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# ES 154

## Electronic Devices and Circuits

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# Course Objectives

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- The objective of this course is to provide you with a comprehensive understanding of electronic circuits and devices. The course presents a basic introduction to physical models of the operation of semiconductor devices and examines the design and operation of important circuits that utilize these devices.
- Due to the varying background of students in the class, we will start with the basics (of circuit theory), review the operation and characteristics of semiconductor devices (namely, BJTs and MOSFETs), and build up to more advanced topics in analog circuit design.
- Due to time constraints, we will only briefly look at digital MOS circuits during the last week of the course. Digital CMOS circuits and VLSI design issues are covered more extensively in CS148.

# Course Material

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The lecture notes and the textbook, *Microelectronic Circuits*, 4<sup>th</sup> Edition by Sedra and Smith ([www.sedrasmith.org](http://www.sedrasmith.org)), will be the principle reference materials used in the class. The notes will cover specific material in the textbook that I find important and interesting. The notes may also include material not covered in the textbook.

You are responsible for all of the material in the notes and sections in Sedra and Smith (S&S) that are assigned as reading. Assigned reading will be indicated at the beginning of each set of lecture notes.

Supplementary reading may also be assigned. They will usually be in the form of supplementary web pages found on the course web site and also indicated on the lecture notes.

# Additional Reading

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To provide additional information and/or an alternative explanation of the material in the notes and S&S, supplemental reading from other textbooks will be included in the notes. While these readings are not required, they are often helpful in understanding the material.

- References (found in G. McKay Library soon)
  - *Electric Circuits*, Nilsson and Riedel, Prentice, 6<sup>th</sup> Ed., 2001.
  - *Electric Circuit Analysis*, Johnson et al, Prentice Hall, 1997.
  - *The Art of Electronics*, Horowitz and Hill, Cambridge, 1989.
  - *Analysis and Design of Analog Integrated Circuits*, Gray et al, Wiley, 2001.
  - *The Design of CMOS Radio-Frequency Integrated Circuits*, Lee, Cambridge, 1998.
  - *Device Electronics for Integrated Circuits*, Muller and Kamins, Wiley, 1986.
  - *Design with Operational Amplifiers and Analog Integrated Circuits*, Franco, McGraw Hill, 2002.
  - *Design of Analog CMOS Integrated Circuits*, Razavi, McGraw Hill, 2001.

# Course Information

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- Lectures
  - Tues and Thurs 10 – 11:30AM in Cruft 318
  - Lecture notes will be handed out in class and will be available on the course web page ([www.deas.harvard.edu/courses/es154](http://www.deas.harvard.edu/courses/es154))
- Homework
  - Assigned on Thurs and due the following Thurs *in class* – No late homework unless arranged one class period in advance
- Lab
  - Maxwell Dworkin B129 (in the basement)
  - There will be four laboratory assignments throughout the semester. You may be required to complete pre-lab assignments prior to going into lab.
  - Lab write-ups due with homework assignments on Thurs
- Exams
  - In-class midterm (tentative date Nov. 5)
  - Final exam (date TBA)

# Organization of Lectures

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The lecture notes will include some additional information to help you understand the material:

- + in a slide title means that this slide gives additional information about the previous slide, providing either an interesting aside, or some additional background information that might be helpful for understanding the material. It is for your benefit and is not part of the core material.
- in a slide title give some examples of the previous material to make sure you really understand what is going on.

These additional sections are in progress, so please let me know if they are helpful, and where more background or examples are needed.

# Homework Grading

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- One additional requirement that I have is for each of you to participate in *at least* one homework grading session.
- Several reasons why they are useful
  - Forces you to revisit the homework assignment at least once
  - Provides insight into alternative ways of thinking about a problem
  - Shows you how difficult (and easy) it can be grade one's homework write-up
  - Free pizza and drinks!
- Organization
  - We will provide the solutions and point distribution
  - TF(s) will schedule them

# Labs and Weekly Review Sessions

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- Once we have finalized the enrollment, we will schedule lab and TF-led review sessions

# Class Participation and Office Hours

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- ASK QUESTIONS!!!
  - I will make an effort to periodically stop and see if everyone understands the lecture material. However, you should stop me at any time if you have any questions.
  - If you are confused about something, chances are so is someone else.
- OFFICE HOURS
  - You are also encouraged to stop by our office hours. Or, if you are around on the 3rd floor of MD and you see my door open, stop by and say hello. My office is MD333.
  - Take advantage of office hours. It's a resource that too many students seem to neglect.

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## Lecture 1:

# A Brief Overview of Electronic Devices and Circuits

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# Overview

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- **Reading**

- S&S: Chapter 1, Appendix E

- **Supplemental Reading**

- Lee: Chapter 1 – “A nonlinear history of radio”
- Nilsson: Chapters 1-4 (basic circuit analysis)

- **Background**

This lecture is intended to give you a brief overview of what you can expect to learn from this course. There are additional interesting tidbits of historical trivia sprinkled into the lecture for fun. At the end, we review basic circuit theory that you should've all seen before in a physics course or ES50. If not, do the Nilsson reading above. It should be pretty straight forward if you have seen the material before.

# Why Electronics?

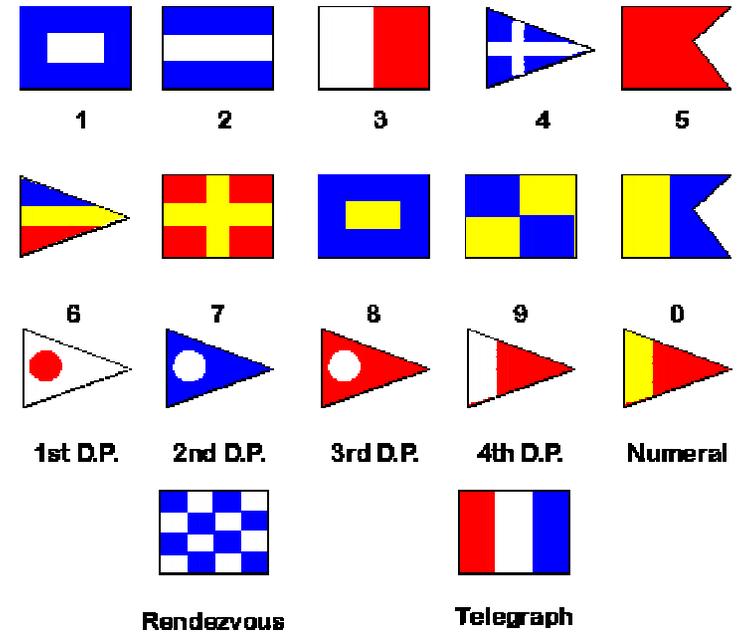
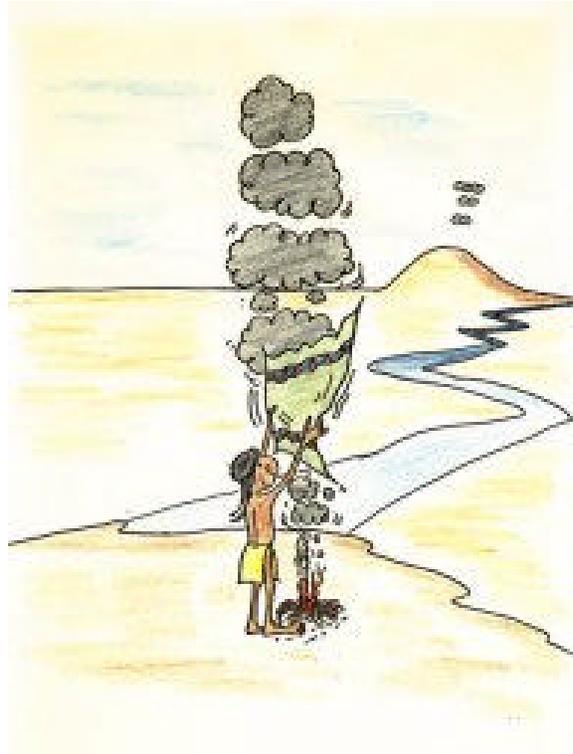
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- Why use electronics
  - Electrons are easy to move / control
    - Easier to move/control electrons than real (physical) stuff
    - Discovered by J.J. Thomson in 1898
  - Move information, not things
    - phone, fax, WWW, etc.
    - Takes much less energy and \$
- Development of modern electronics has been driven by
  - Communication
  - Computation

