# ELECTRIC CIRCUITS
# ECSE-2010

Lecture 6.1

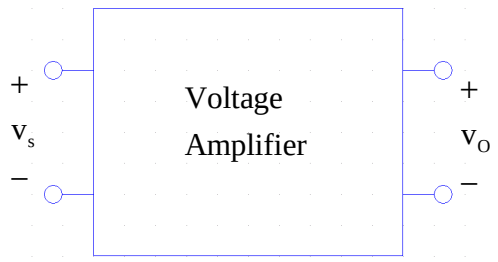
Rensselaer

## LECTURE 6.1 AGENDA

- Amplifier circuit model
- Ideal Operational Amplifiers (Op Amps)



## VOLTAGE AMPLIFIER

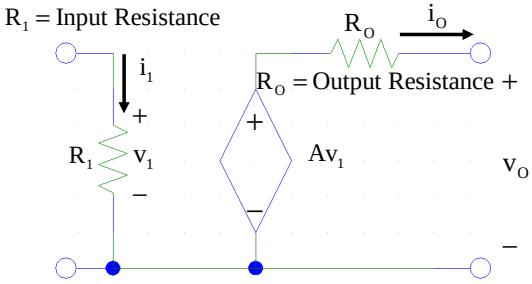



Want $v_O \approx A\, v_s$; $A$ = Voltage Gain



## AMPLIFIER CIRCUIT MODEL

$R_I$ = Input Resistance




$v_O = Av_1 - i_O R_O$ For small $R_O$; $v_O \approx Av_1$

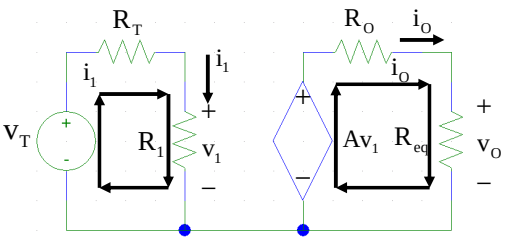


## AMPLIFIER CIRCUIT

- Add source network at input:
  - Model with Thevenin Equivalent circuit
  - $v_T$ in series with $R_T$
- Add load network at output:
  - Model with $R_{eq}$



## AMPLIFIER CIRCUIT




$$v_1 = \left(\frac{R_1}{R_1 + R_T}\right) v_T \qquad v_O = \left(\frac{R_{eq}}{R_O + R_{eq}}\right) Av_1$$

# ELECTRIC CIRCUITS
# ECSE-2010

Lecture 6.2

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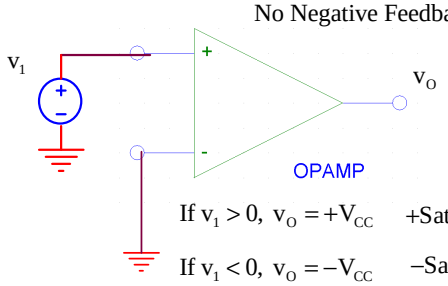
## LECTURE 6.2 AGENDA

- Op Amps
  - Without negative feedback
  - With negative feedback (Circuits)
- OP Amp CAD Interactive Learning Module (ILM)



## ZERO CROSSING DETECTOR

No Negative Feedback



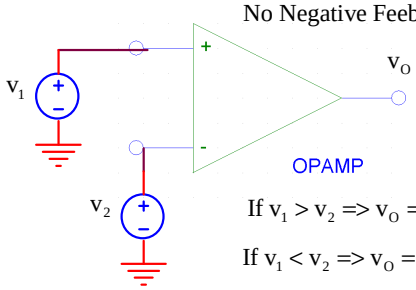

If $v_1 > 0$, $v_O = +V_{CC}$ +Saturation

If $v_1 < 0$, $v_O = -V_{CC}$ −Saturation



## COMPARATOR

No Negative Feeback




If $v_1 > v_2 \Rightarrow v_O = +V_{CC}$

If $v_1 < v_2 \Rightarrow v_O = -V_{CC}$

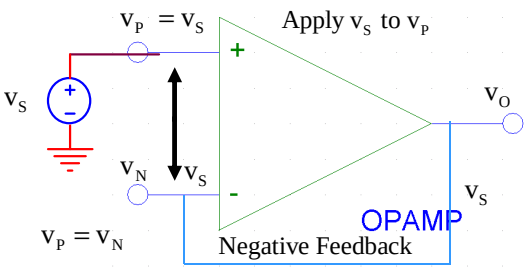


## OP AMP CIRCUITS

- For most Op Amp circuits, we add negative feedback:
  - Circuit connection between $v_O$ and $v_N$
  - Helps to keep Op Amp in Linear Range
  - This will help keep $v_P = v_N$
  - Output, $v_O = A(v_p - v_N)$, will be finite, as long as its magnitude is less than $V_{CC}$
  - Output can never be greater than $\pm V_{CC}$



