EE 551
Linear Integrated Circuits

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What You Are Expected To Know

- Basic circuit analysis
  - KVL, KCL, voltage dividers, etc.
  - Basic familiarity with transistors
- Basic signal processing (helpful, not required)
  - Laplace transforms
  - Frequency response
  - Use of MATLAB
- Basic pn junction device physics (helpful, not required)

How To Do Well in EE 551

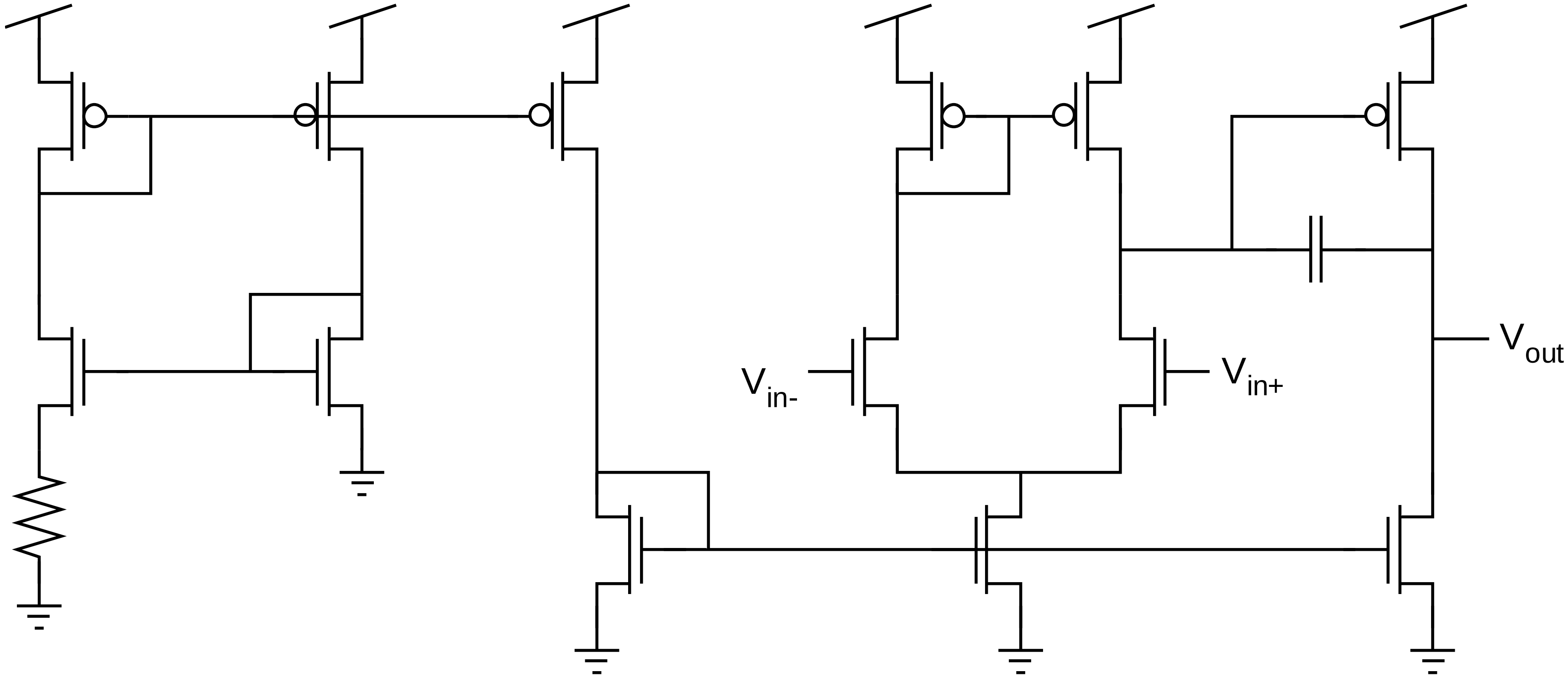
- Come to Class
  - Pay attention
  - Take good notes
  - If I talk about it in class, then it is probably important
  - Do whatever you have to do to stay awake
- Do the homework problems
  - Do them again
  - Do them yet again (These problems are typical of analog IC problems)
  - Hide the solutions when you do them
  - Write out every step
  - Do not assume that if you can follow the solutions you will be able to do the problems at test time
- Start early on the projects
  - Do the individual parts as they are covered in class
  - Do not wait until the last minute
- If you do not understand, then ask questions
  - In class
  - In office hours

Pop Quizzes

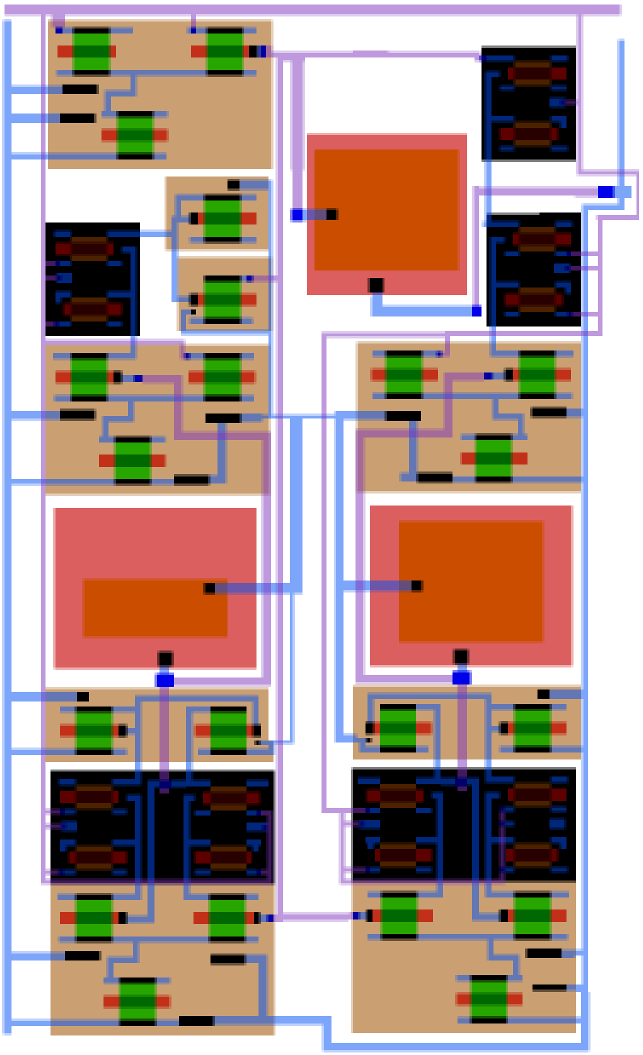
- Extra Credit!
- At least one per class
  - Beginning (from last class)
  - End (from that day's class)
- Short – Generally 2-5 minutes
- We will go over solutions right away