# Communication Alternatives...

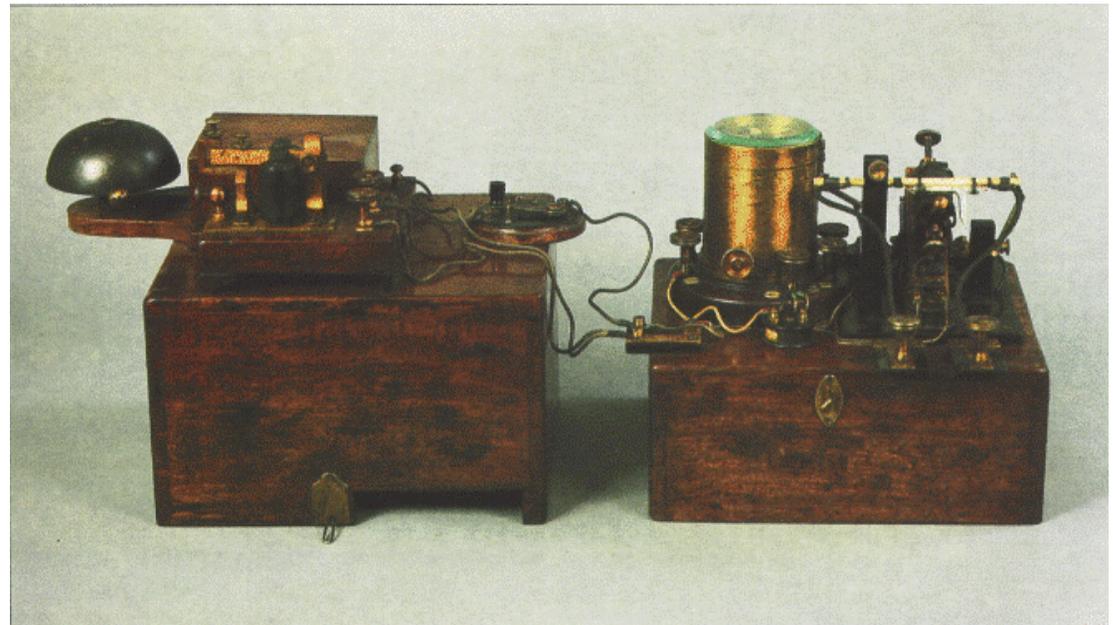
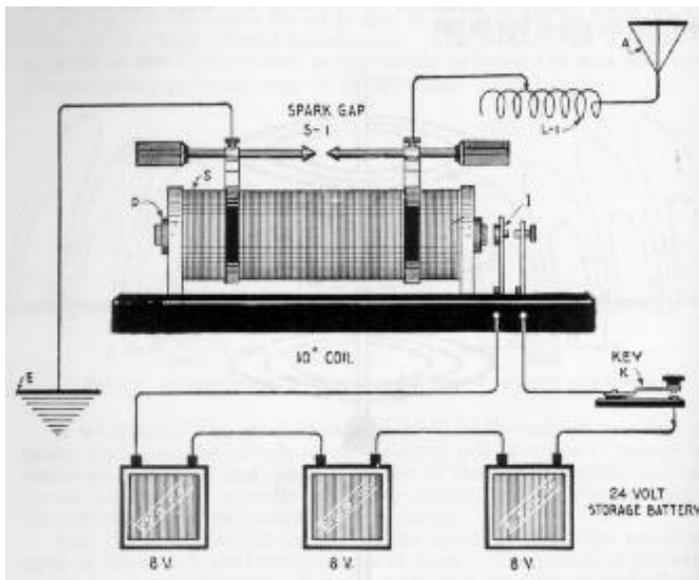


Hand signal for  
come to me



# Origins of Radio

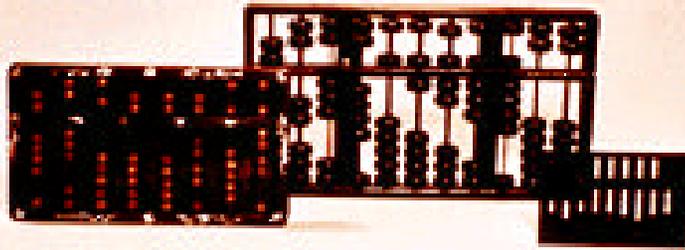
- Marconi generally regarded as the inventor of the radio in 1896
  - Used a spark gap transmitter (used by Heinrich Hertz to verify Maxwell's prediction that electromagnetic waves exist and propagate with a finite velocity) and Eduardo Branly's "coherer" as the receiver.



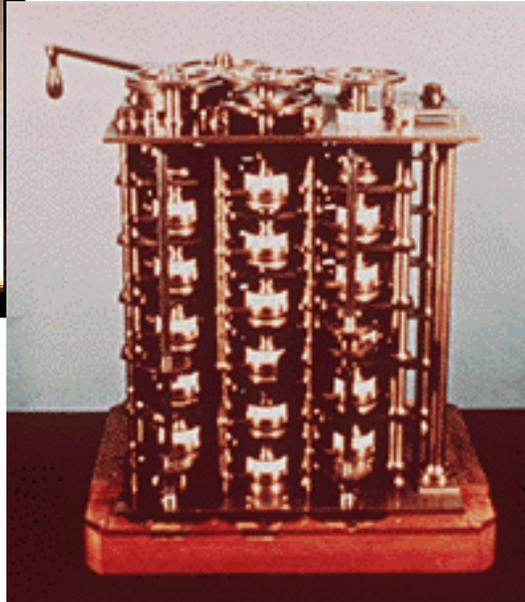
- Demonstrated transatlantic wireless communication in 1901