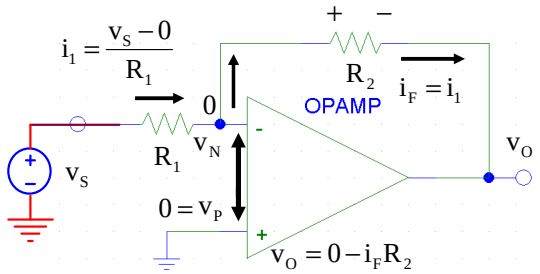
## VOLTAGE FOLLOWER




Draws No Current from Source $v_O = v_S$

Buffer, or Isolation Amplifier

## INVERTING AMPLIFIER




$$i_1 = \frac{v_S - 0}{R_1}$$

$$v_O = 0 - i_F R_2$$

$$\frac{v_O}{v_S} = -\frac{R_2}{R_1} \qquad = -\frac{v_S}{R_1} R_2$$

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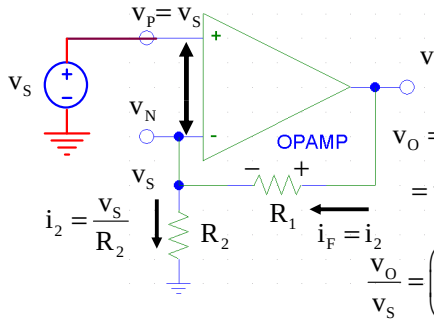
## NON-INVERTING AMPLIFIER



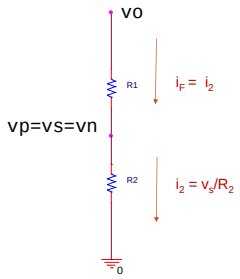

$$i_2 = \frac{v_S}{R_2}$$

$$v_O = v_S + i_F R_1 = v_S + \frac{v_S}{R_2} R_1$$

$$\frac{v_O}{v_S} = \left(1 + \frac{R_1}{R_2}\right)$$

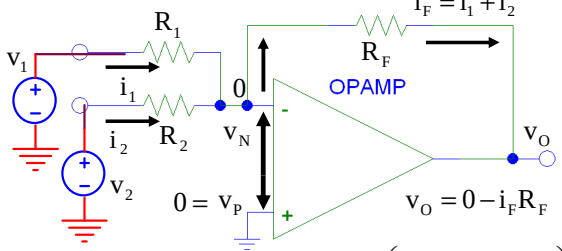


## NON-INVERTING AMPLIFIER





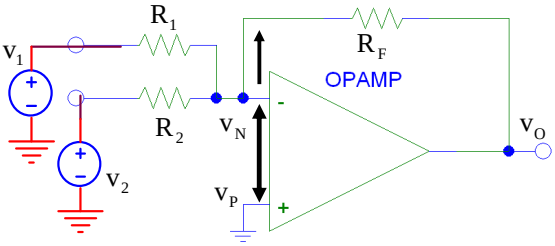

## SUMMER




$$i_1 = \frac{v_1 - 0}{R_1} \qquad i_2 = \frac{v_2 - 0}{R_2} \qquad v_O = -\left(\frac{R_F}{R_1} v_1 + \frac{R_F}{R_2} v_2\right)$$



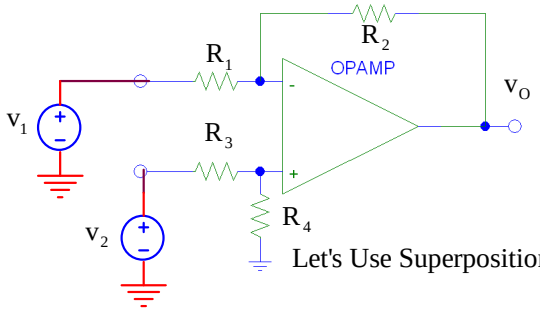
## SUMMING AMPLIFIER




$$v_O = -\left(\frac{R_F}{R_1} v_1 + \frac{R_F}{R_2} v_2\right)$$



## DIFFERENTIAL AMP




Let's Use Superposition

## OP AMP CAD ILM

- Go to WebCT Site, Click on Modules
- Click on Op Amp CAD Module
- Move top slider to choose type of circuit
- Inverting, Non-Inverting Amplifier
- Differential Amplifier, Comparator
- Integrator, Differentiator (Later in Course)

http://www.academy.rpi.edu/projects/ccli/module_display.php?ModulesID=11



## OP AMP CAD ILM

- Move slider to Inverting Amplifier
- Change $R_F$ from 1k to 4k
- => Observe Clipping
- Change $R_F$ from 4k to 10k
- => Observe $\approx$ Square Wave
- Change f from 1 kHz to 5 kHz