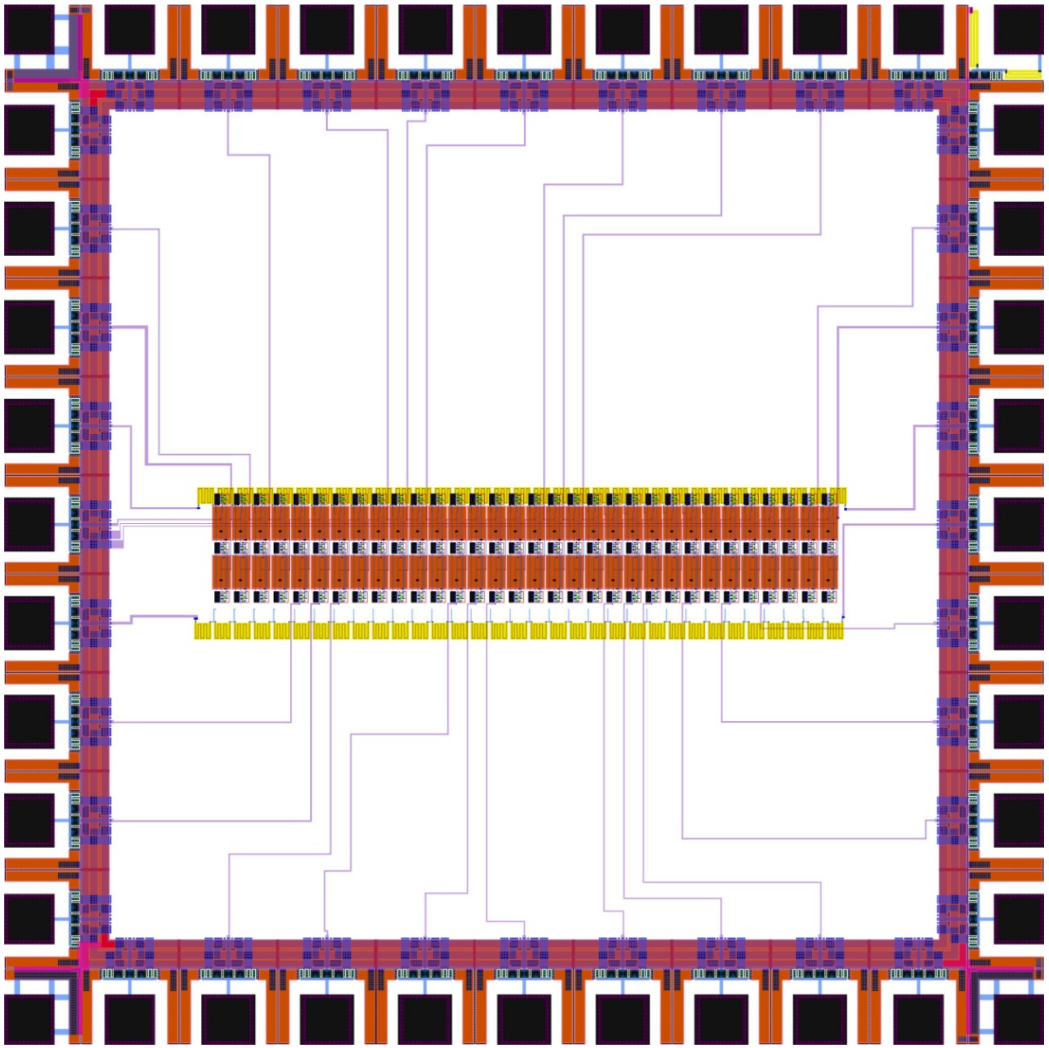
3	Correct
2	Close
1	Attempt (but not close)
0	No Attempt

Analyze and Design



What Design Really Looks Like





WestVirginiaUniversity.

Why Analog?

(Actual Fortune Cookie)

- We have no choice
- Career stability
- More efficient (power, processing time, etc.)
- The best of both worlds = Analog AND Digital
- New advancements = new opportunities

Alexa Accelerator names 9 startups for inaugural Amazon and Techstars program

BY TAYLOR SOPER on July 17, 2017 at 6:24 am

The Alexa Accelerator, a new program that Amazon is running in partnership with Techstars, kicked off its first class on Monday.

Nine startups from across the globe will spend the next three months in Seattle at the new Amazon Alexa Accelerator, which will support early-stage companies that are working on B2C and B2B technologies related to Amazon's popular artificial intelligence and machine learning-powered voice platform.

The companies range from Tinitell, a Swedish-based startup that makes mobile phones for children, to Aspinity, a West Virginia-based startup building ultra-low power processors for IoT devices. Companies from 54 countries applied to the program after Amazon and Techstars went on a 10-city tour.

Here are the nine startups in the accelerator, which wraps up with a Demo Day on October 17.

- **Aspinity**: Ultra-low power processors for IoT devices.
- **Botnik Studios**: Digital tools for self-expression.
- **Novel Effect**: Powering voice interactive entertainment.
- **Play Impossible**: An active gaming system that brings digital action outdoors.
- **Semantica**: Humans and AI working side by side.
- **Sensible Object**: Merging physical and digital and harnessing the power of

Why Analog Could be Important to You

~20% of IC market since 1970

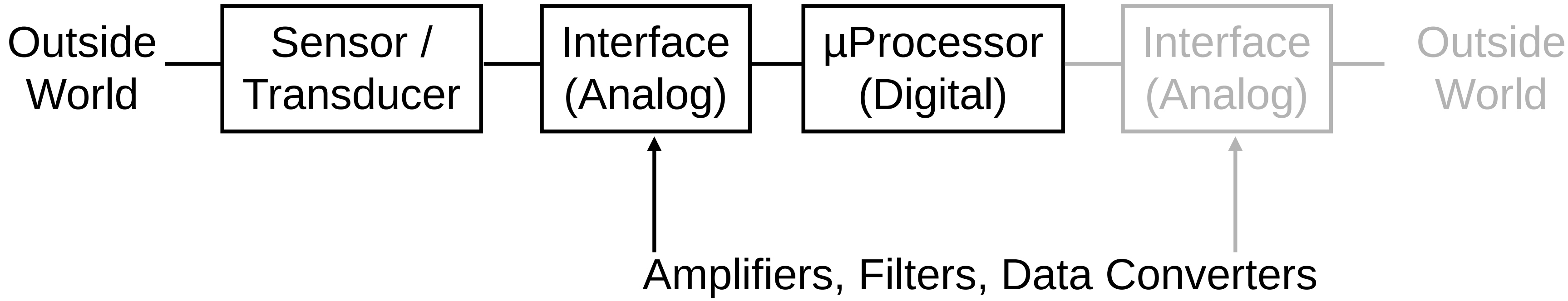
“If you’re a 20- to 30-year-old analog engineer, you’re sitting pretty right now. It’s a buyer’s market for you.”