# Computing Alternatives

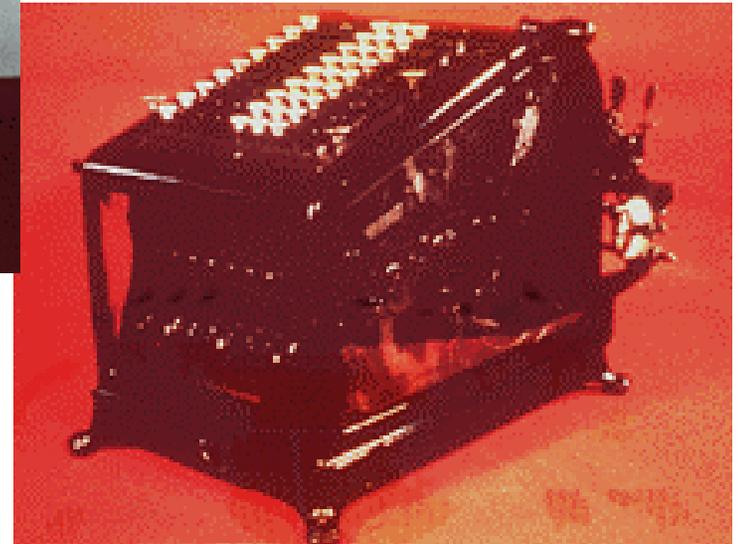
Abacus



Babbage Difference Engine

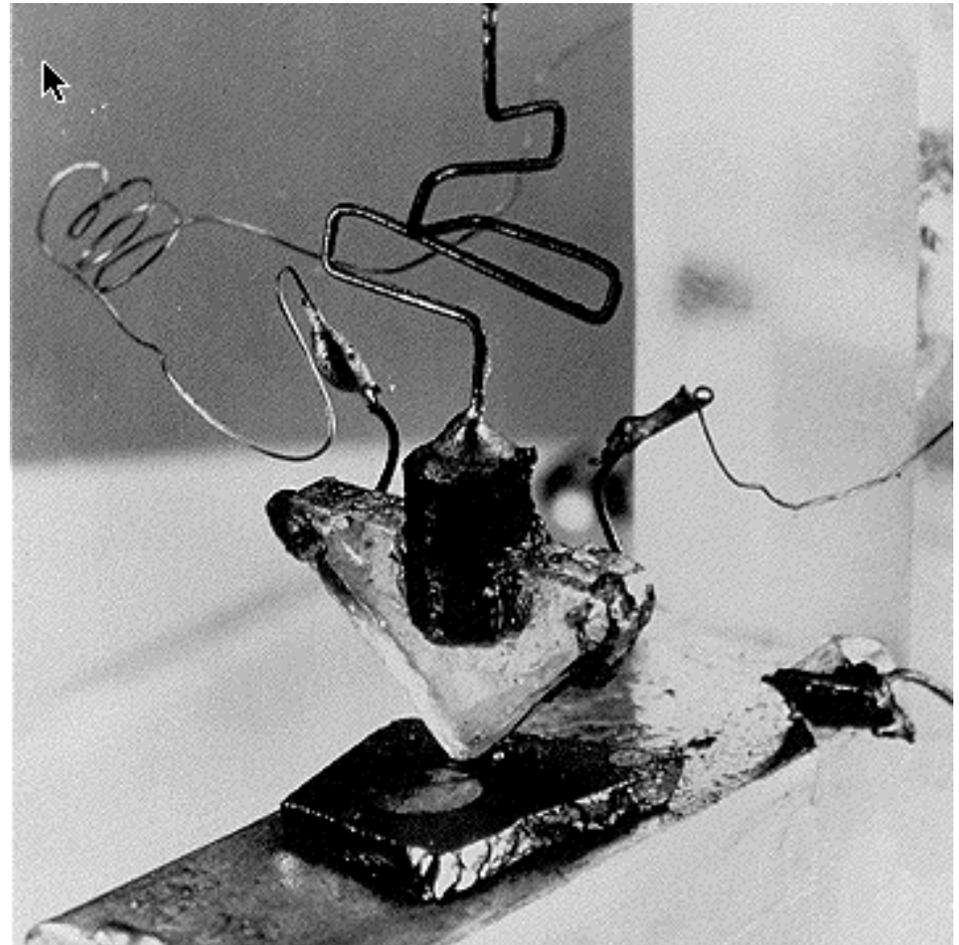


Mechanical Cash Register



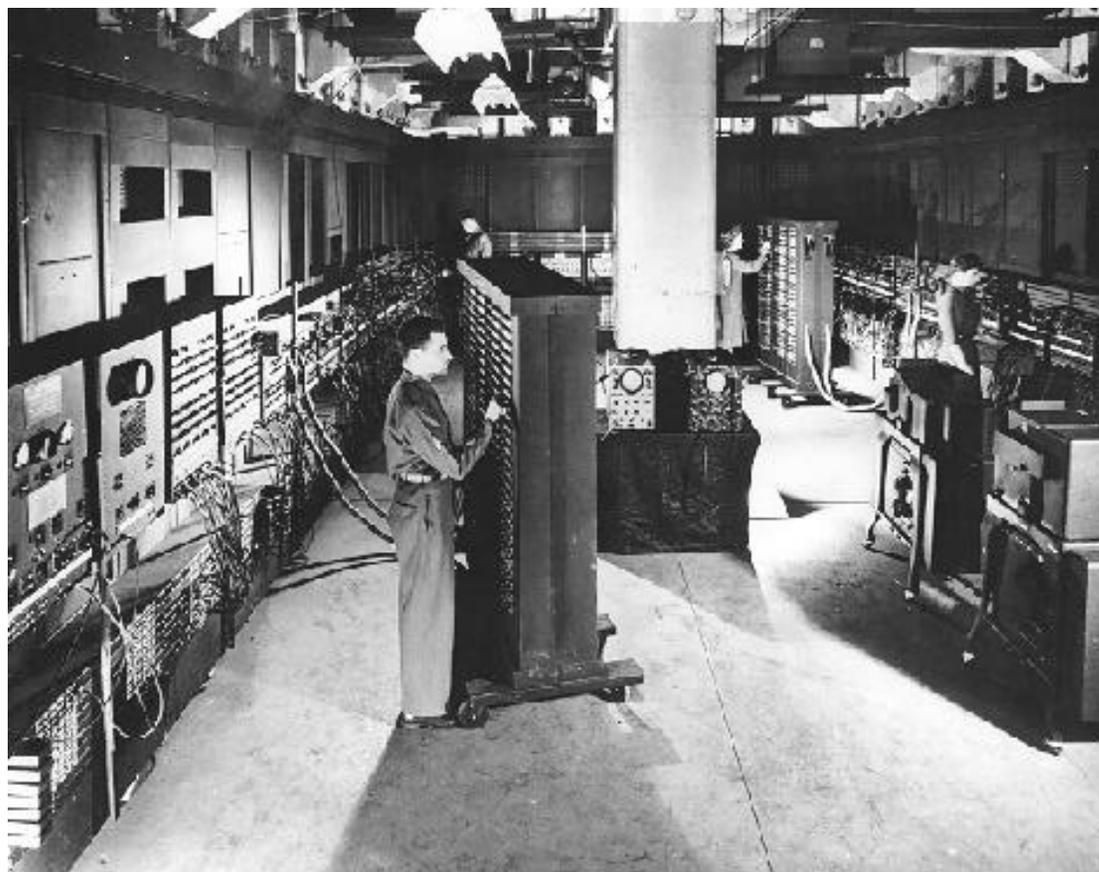
# Early Electronic Devices

- Building electronics:
  - Started with tubes, then miniature tubes
  - Transistors, then miniature transistors
    - Bardeen, Brattain, and Shockley invent the first germanium point-contact transistor at Bell Labs in 1947 (they received a Nobel prize for this discovery).  
Built an amplifier
- Components were getting cheaper, more reliable but:
  - There is a minimum cost of a component (storage, handling ...)
  - Total system cost was proportional to complexity



# Big Electronic Computers

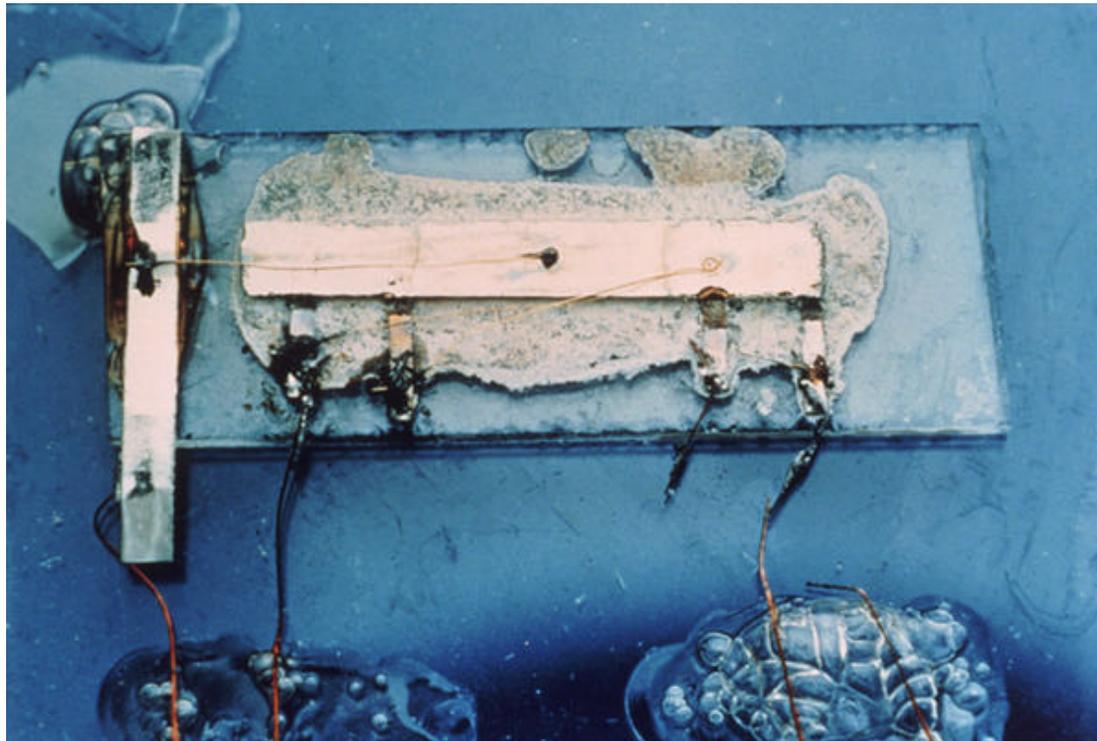
- ENIAC (Electrical Numerical Integrator And Calculator)
  - developed by Mauchly and Eckert in 1946
  - 17,468 vacuum tubes, 70,000 resistors, 10,000 capacitors, 1500 relays, 6000 manual switches, and 5 million solder joints; covered 1800 sq. feet of floor space; weighed 30 tons; consumed 160kW
  - Built to calculate ballistic trajectories (ballistic firing tables)



# Beginning of Modern Devices

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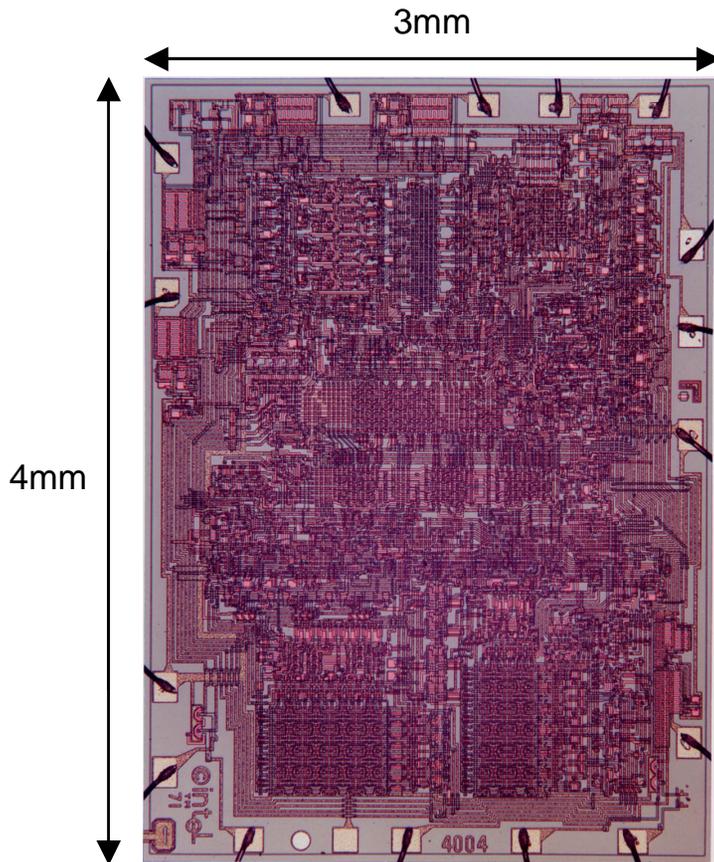
- Then along came the Integrated Circuit (IC)
  - Invented by Jack Kilby of Texas Instruments in 1958 (received a Nobel Prize in Physics 2000)



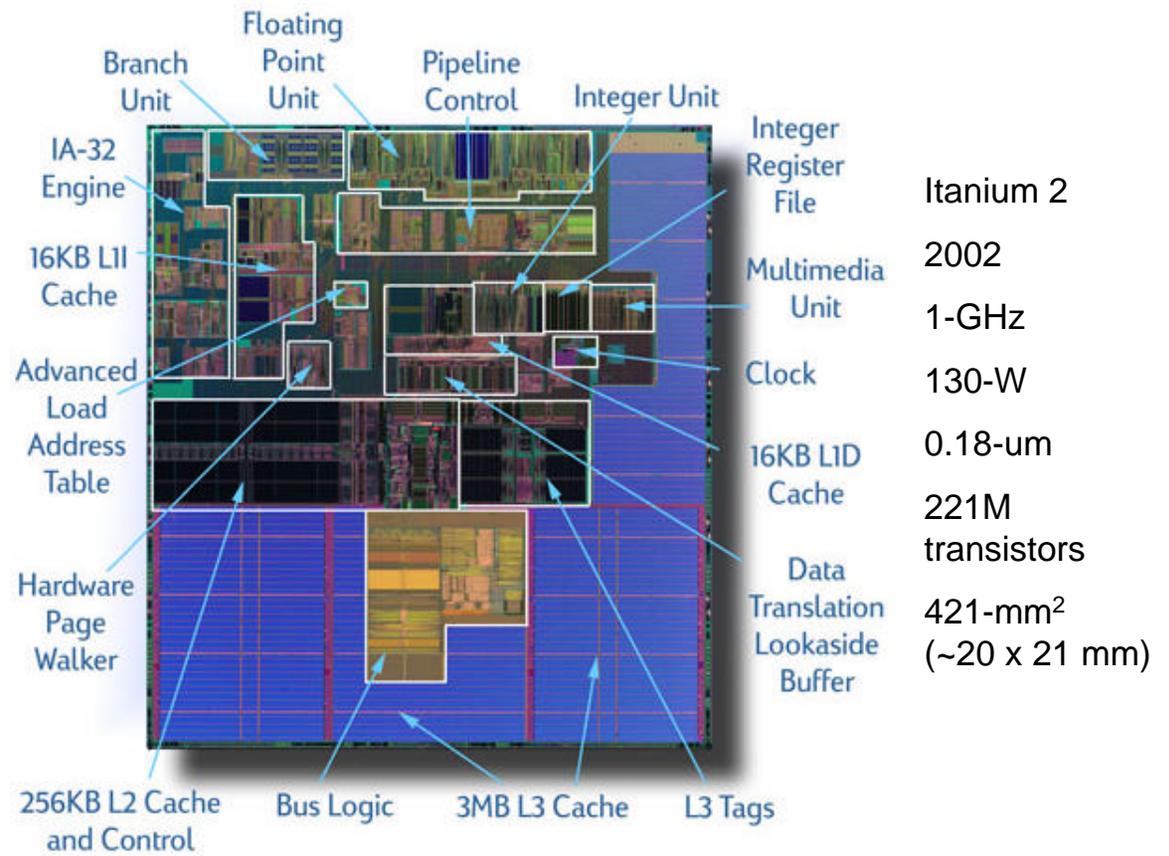
- Independently, Robert Noyce of Fairchild Semiconductor had an idea for “unitary circuits”