## OP AMP CAD MODULE

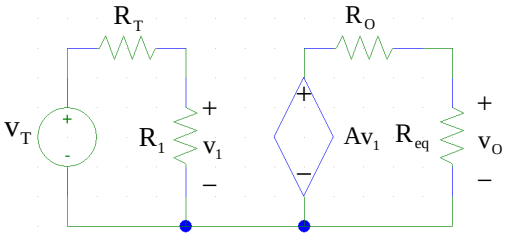
- Move slider to Non-Inverting Amplifier
- Change $V_{DC}$ to $+5,\ -5$ V
- => Observe Clipping
- Change f from 1 kHz to 5 kHz
- Same effect as changing Gain



## OP AMP CAD MODULE

- Move slider to Differential Amplifier
- Change $R_F,\ R_1,\ R_2,\ f$
- Observe what happens
- Will Discuss Differential Amplifiers More Next Class

## AMPLIFIER CIRCUIT

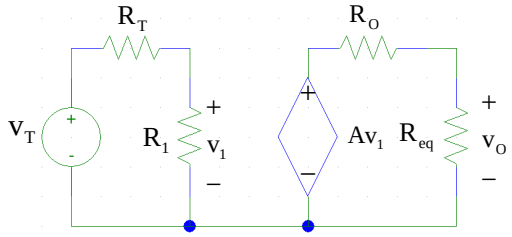



$$v_1 = \left(\frac{R_1}{R_1 + R_T}\right) v_T \quad \text{If: } R_1 >> R_T \quad v_1 \approx v_T$$

Want Input Resistance  Large



## AMPLIFIER CIRCUIT

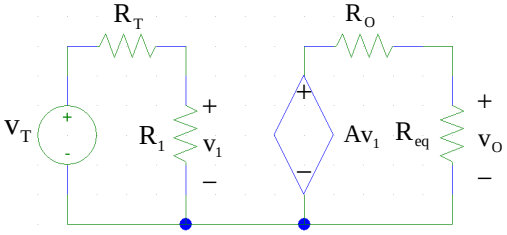



$$v_O = \left(\frac{R_{eq}}{R_O + R_{eq}}\right) Av_1 \quad \text{If: } R_{eq} >> R_O \quad v_O \approx Av_1$$

Want Output Resistance Small



## AMPLIFIER CIRCUIT




If: $R_1 >> R_T$, $R_{eq} >> R_O$ => $\frac{v_O}{v_T}$ = Voltage Gain ≈ A

Design Challenge



## OPERATIONAL AMPLIFIERS

- An Operational Amplifier is a *High Gain Voltage Amplifier that can be used to perform* ***Mathematical Operations:***
  - Addition and Subtraction
  - Differentiation and Integration
  - Other Functions as Well
- Op Amps are the building blocks for many, many electronic circuits



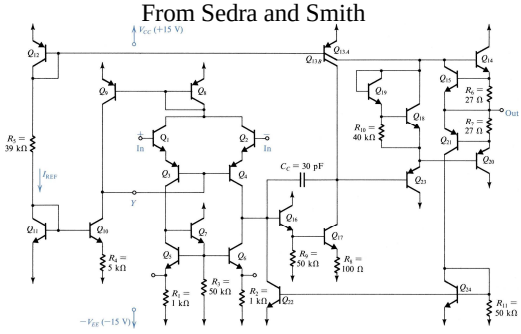
## OPERATIONAL AMPLIFIERS

- Op Amps have existed since 1947:
  - First made with vacuum tubes
  - Then with discrete transistors
  - Now with Integrated Circuits
- Op Amps are complex arrays of transistors, diodes, resistors and capacitors – All on a chip:
  - But can be modeled quite simply