- Freescale Semiconductor
From IEEE Spectrum

Why This Class Is Important To You

Even if you have no plans of going into analog IC design, you will have a hard time not using analog ICs in your work. Understanding the guts of analog IC design will enable you to better evaluate their performance and choose the right parts.

Why Analog for Linear Systems?



The real world is *analog*, so if we need to interface with it, then we *must* have analog circuitry.

Why Integrated Circuits?

- Cheaper (and easier to mass produce)
- Smaller
- Reduces power
- Keeps everything contained
  - Reduces noise
  - Reduces coupling from the environment
- Need a large number of transistors to perform real-world computations/tasks
- Allows a high density or circuit elements (therefore, VLSI reduces costs)

Difference Between Discrete and IC Design

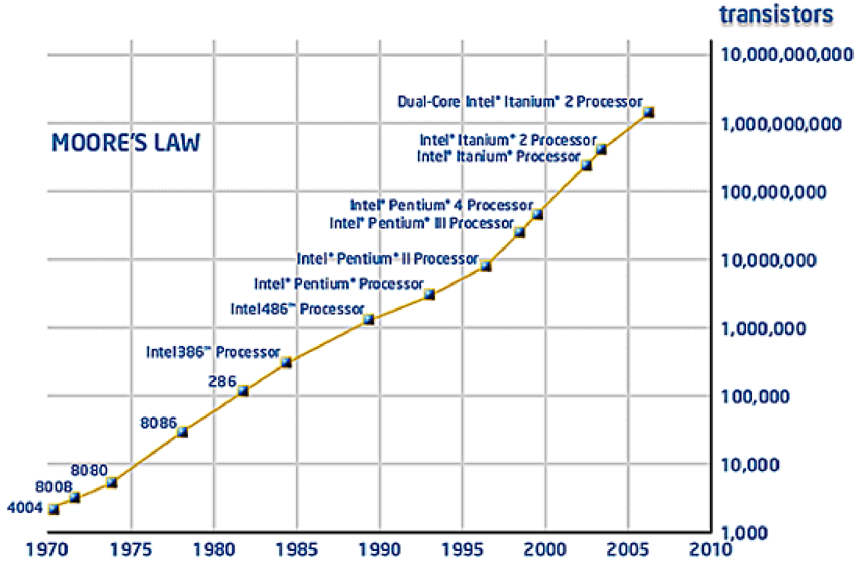
	Analog ICs	Discrete Analog
Device Size and Values	Relatively Small ex. Capacitors 10fF-100pF	Large ex. Capacitors 100pF-100µF
Resistors	Mostly bad Very expensive (large real estate)	Easy to Use Cheap
Inductors	Only feasible for very high frequencies Extremely expensive	Use when needed
Parasitics	Very big concern Seriously alter system performance	Exist, but rarely affect performance (Large size of devices and currents)
Matching	Difficult to deal with Major concern Stuck with whatever was fabricated ex. 50% mismatch is not uncommon	Concern Can more easily match/replace
Power	Efficient (Small currents pA-mA)	Use more power (Large currents >mA)

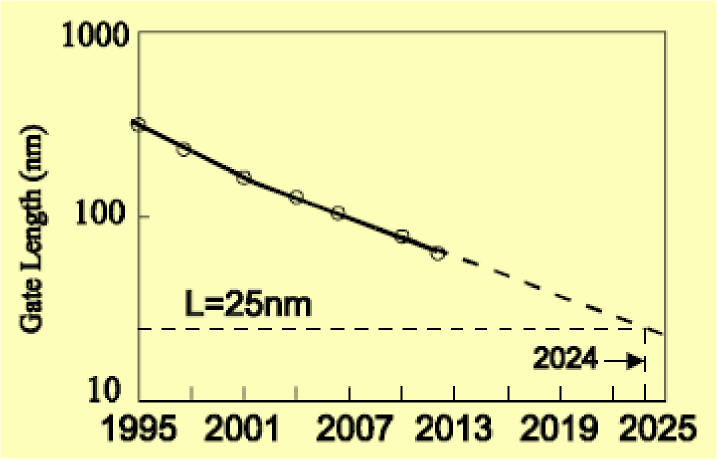
Process Considerations

- What processes are…
  - A specific technology for producing integrated circuits
  - Typically specified by their
    - Type (bipolar, CMOS, or BiCMOS)
    - Minimum device size (length) for CMOS (e.g. 0.5µm, 0.35µm)
    - Various other parameters (e.g. maximum/supply voltage, intended disposition – digital or mixed-signal, etc.)
  - Fabricated by a trusted foundry (e.g. AMI, AMS, TSMC)
- Everything is geared towards a digital process
  - Processes not designed with analog in mind
  - Easiest (best method / most flexible) to design with standard process rules
  - Typically not able to construct many analog circuits in a brand new process

Moore's Law and Its Affect on CMOS Processes

- Moore's Law (1965)
  - The number of transistors on an integrated circuit doubles every (approximately) 18-24 months
- Processes vs. time
  - Introduction of a new process approximately every two years
    - This shrinks the transistors, so more can fit in a given space
    - Minimum transistor length decreases over time
    - Most digital circuits are purely [minimum-sized] transistors
  - Greatly speeds up processing speeds
  - Greatly reduces power consumption
  - Intended to reduce cost, as well (but new processes can be quite expensive)





Effect of Changing Processes

What changing processes mean (for design)

- Supply voltages drop (big difference)
  - e.g. 0.5µm → V_{dd} = 3.3V; 0.18µm → V_{dd} = 1.8V
  - New techniques for reduced operating range
- Device sizes
  - Transistor sizes decrease with every process
  - Capacitors may not
- Short channel effects
  - Traditional MOSFET models are a poor fit to small devices
- Varying design rules from process to process (submicron processes)
  - Must relearn "design rules" for each process
  - Specific rules to make sure nothing breaks