# Modern IC's

- The IC industry has been able to continue to reduce the size of transistors and increase the number of devices that can be integrated onto a single device



intel 4004 ('71, 2.3K transistors, 10-um technology, 108-kHz)



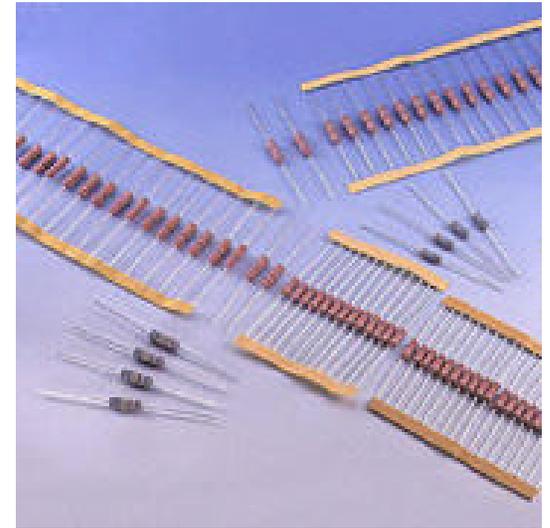
McKinley microprocessor

Itanium 2
2002
1-GHz
130-W
0.18-um
221M transistors
421-mm <sup>2</sup> (~20 x 21 mm)

# Where Do We Start?

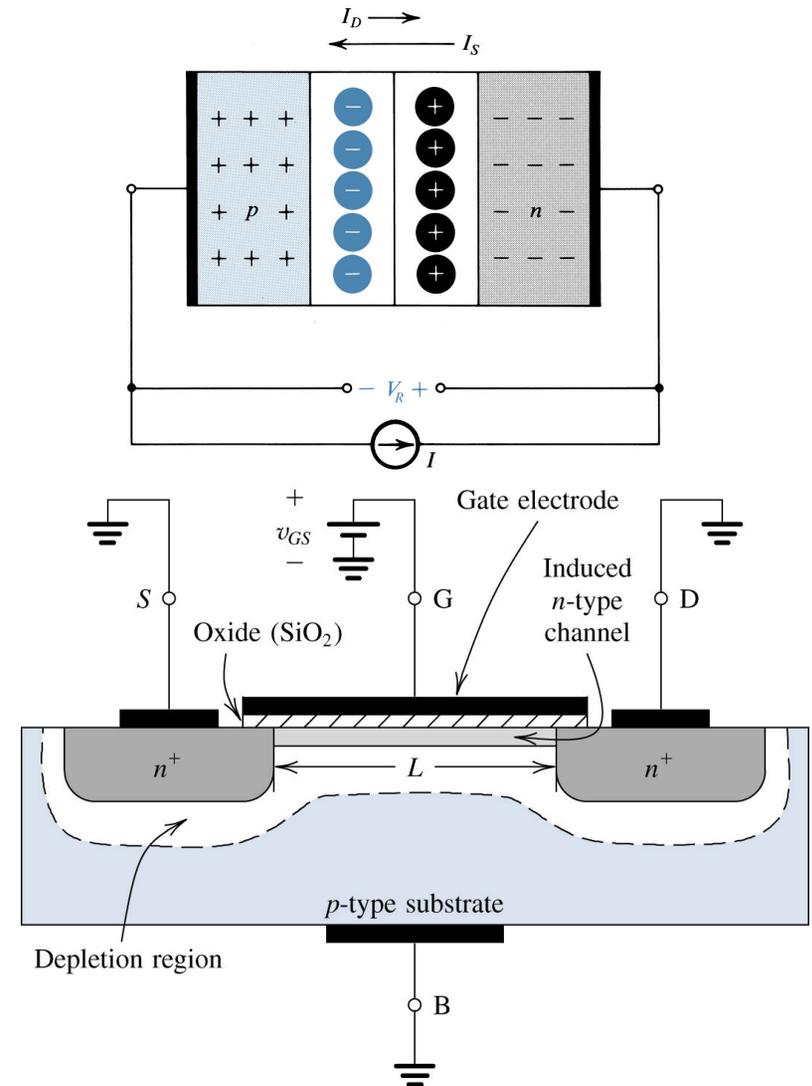
Ostensibly from the beginning....

- Volts and Amps (basic circuit analysis)
  - Independent voltage sources and current sources
  - Dependent sources
  - Passive elements – resistors, capacitors, inductors
- Operational Amplifier (Op Amp)
  - A general purpose, closed loop, amplifier used to implement linear functions. Its performance and function are defined by the external components (feedback network or loop) surrounding it.
  - First introduced in early 1940's
  - Originally comprised of vacuum tubes
  - Used for computation (i.e., addition, subtraction, multiplication, etc.)



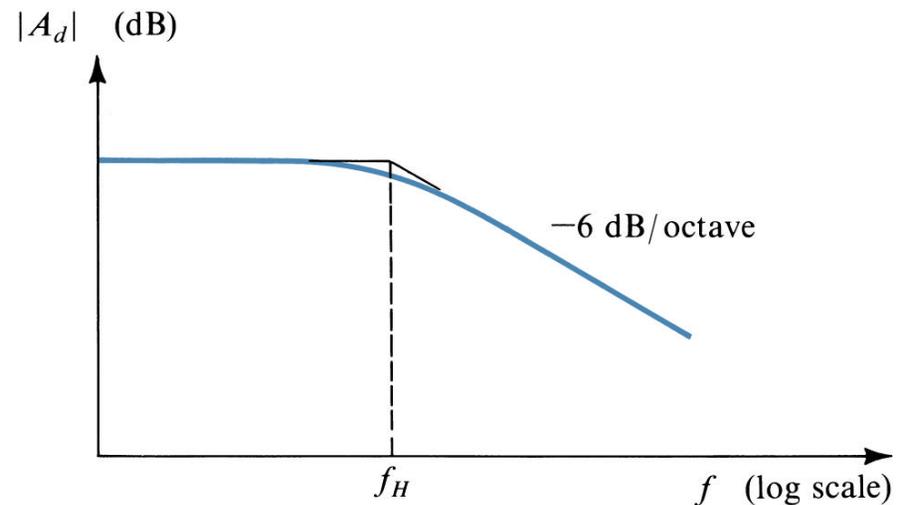
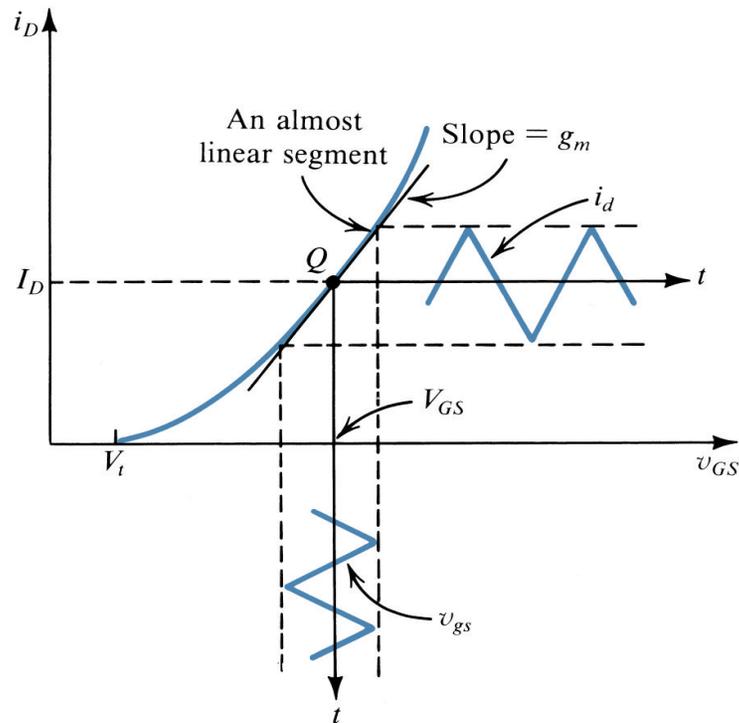
# What's inside these OpAmps?

- Brief introduction to semiconductors
  - Conductors vs. Insulators vs. Semiconductors
  - P-type, N-type
- PN Junctions
  - Diodes and diode circuits
- Bipolar Junction Transistors (BJT)
  - How they work
  - Different types of BJT circuits
- Metal Oxide Semiconductor Field Effect Transistors (MOSFET)
  - How they work
  - Different types of MOSFET circuits



# Modeling the Operation of Circuits

- Frequency Response Analysis
  - Circuits operate over a limited frequency range of the incoming and output signal
  - We will construct models for the circuits and look at gain and bandwidth relationships