## TYPICAL 741 OP AMP CIRCUIT

From Sedra and Smith

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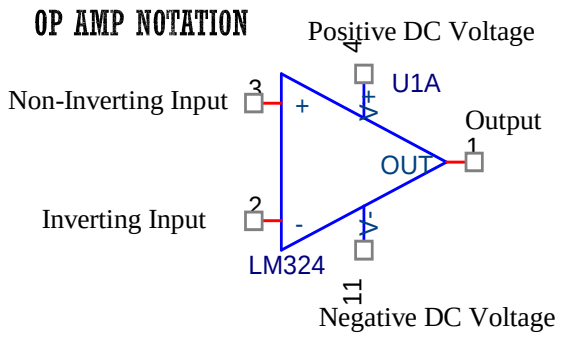
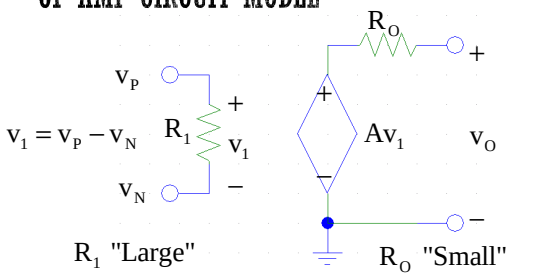
## OP AMP NOTATION






## OP AMP CIRCUIT MODEL




$R_1$ "Large"

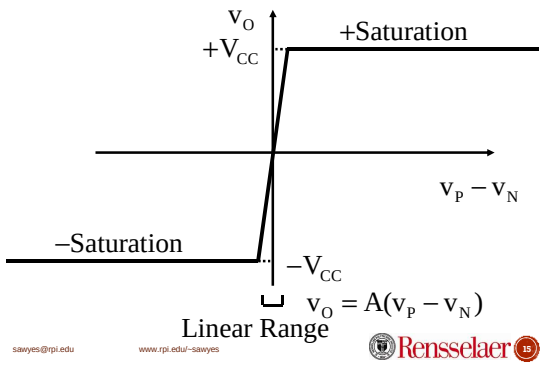
$10^6 \le R_1 \le 10^{12}\ \Omega$

$R_O$ "Small"

$10 \le R_O \le 100\ \Omega$

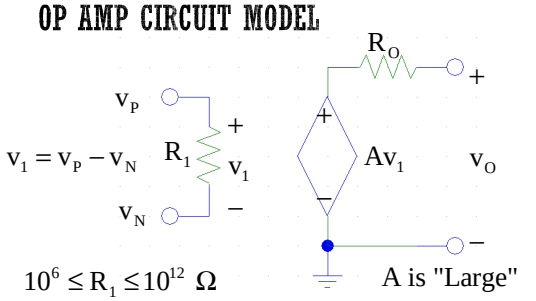


## TRANSFER CHARACTERISTIC






## OP AMP CIRCUIT MODEL




$10^6 \le R_1 \le 10^{12}\ \Omega$

$10 \le R_O \le 100\ \Omega$

A is "Large"

$10^5 \le A \le 10^8$



## IDEAL OP AMP

Model for Real Op Amp

Ideal Op Amp has:

Input Resistance $= R_1 \to \infty\ \Omega$

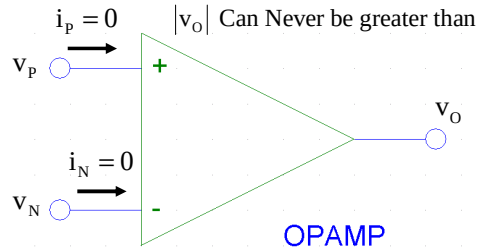
Output Resistance $= R_O \to 0\ \Omega$

Gain $= A \to \infty$



## IDEAL OP AMP

$|v_O|$ Can Never be greater than $|V_{CC}|$

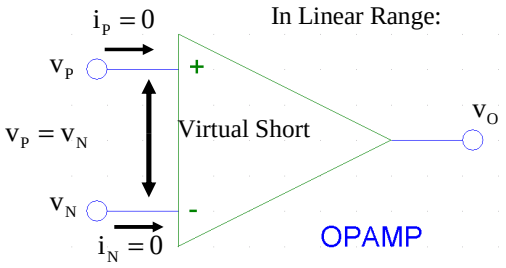



Since $R_1 \to \infty$, Ideal Op Amp Draws No Current!

Since $A \to \infty$, $v_P = v_N$ in Linear Range

# IDEAL OP AMP

In Linear Range:




Ideal Op Amp has a Virtual Short at Input

$$v_P = v_N;\ i_P = i_N = 0$$