect transistors (FET). Similarly to BJTs, the voltage across the base controls whether current can flow from the emitter to the collector.

An advantage of CMOS is that power is only used when the pair flips state from low to high voltage or vice versa.

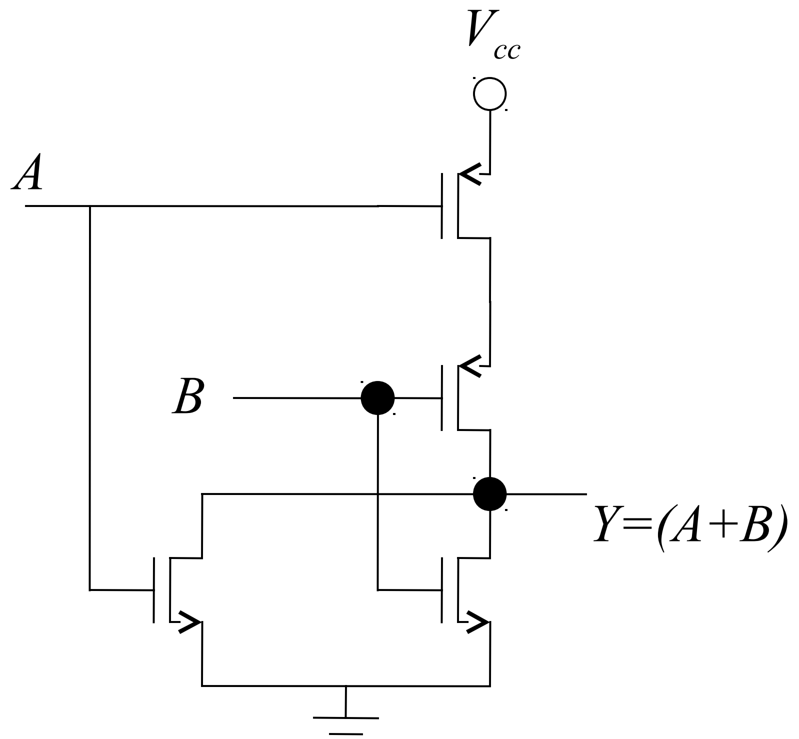



In the inverter circuit, if *A* is high, the lower gate opens and the output *A*' goes low. If *A* is low, the upper gate opens and *A*' goes high.

# NAND and NOR Gates




NAND Gate




NOR Gate

# Moore's Law

Demand for computation is insatiable. Roughly every 18 months, the number of transistors produced doubles as they get smaller and faster. That is, more are produced in this time period than in all prior history.

Moreover, considering other computational elements such as relays and vacuum tubes, Moore's Law has extended back through multiple technologies over 70 years.