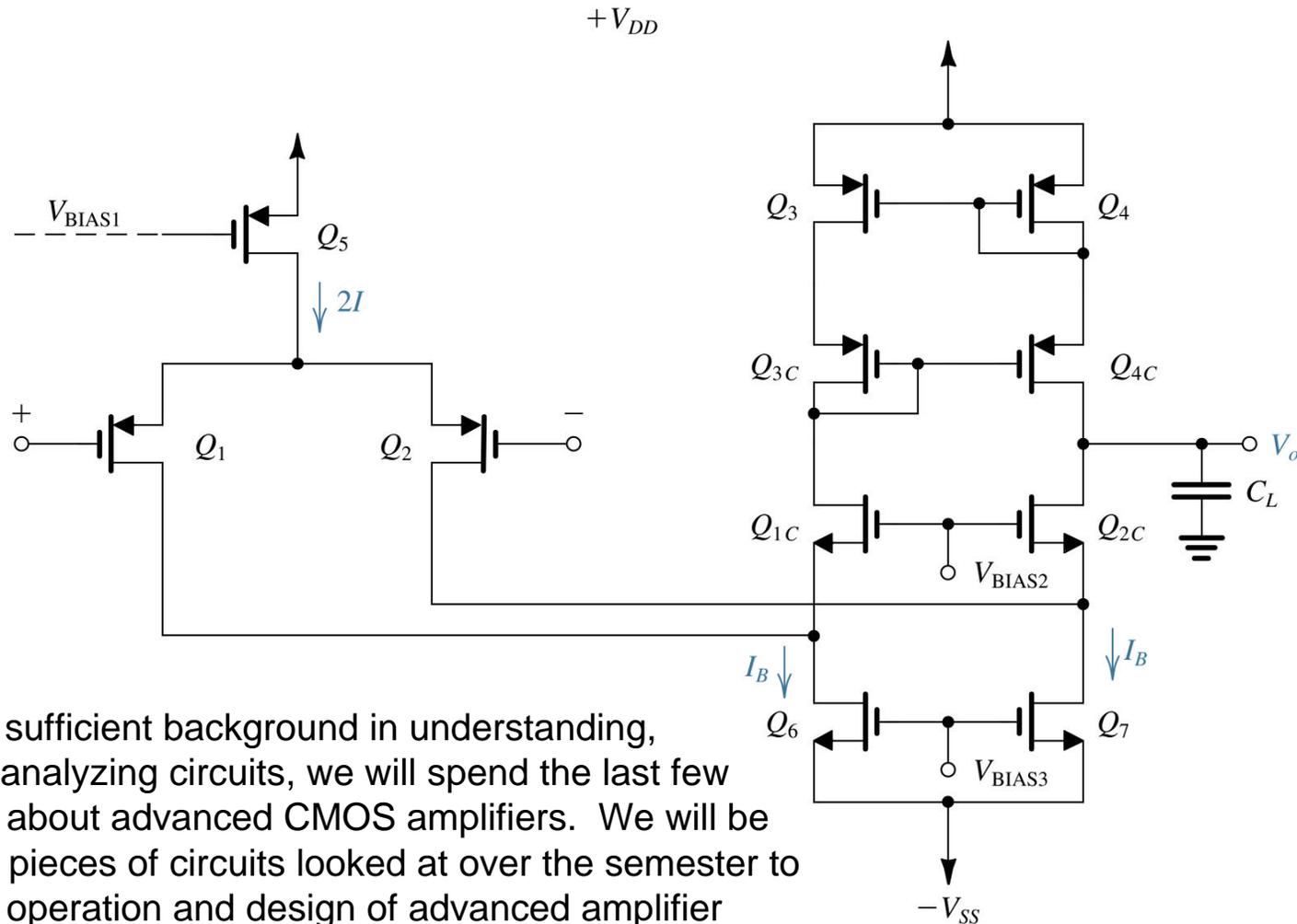


# Feedback

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- Once we've looked at the frequency response of circuit operation, it becomes important to spend some time on basic feedback. At this point, we should've seen feedback at work in OpAmp circuits, but we didn't worry about frequency response and stability b/c we assumed an ideal amplifier.
- We will spend some time on open-loop and closed-loop response characteristics of circuits given feedback.
- Then, we will investigate compensation techniques for extending the bandwidth of amplifiers

# Advanced CMOS Amplifiers



- Having built up sufficient background in understanding, designing, and analyzing circuits, we will spend the last few lectures talking about advanced CMOS amplifiers. We will be taking all of the pieces of circuits looked at over the semester to understand the operation and design of advanced amplifier designs.

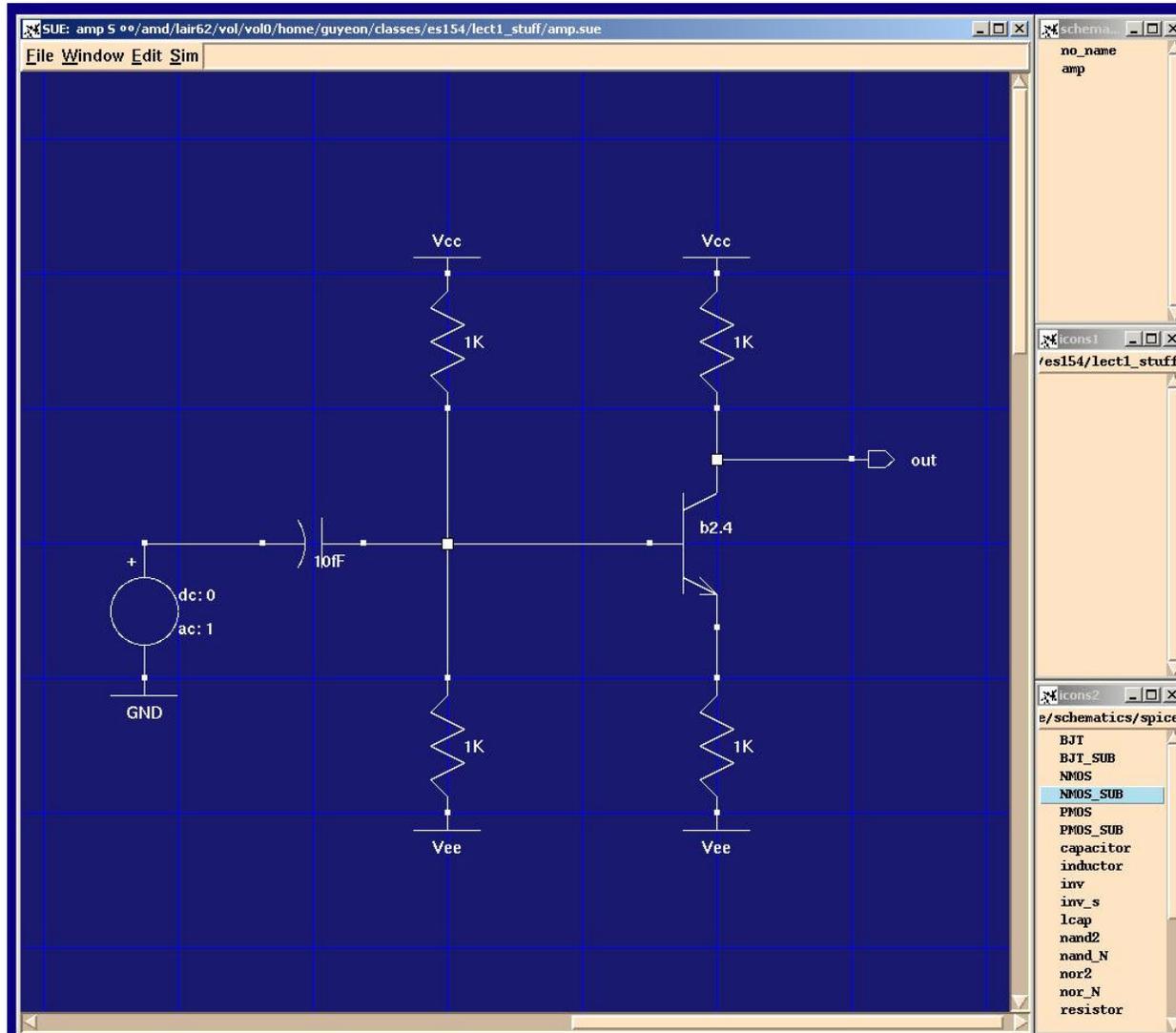
# CAD Tools...

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We will rely on two sets of tools to help us design and verify our circuits.

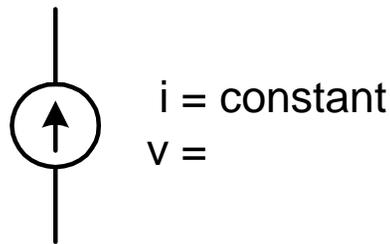
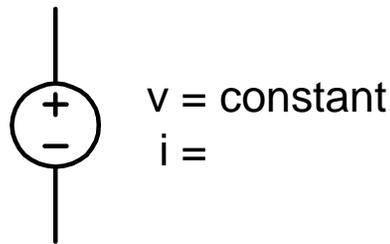
- Circuit Simulations
  - HSPICE – an analog circuit simulator
  - SUE – Schematic User Environment is a graphical tool for drawing circuits and then creating a netlist from HSPICE
- MATLAB
  - Mathematical tool for frequency response analysis and create pretty graphs

# SUE looks like....



# Review of Circuit Basics

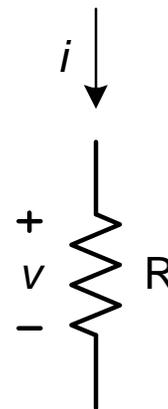
- Some basic circuit elements (and their symbols) that we will be using extensively in the class



Ideal Independent Sources

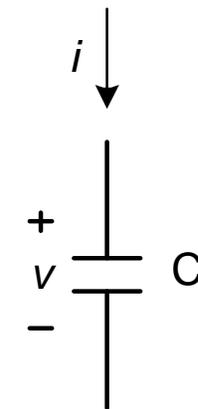


Ideal Dependent Sources



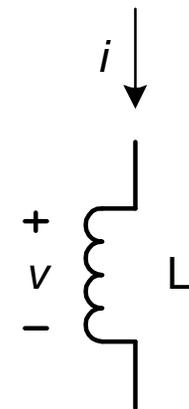
$$v = iR$$

Resistor



$$i = C \, dv/dt$$

Capacitor



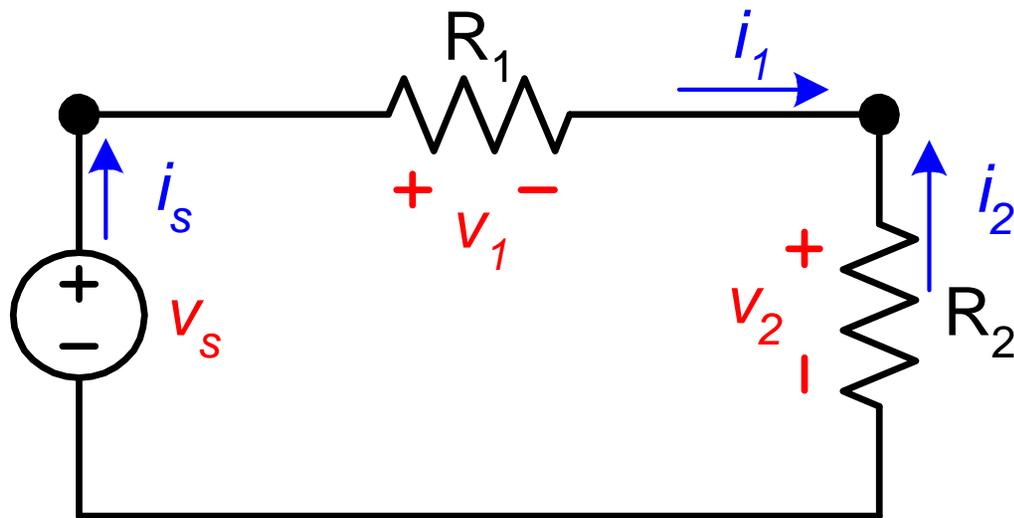
$$v = L \, di/dt$$

Inductor

- Examples from Nilsson, *Electric Circuits*, 3<sup>rd</sup> ed., 1991

# Kirchhoff's Laws

- Kirchhoff's Current Law (KCL): The algebraic sum of all of the currents at a node in a circuit equals zero.
- Kirchhoff's Voltage Law (KVL): The algebraic sum of all of the voltages around any closed path in a circuit equals zero.