Process Type

Bipolar vs. CMOS

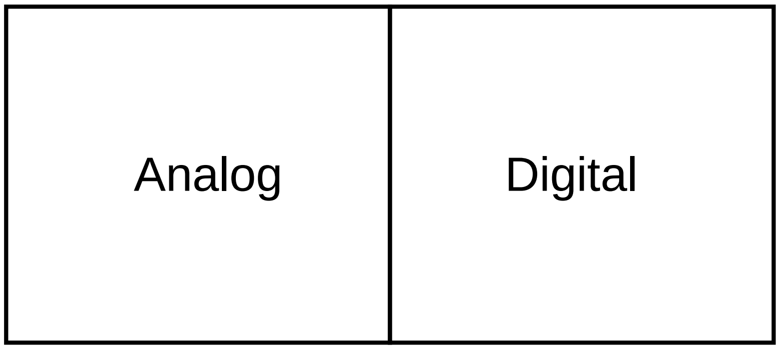
Pros for Bipolar
- Work well for analog
- High gain
- High speed

Pros for CMOS
- Cheap, cheap, cheap!
- Scales nicely with Moore's Law
- Mixed-signal ICs (SOC)

System-On-A-Chip (SOC)

The real reason why CMOS dominates analog ICs – Systems on a chip

Complete Integrated Circuit



Easier, cheaper, and better to do a complete design on a single chip.

Real designs include both analog and digital portions

- Digital Portion
  - Scales nicely with Moore's Law
  - Straightforward design procedures
  - Uses mostly small transistors (can really pack them in) and very few capacitors
- Analog Portion
  - Scaling mostly comes through ingenuity
  - No straightforward/automated design procedures
  - Uses often relatively large transistors and capacitors
  - Consumes a large amount of the chip real estate and design time

To Summarize …

<u>Good Things about Analog IC Design</u>

- Inexpensive
- Compact
- Power Efficient

<u>Not So Good Things about Analog IC Design (not necessarily bad)</u>

- Limited to transistors and capacitors (and sometimes resistors if a very good reason)
- Parasitics and device mismatch are big concerns
- You are stuck with what you built/fabricated (no swapping parts out)

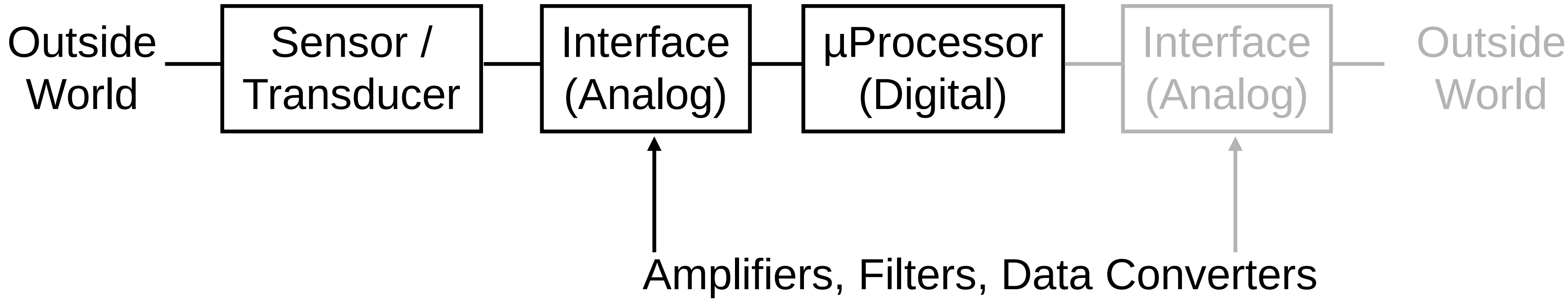
Important Considerations

We will limit our discussion to CMOS technologies

- Only MOSFETs
- Limited use of BJTs

Therefore, we will discuss only silicon processes

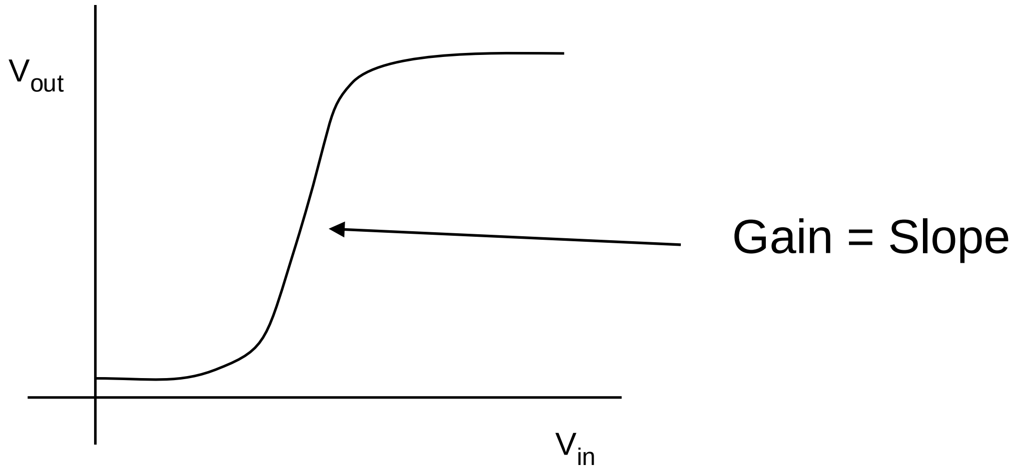
Linear Integrated Circuits



- Circuits and systems are *linear* only over a specific range
- We will constantly talk about
  - Large-signal operation
    - Nonlinear equations
    - DC operating point, bias conditions
  - Small-signal analysis
    - Linear equations
    - Amplification region
- Every circuit must be analyzed with *both* the large- and small-signal analyses