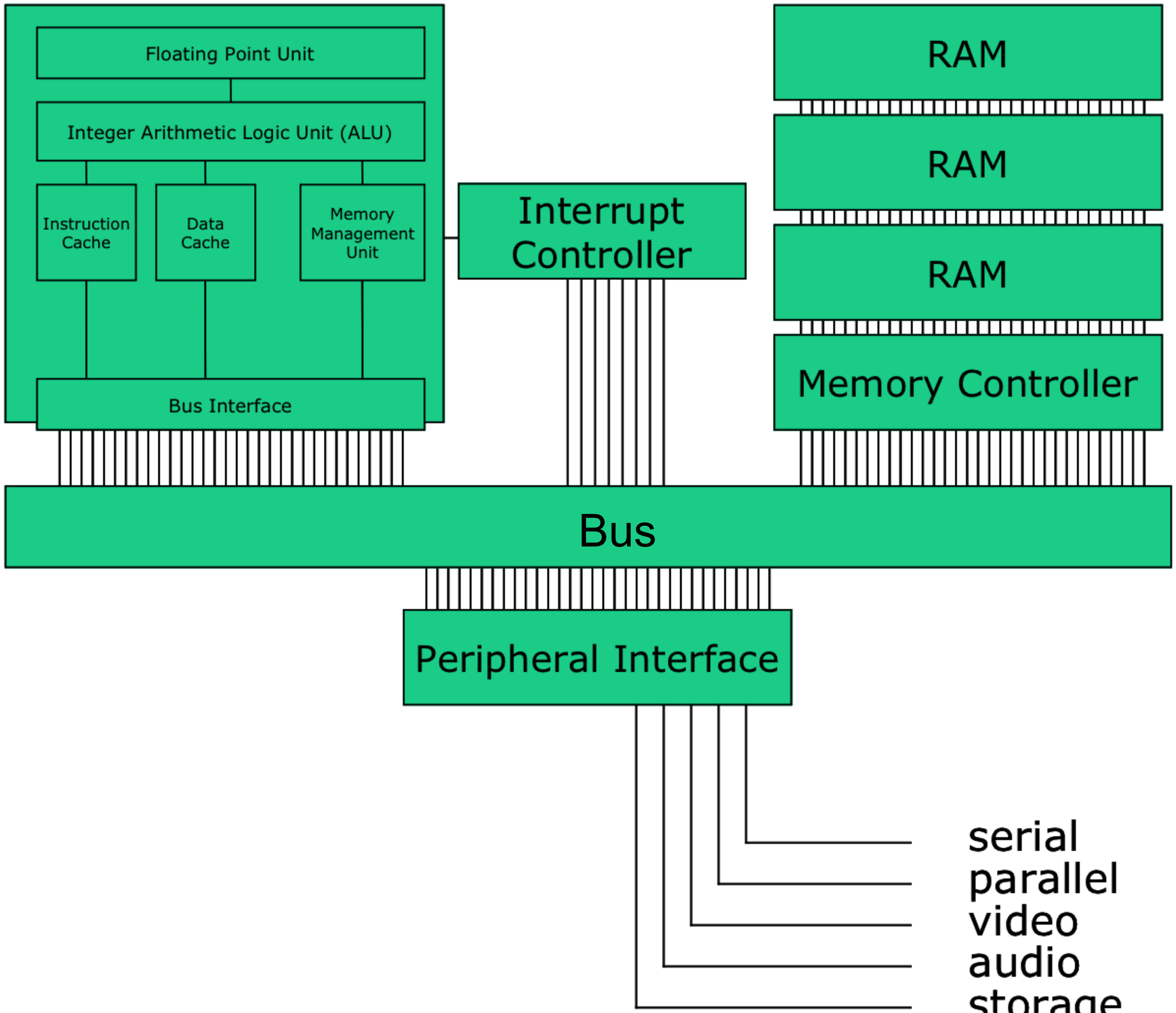
This has had revolutionary impact on computing and signal processing.

1. Closed form solutions are less necessary; the relaxed goal of finding an algorithm is often sufficient
2. Wasteful but convenient programming abstractions become possible, e.g. ASIC to Java~100,000 energy factor

# Computer Abstractions

| | |
|---|---|
| Transistors | EE 2, 121B, 115A |
| Logic gates | M16, M116L |
| Macro | EE 115C |
| Machine language | |
| Assembly code | CS 33 |
| Compiler/OS | CS 111 |
| High level language | CS 31,32 |
| Virtual machine | |
| Object oriented code | MATLAB |

# Simplified Computer Architecture



# Embedded Systems: EFTS

A tiny fraction of devices that contain computational elements are "computers;" most are used for control functions or otherwise interface with sensors.

Such embedded systems can contain many electronic elements. In a smartphone, what sensors, radios, actuators, processors, energy sources and memory elements are present?

Sensors: microphone; 3-axis accelerometer, gyros, and magnetometer; camera(s), touchpad(s)

Radios: 2G, 3G, 4G, Bluetooth, WiFi, ANT, GPS

Actuators: speaker, video display, vibration motor

Processors: main, video, communication control, …

Power: rechargeable battery, voltage converters, distribution of multiple supply voltages

Memory: ROM, many GB of RAM

# System Evolution

Compare to 1970.

PDP 11 mini-computer had main memory of 64K, used 9 inch floppy drives, and stood 6 feet tall

A few years earlier a science fiction novel "The Moon is a Harsh Mistress" had the premise that video rendering of faces would denote sentience

However, the principles of computation were already well understood.
What changed?
Size, cost, power consumption of transistors has decreased, enabling massive integration.

This is the (EE!) base on which modern algorithms and programming abstractions rest.

# Summary

- There are many ways to build logic gates
  - Relays, vacuum tubes, transistors
- Transistors have many advantages
  - Low cost, size and power
  - Massive integration is possible
  - Like vacuum tubes, can also be used in amplification
- Moore's Law has made possible revolutionary changes in signal processing
  - Speech and video processing (EE 114)
  - Modern digital communications (EE 132A)
  - Signal analysis (EE 113)
  - Apps