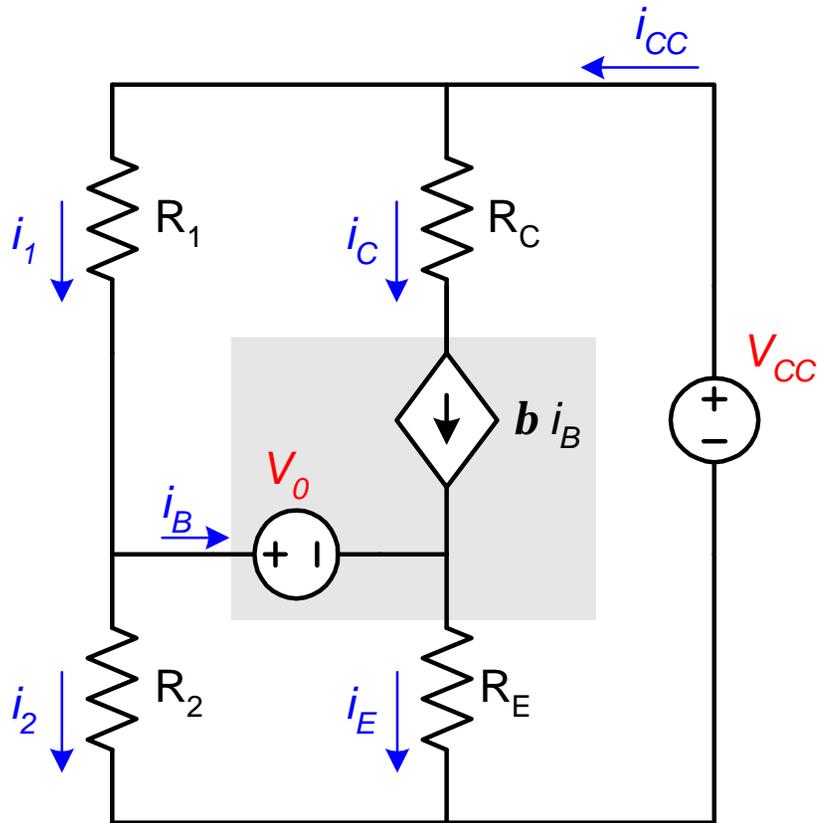


$$\text{KVL: } V_s - V_1 - V_2 = 0$$

$$\text{KCL: } \begin{aligned} i_s - i_1 &= 0 \\ i_1 + i_2 &= 0 \end{aligned}$$

# Example with a Dependent Source

- Here's a quick example of a circuit that we will see later when we model the operation of transistors. For now, let's assume ideal independent and dependent sources



We can write the following equations:

$$i_1 + i_C - i_{CC} = 0$$

$$i_B + i_2 - i_1 = 0$$

$$i_E - i_B - i_C = 0$$

$$i_C = b i_B$$

$$V_0 + i_E R_E - i_2 R_2 = 0$$

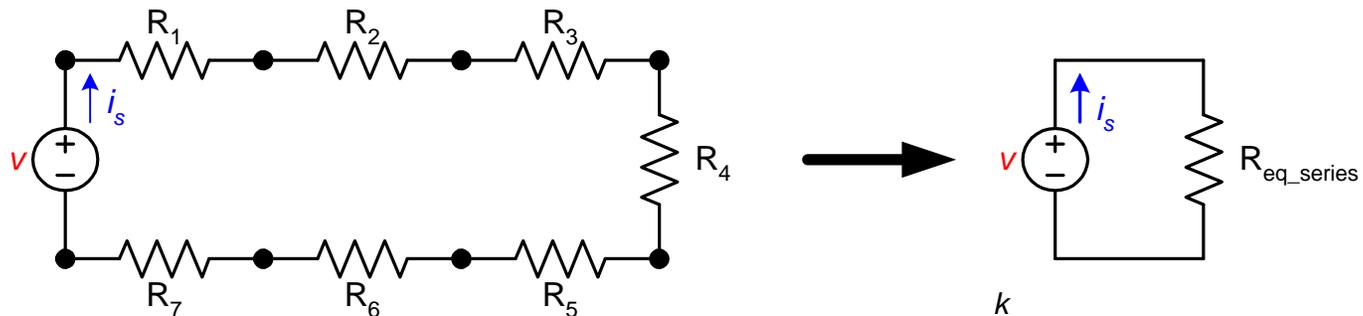
$$-i_1 R_1 + V_{CC} - i_2 R_2 = 0$$



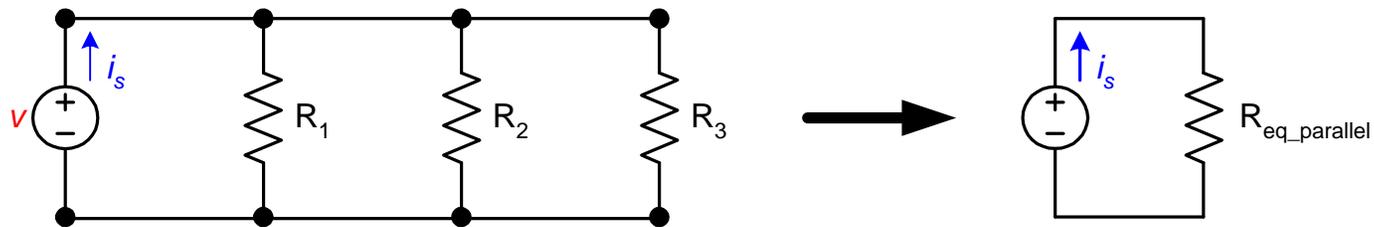
$$i_B = \frac{\frac{V_{CC} R_2}{R_1 + R_2} - V_0}{\frac{R_1 R_2}{R_1 + R_2} + (1 + b) R_E}$$

# Resistive Circuits

- Series vs. Parallel Resistors



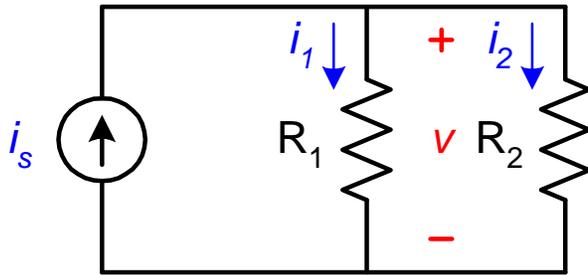
$$R_{eq\_series} = \sum_{i=1}^k R_i = R_1 + R_2 + R_3 + \dots + R_k$$



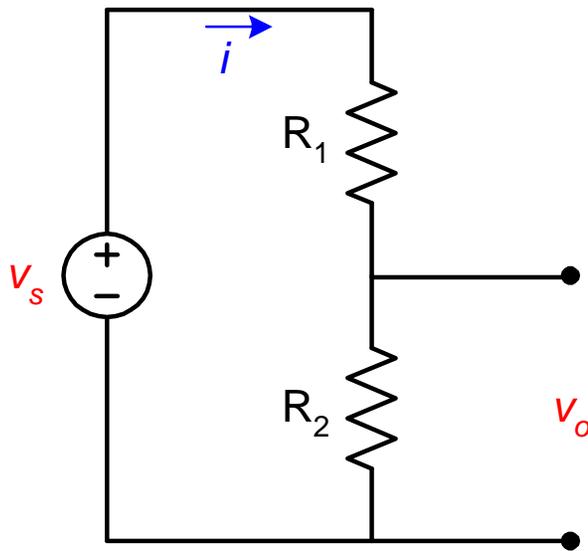
$$\frac{1}{R_{eq\_parallel}} = \sum_{i=1}^k \frac{1}{R_i} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots + \frac{1}{R_k}$$