Large-Signal vs. Small-Signal

Typical Amplifier Transfer Function

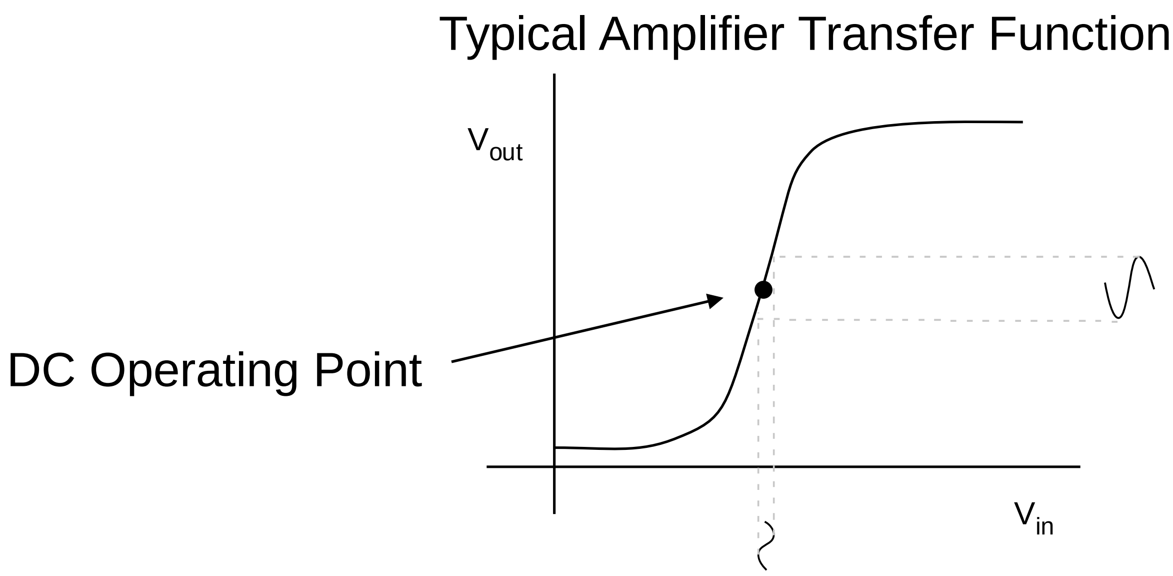


Linear, high-gain region (amplifier)

Nonlinear portions

- Must first do a *large-signal analysis* to get the amplifier into range
  - Bias in the amplification region
  - DC operating point (DC voltages and currents) from the large-signal operation
- Once in the amplification region, assume a *small-signal* input
  - Everything will stay within the linear region / linear range
  - Linear, time-invariant (LTI) analysis applies

Large-Signal vs. Small-Signal



- Large signal (Biases / DC conditions)
  - Moves amplifier into range
  - Amplifier is now ready to perform amplification
- Small signal (AC inputs / outputs)
  - Small sinusoidal inputs makes bigger sinusoidal outputs

Creating Linear Blocks

What are the characteristics of the ideal blocks we need in order to make linear circuits and systems?

Input / Output Relationships

Device	Z_{in}	Z_{out}	Reason
Independent Voltage Source	-	0Ω	0V output → no voltage drop; no resistance 0V output → replace with a short circuit
Independent Current Source	-	∞Ω	0A output → no current flows; infinite resistance 0A output → replace with an open circuit
Voltmeter	∞Ω	-	Minimizes loading effects No resistance in parallel
Ammeter	0Ω	-	Minimizes loading effects No resistance in series
Voltage-Controlled Voltage Source (VCVS)	∞Ω	0Ω	
Voltage-Controlled Current Source (VCCS)	∞Ω	∞Ω	
Current-Controlled Voltage Source (CCVS)	0Ω	0Ω	
Current-Controlled Current Source (CCCS)	0Ω	∞Ω	

Input / Output Impedances

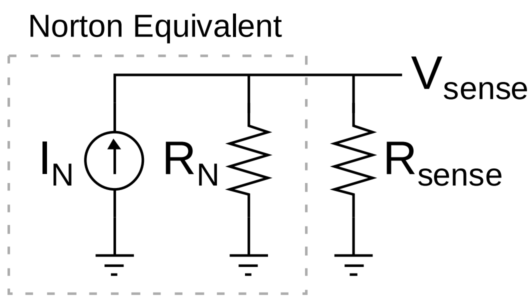
Lessons learned

- Inputs
  - Voltage sensing → Want high input impedance
  - Current sensing → Want low input impedance
- Outputs
  - Voltage output → Want low output impedance
  - Current output → Want high output impedance

Input Impedances

- Inputs
  - Voltage sensing → Desire high input impedance
  - Current sensing → Desire low input impedance

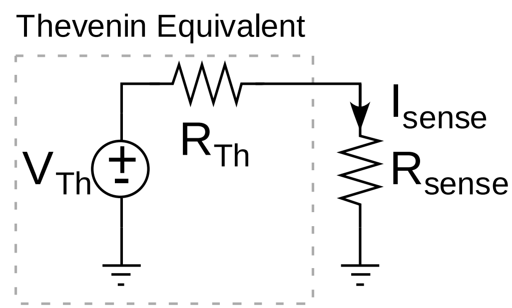
Voltage Sensing



$$V_{sense} = I_N R_N \,\|\, R_{sense}$$

$$V_{sense} \to I_N R_N \quad as \quad R_{sense} \to \infty$$

Current Sensing



$$I_{sense} = V_{Th} / \left(R_{Th} + R_{sense}\right)$$

$$I_{sense} \approx V_{Th} / R_{Th} \quad as \quad R_{sense} \to 0$$

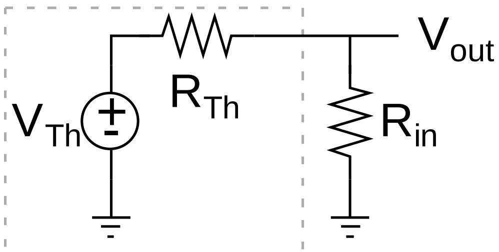
Norton and Thevenin equivalents represent the circuit we are sensing

Output Impedances

- Outputs
  - Voltage outputs → Desire low output impedance
  - Current outputs → Desire high output impedance

<u>Voltage Output</u>

Thevenin Equivalent

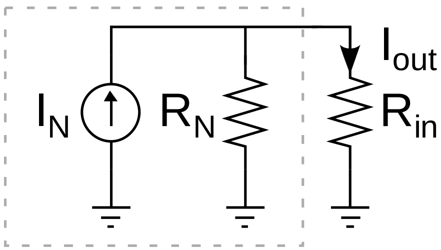


$$V_{out} = V_{Th} \frac{R_{in}}{R_{in} + R_{Th}}$$

$$V_{out} \approx V_{Th} \quad as \quad R_{Th} \to 0$$

<u>Current Output</u>

Norton Equivalent

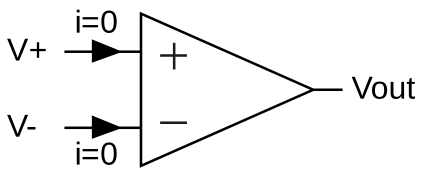


$$I_{out} = I_N \frac{R_N}{R_N + R_{in}}$$

$$I_{out} \approx I_N \quad as \quad R_N \to \infty$$

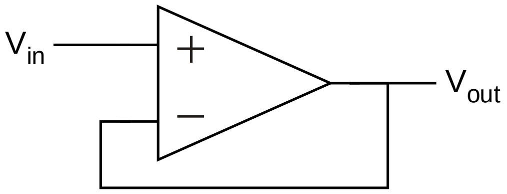
Norton and Thevenin equivalents represent the circuit we are sensing.
R_{in} represents the input impedance of the subsequent stage.