# Divider Circuits

- Current and voltage divider circuits using resistors



$$v = i_1 R_1 = i_2 R_2 = i_s \frac{R_1 R_2}{R_1 + R_2}$$

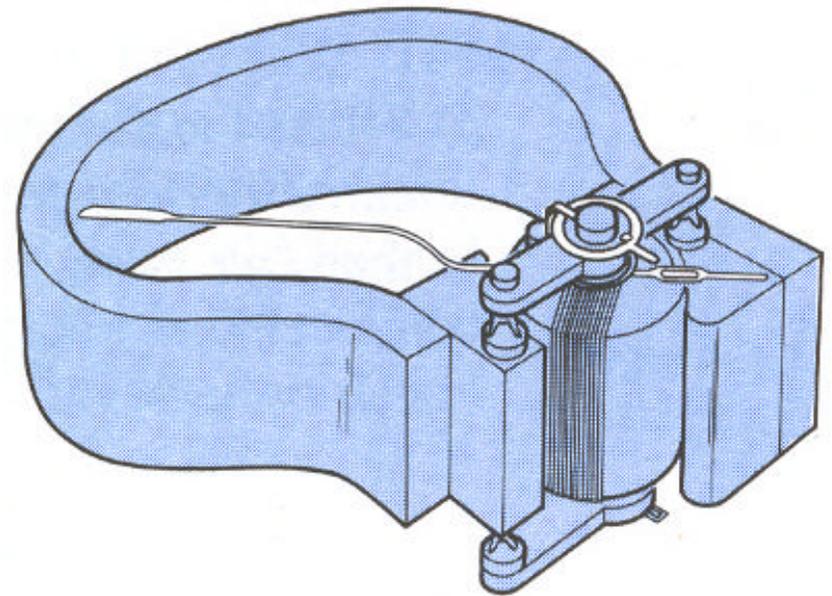
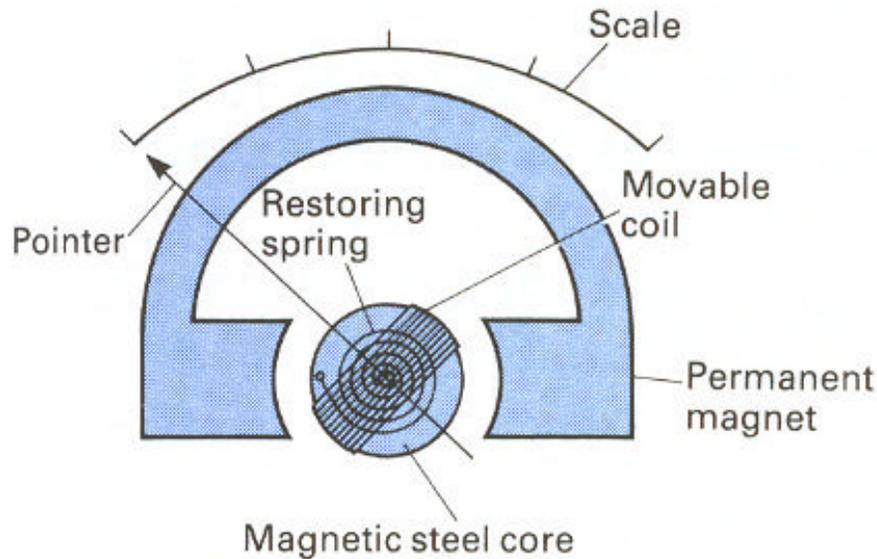


$$v_s = iR_1 + iR_2$$

$$v_o = iR_2 = v_s \frac{R_2}{R_1 + R_2}$$

# How can we measure current and voltage?

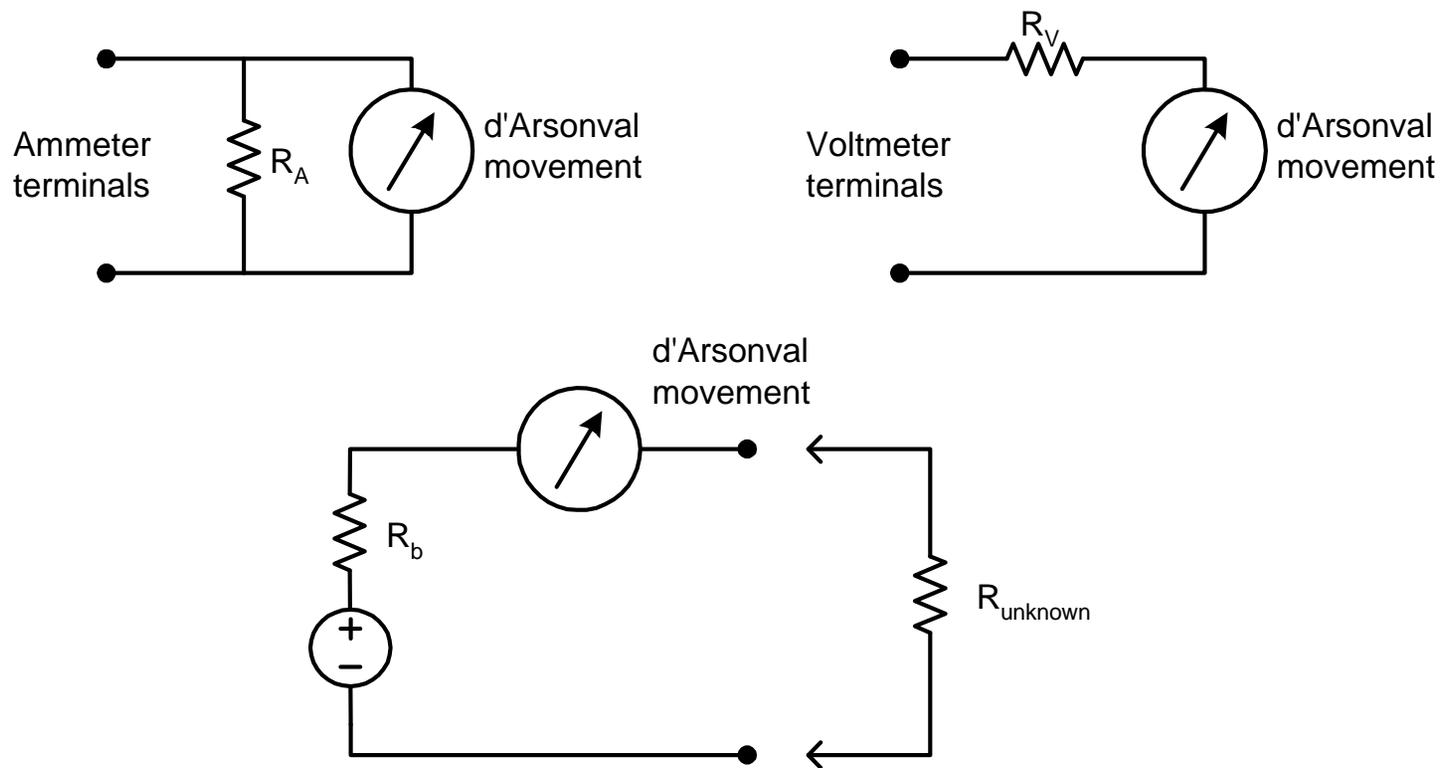
- ***d'Arsonval meter movement*** consists of a movable coil placed in the field of a permanent magnet. Current in the coil creates a torque in the coil, which rotates until torque is balanced by restoring spring. Designed so deflection of the pointer is directly proportional to current in the movable coil.



(from Nilsson, 3<sup>rd</sup> edition)

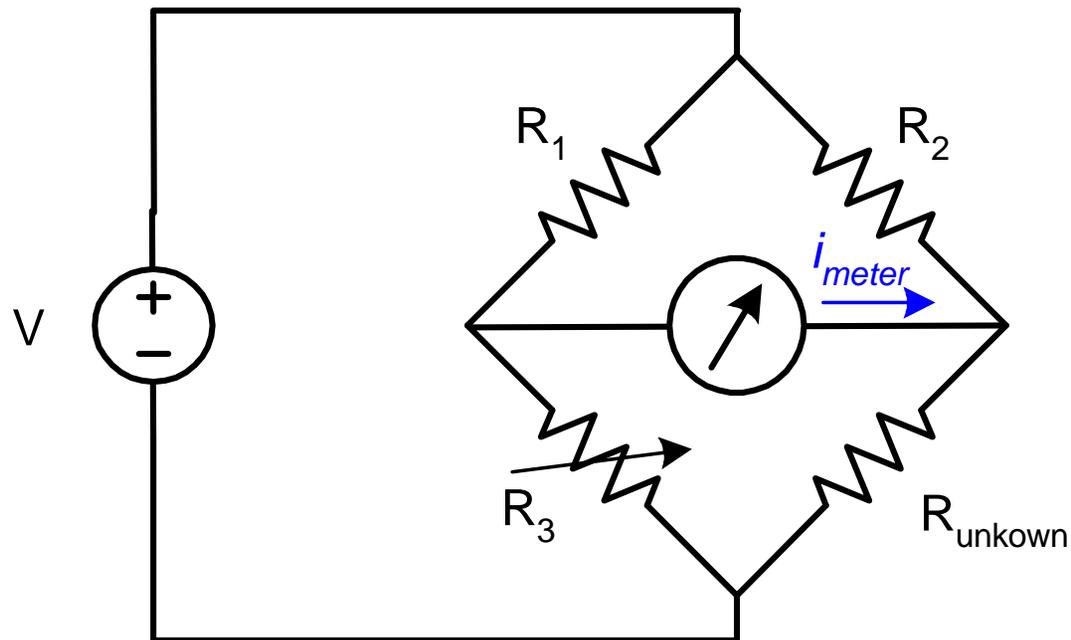
# Ammeter, Voltmeter, and Ohmmeter

- DC Ammeter: The shunting resistor  $R_A$  and d'Arsonval movement form a current divider
- DC Voltmeter: Series resistor  $R_V$  and d'Arsonval movement form a voltage divider
- Ohmmeter: Measures the current to find the resistance



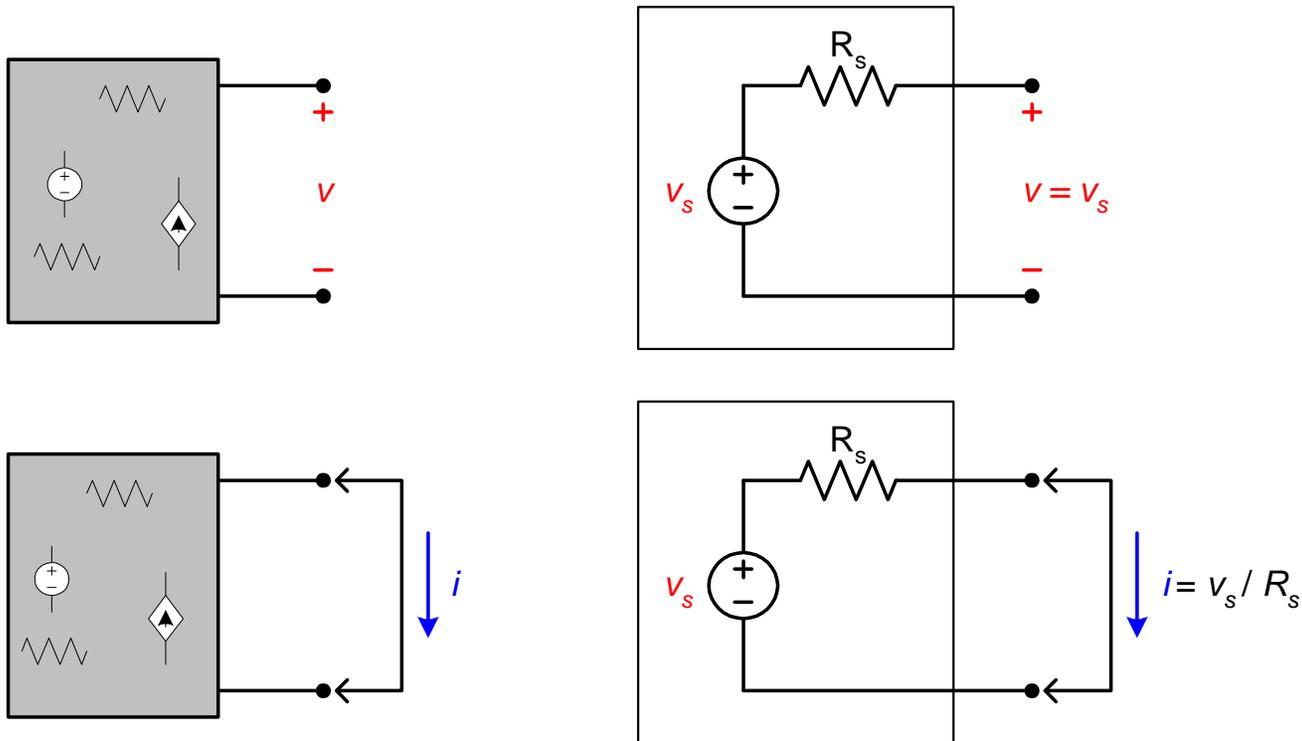
# Wheatstone Bridge

- Used for precision measurements
  - One example is to measure resistance of  $R_{\text{unknown}}$   
Adjust  $R_3$  until  $i_{\text{meter}} = 0$ , then  $R_{\text{unknown}} = R_2 R_3 / R_1$



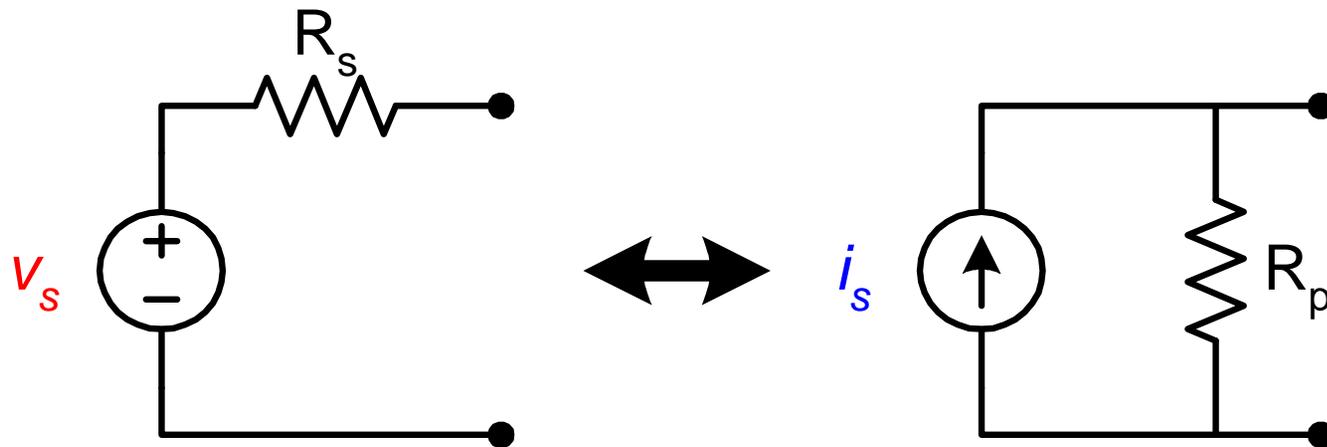
# Source Transformations

- Source transformations can be a useful way to simplify circuits
- Thevenin and Norton Equivalents
  - Can represent any sources made up of sources (both independent and dependent) and resistors
  - Converting to a Thevenin equivalent



# Thevenin $\leftrightarrow$ Norton

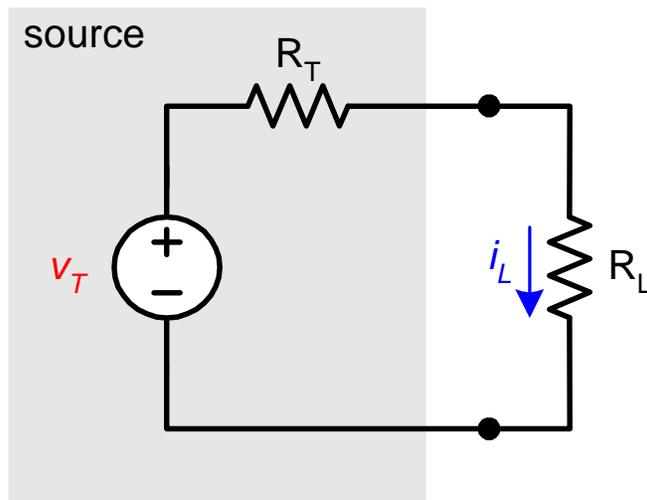
- Thevenin and Norton are equivalent from the terminals



- But, if I gave you two black boxes and said one is a Thevenin and one is Norton, how could you tell them apart?

# Maximum Power Transfer

- It is often important to design circuits that transfer power from a source to a load. This will be an important concept when we are designing amplifiers. There are two basic types of power transfer:
  - Efficient power transfer (e.g., power utility)
  - Maximum power transfer (e.g., communication circuits)
    - Transfer an electrical signal (data, information, etc.) from the source to a destination with the most power reaching the destination. There is limited power at the source and power is small so efficiency is not as much of a concern.
    - Assume there is a source that can be represented as a Thevenin equivalent circuit. Determine  $R_L$  so that the maximum power is transferred.



$$p = v_T i_L = i^2 R_L = \left( \frac{v_T}{R_T + R_L} \right)^2 R_L$$
$$\frac{d}{dR_L}(p) = v_T^2 \left[ \frac{(R_T + R_L)^2 - 2R_L(R_T + R_L)}{(R_T + R_L)^4} \right] = 0$$

↓

$$R_T = R_L \quad p_{\max} = \frac{v_T^2}{4R_L}$$

# Superposition

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- A distinguishing characteristic of linear systems is the principle of superposition:

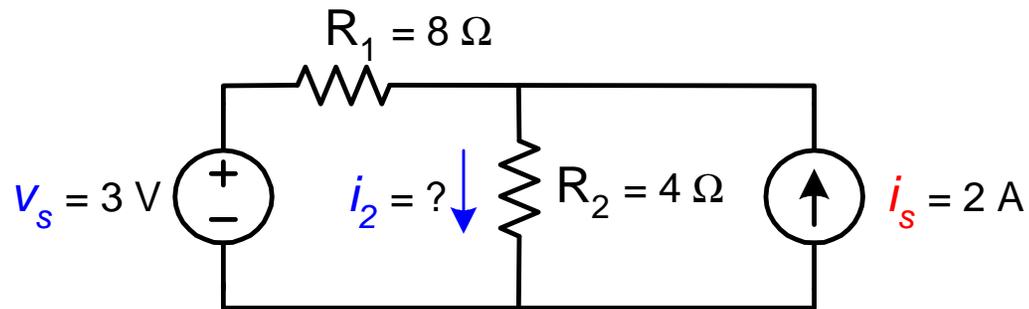
Whenever a linear system is excited, or driven, by more than one independent source of energy, we can find the total response by finding the response to each independent source separately and then summing the individual responses.

- Mathematically,
  - A system specified by  $T[\cdot]$  is linear if for all  $a_1$ ,  $a_2$ ,  $x_1(n)$ , and  $x_2(n)$ , we have:

$$T[a_1 x_1(n) + a_2 x_2(n)] = a_1 T[x_1(n)] + a_2 T[x_2(n)]$$

- Technique:
  - short circuit voltage sources and open circuit current sources
  - calculate for one source at a time and then sum

# Example of Superposition

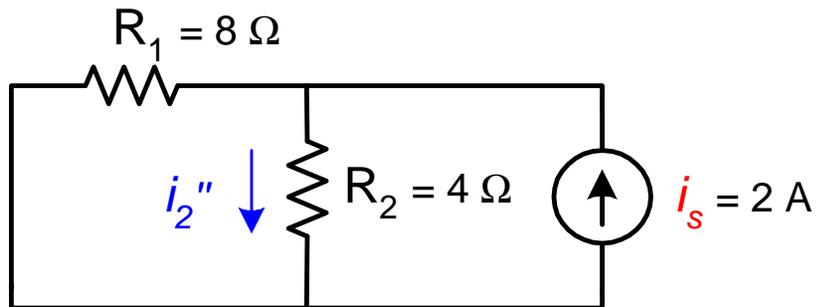
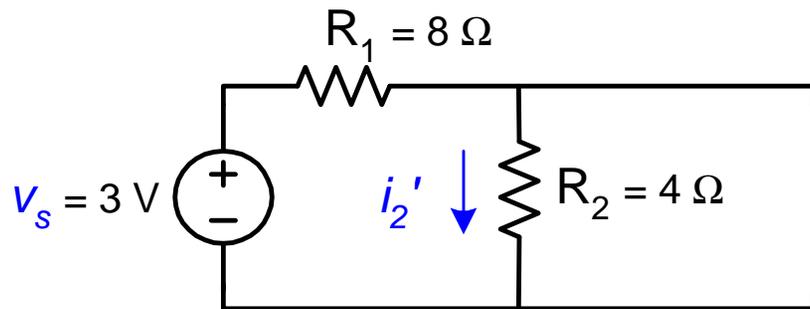


Find  $i_2$  using superposition

$$i_2' = \frac{V_s}{R_1 + R_2} = \frac{3}{8 + 4} = 0.25$$

$$i_2'' = \frac{i_s R_2}{R_1 + R_2} = \frac{2 \cdot 4}{8 + 4} = 0.667$$

$$i_2 = i_2' + i_2''$$



# Next Lecture

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There is a set of web pages (from 2001 ES154) that provides additional information on the [basics](#).

We will continue to review basic concepts in electric circuits. In particular, we will review circuits containing inductors, capacitors, and resistors, and some analytical tools to deal with them.

- Reading
  - S&S: Appendix E
- Supplemental reading
  - Nilsson: Chapters 6-13