Ideal Operational Amplifier



Ideal Opamp Model

- Zero input current
  - Infinite input impedance
- Zero output impedance
- Vout = $A(V^+ - V^-)$
- Gain is infinite
- If negative feedback, $V^+ = V^-$

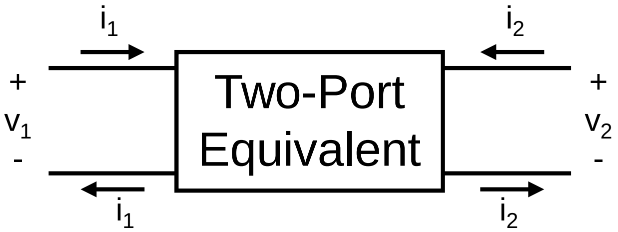


Example – Voltage Buffer

- Infinite input impedance
  - No loading on previous circuit
- Zero output impedance
  - No loading on following circuit
- Closed-loop gain = 1
  - Looks like a VCVS
- Completely "buffers" a voltage
  - Passes V from one circuit to another with no loading effects

Two-Port Models

- Most important parameter in an amplifier is <u>gain</u>
- Must determine how loading affects gain
- Two-port models simplifies this process



- One parameter at each port is independent
- The other port is dependent on both the first port and the two-port network

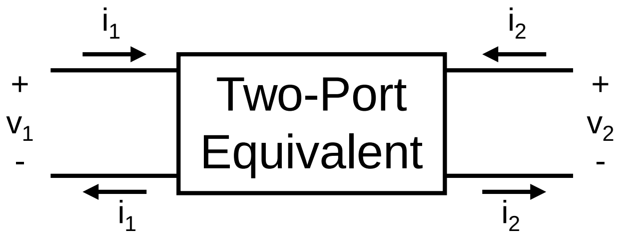
<u>Admittance Parameter Equations</u>

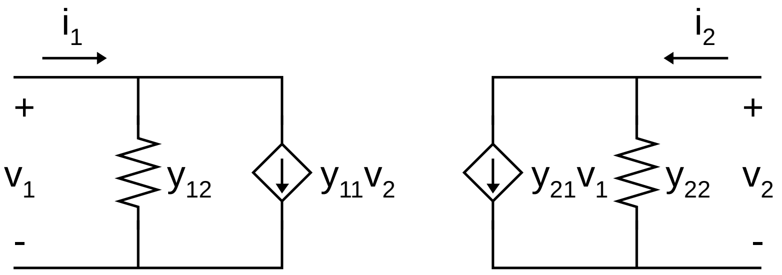
- Voltage is independent
- Current is dependent
- (Typical of most "voltage-mode" circuits)

$$i_1 = y_{11}v_1 + y_{12}v_2$$

$$i_2 = y_{21}v_1 + y_{22}v_2$$

Two-Port Model Admittance Parameters





$$y_{11} = \left.\frac{i_1}{v_1}\right|_{v_2=0}$$ Input admittance
Output short circuited

$$y_{12} = \left.\frac{i_1}{v_2}\right|_{v_1=0}$$ Reverse transconductance
Input short circuited

$$y_{21} = \left.\frac{i_2}{v_1}\right|_{v_2=0}$$ Forward transconductance
Output short circuited

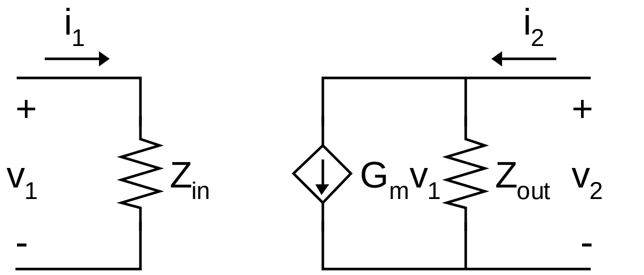
$$y_{22} = \left.\frac{i_2}{v_2}\right|_{v_1=0}$$ Output admittance
Input short circuited

$$i_1 = y_{11}v_1 + y_{12}v_2$$
$$i_2 = y_{21}v_1 + y_{22}v_2$$

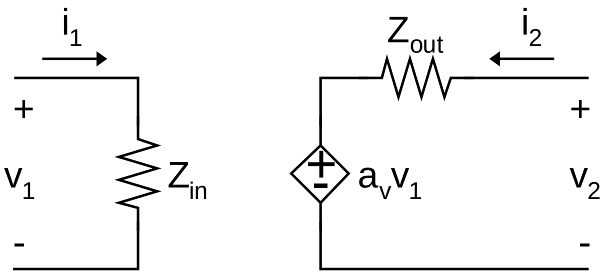
Unilateral Two-Port Model

- Typically, there is no feedback → $y_{12} = 0$
- y_{21} is referred to as "transconductance" (G_m)
- Convert admittances into impedances
  - Z_{in} = input impedance
  - Z_{out} = output impedance

Unilateral Two-Port Model (Norton Output)



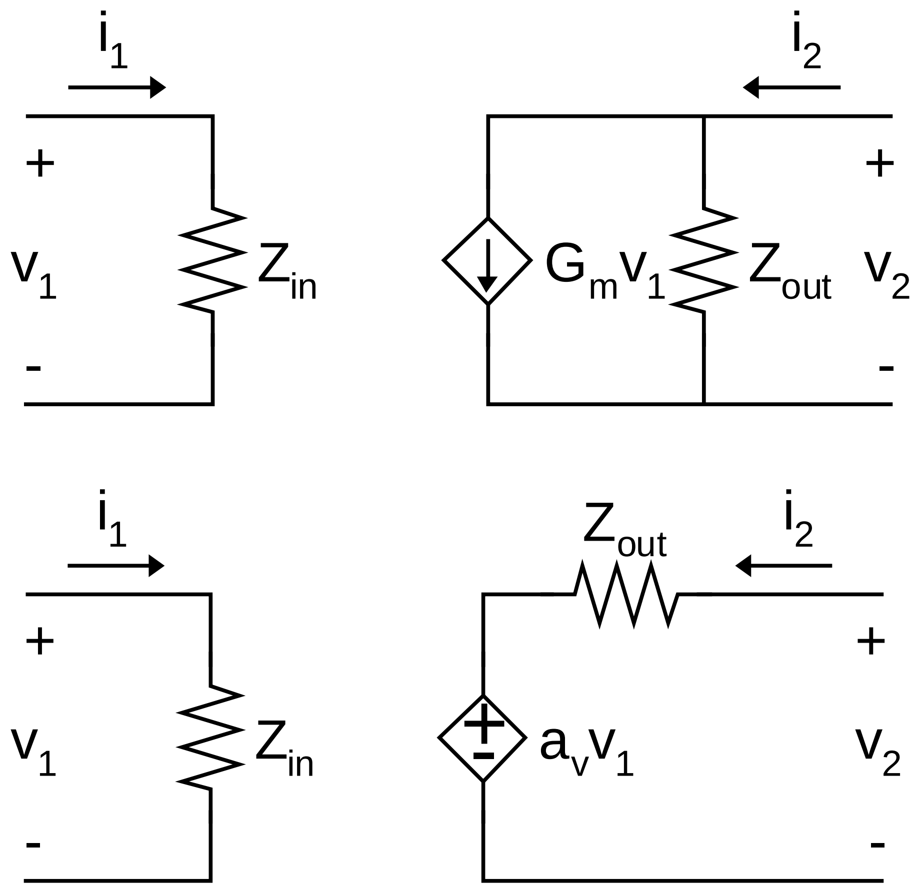
Unilateral Two-Port Model (Thevenin Output)



Gain

$$a_v = \left.\frac{v_2}{v_1}\right|_{i_2=0} = -G_m Z_{out}$$

Two-Port Model Summary



$$A_v = \left.\frac{v_2}{v_1}\right|_{i_2=0} = \left.\frac{v_{out}}{v_{in}}\right|_{i_{out}=0} = -G_m Z_{out}$$

$$Z_{in} = \frac{v_1}{i_1} = \frac{v_{in}}{i_{in}}$$

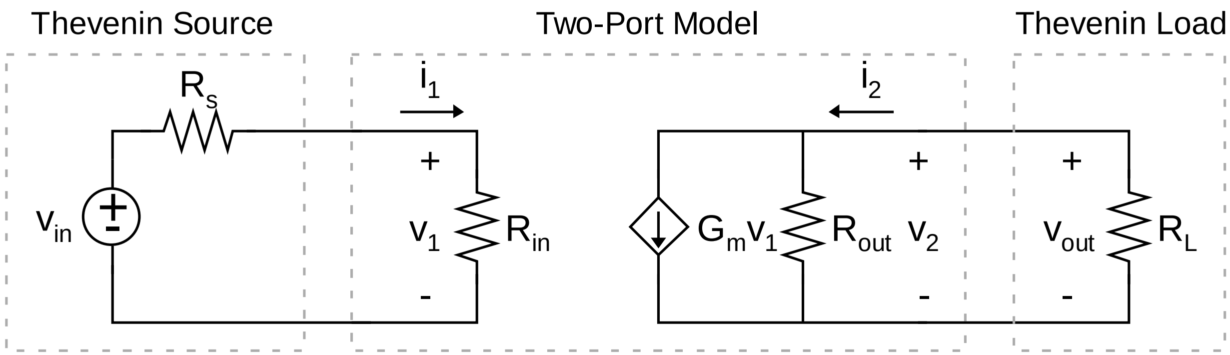
$$Z_{out} = \left.\frac{v_2}{i_2}\right|_{v_1=0} = \left.\frac{v_{out}}{i_{out}}\right|_{v_{in}=0}$$

$$G_m = \left.\frac{i_2}{v_1}\right|_{v_2=0} = \left.\frac{i_{out}}{v_{in}}\right|_{v_{out}=0}$$

For voltage-in voltage-out circuits, we desire

- $Z_{in} = \infty\Omega$
- $Z_{out} = 0\Omega$

Connecting a Two-Port Network to a Circuit



$$a_v = \frac{v_{out}}{v_{in}} = \frac{v_1}{v_{in}} \cdot \frac{v_{out}}{v_1}$$

$$= \left(\frac{v_{in}}{v_{in}} \frac{R_{in}}{R_{in} + R_s} \right) \left(-\frac{G_m v_1}{v_1} R_{out} \| R_L \right)$$

$$= \left(\frac{R_{in}}{R_{in} + R_s} \right) \left(-G_m \left(R_{out} \| R_L \right) \right)$$

Assuming R_s and R_L are fixed

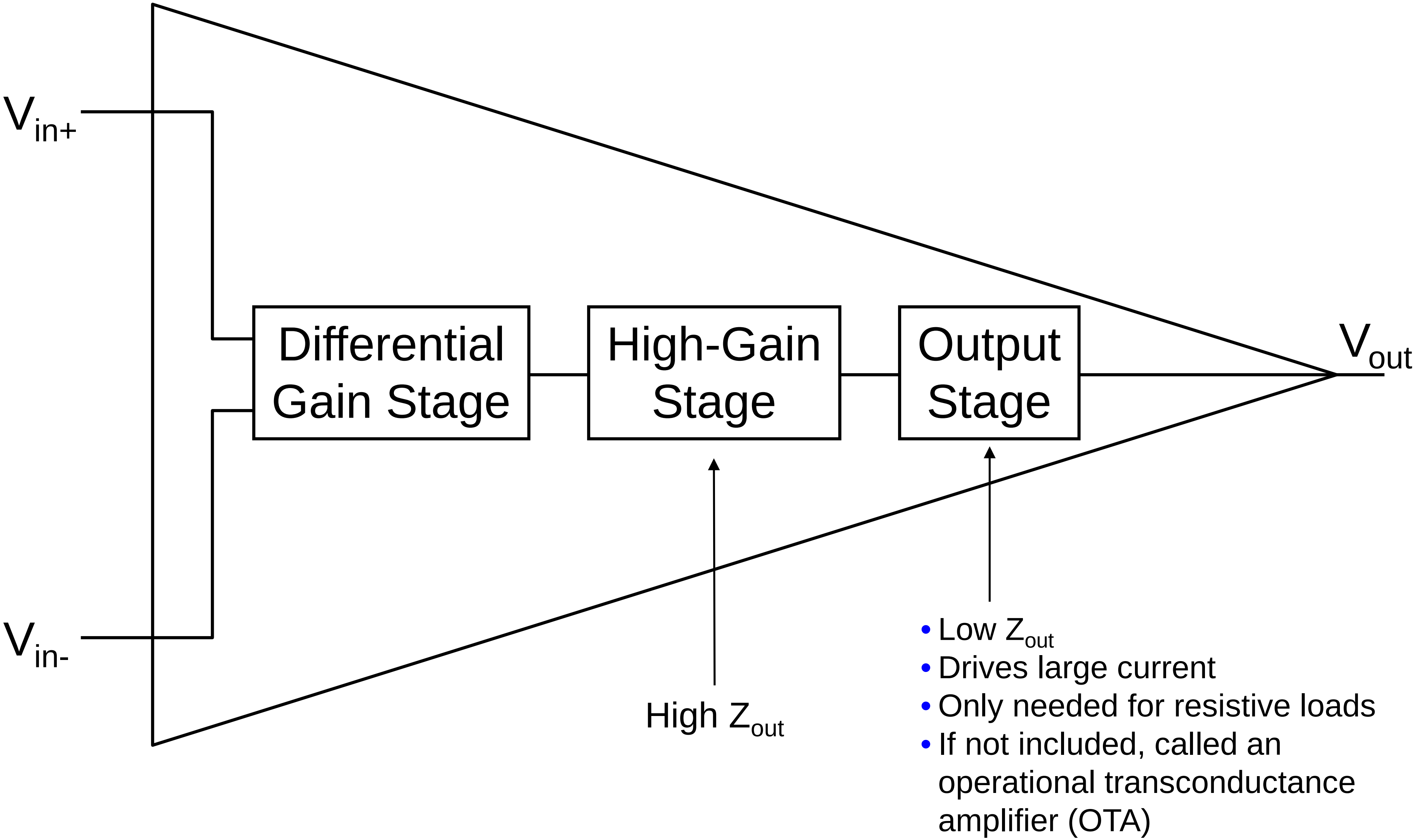
- $a_v \uparrow$ as $R_{in} \uparrow$
- $a_v \uparrow$ as $R_{out} \uparrow$

Therefore, need high output impedance for high gain

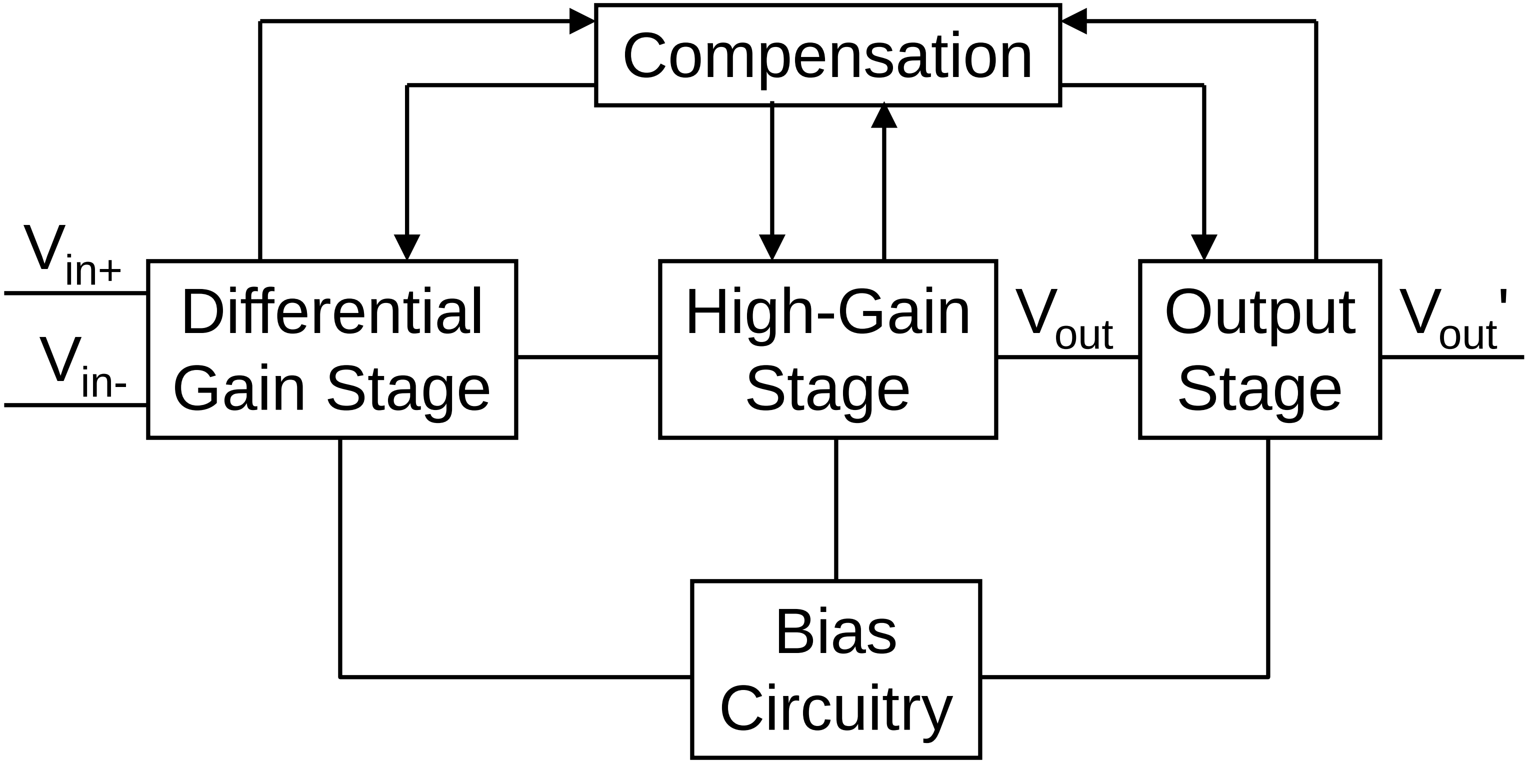
$$a_v = -G_m Z_{out}$$

(But want low output impedance for opamps to reduce loading)

Typical Opamp Design



Complete Opamp Design



One size does **not** fit all.

The Approach for the Semester…

- Gain appreciation of devices from physics
- Build models of basic devices
- Create small circuits
- Use small circuits to build large circuits
- Focus on opamp design and supporting circuitry