# EECS 42 Introduction to Electronics for Computer Science

Andrew R. Neureuther

## Lecture # 14 Op-Amp Circuits and Comparators 4.3-4.4 (light on non-ideal)

A) Cascade Op-Amps
B) Integration/Differentiation Op-Amps
C) I vs. V of Op-Amps – Source Limits
D) Comparator Circuits
E) D to A Converters

**http://inst.EECS.Berkeley.EDU/~ee42/**





## Game Plan 03/19/03

**Monday 03/17/04**

- ❑ Monday: Circuit analysis with dependent sources (4.1-4.2)

**Wednesday 03/19/03:**

- ❑ Comparators and op-amps (Comparator handout)

**Next (10th) Week: After Spring Recess**

- ❑ Monday: 3/31/03 Logic with State Dependent Device 593-595, 604-605
- ❑ Wednesday: 4/02/03 Logic Static: Voltage Transfer Characteristic 606, Handout

**Problem set #8: Half-Set - out Monday 3/17 and due at 2:30 4/02 in box in 240 Cory – input/output impedance, comparators**

## NEGATIVE FEEDBACK

Familiar examples of negative feedback:

Thermostat controlling room temperature
Driver controlling direction of automobile
Photochromic lenses in eyeglasses

Fundamentally pushes toward stability

Familiar examples of positive feedback:

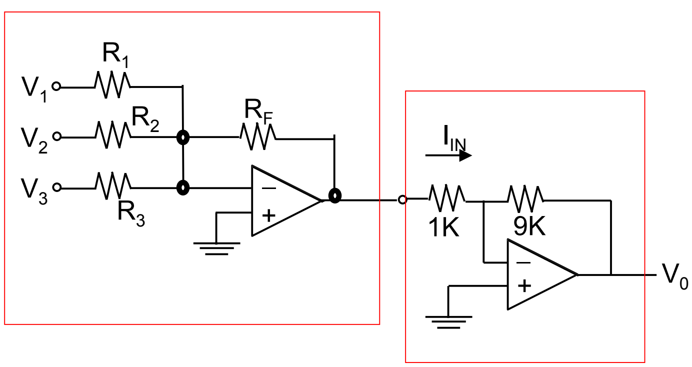
Microphone "squawk" in room sound system
Mechanical bi-stability in light switches
Thermonuclear reaction in H-bomb

Fundamentally pushes toward instability or bi-stability





## CASCADE OP-AMP CIRCUITS




**How do you get started on finding $V_O$?**

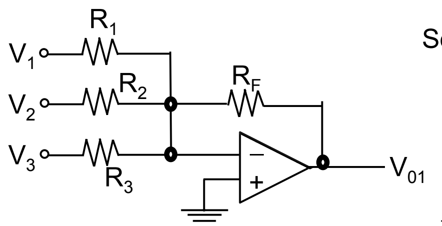
**Hint: Identify Stages**

**Hint: $I_{IN}$ does not affect $V_{O1}$**

See the further examples of op-amp circuits in the reader

## CASCADE OP-AMP SOLUTION

### FIRST STAGE IS "SUMMING JUNCTION" AMPLIFIER



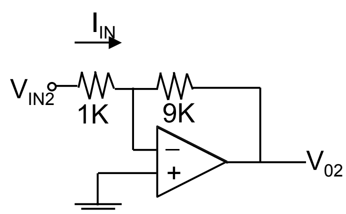

Solution:

$$i_{IN} \cong 0 \text{ and } V_{(-)} \cong V_{+} = 0$$

$$\text{KCL}: \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \frac{V_0}{R_F} = 0$$

$$\Rightarrow V_{01} = -\frac{R_F}{R_1}V_1 - \frac{R_F}{R_2}V_2 - \frac{R_F}{R_3}V_3$$

### SECOND STAGE IS "INVERTING" AMPLIFIER




$$V_{02} \cong \frac{-R_2}{R_1} V_{IN2}$$



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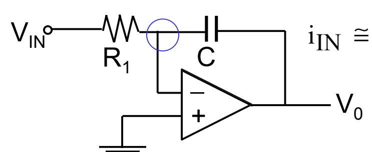
## INTEGRATING OP-AMP




$$i_{IN} \cong 0 \text{ and } V_{(-)} \cong V_{+} = 0$$

**How do you get started on finding $V_O$?**

**Hint:** $i_{IN} \cong 0 \text{ and } V_{(-)} \cong V_{+} = 0$

**Hint: KCL at $V_-$ node with $I_{IN-} = 0$**

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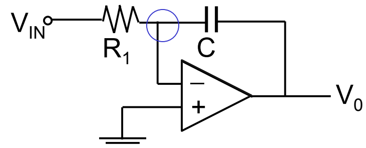
## INTEGRATING OP-AMP




$$\frac{0 - V_{IN}}{R_1} + C\frac{\partial\left(0 \;\; - V_O\right)}{\partial t} = 0$$

**Integrate from $t_0$ to t to get $V_O(t)$**

$$V_O(t) = \frac{-1}{R_1 C}\int_{t_0}^{t} V_{IN}(t)\,dt'$$



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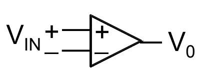
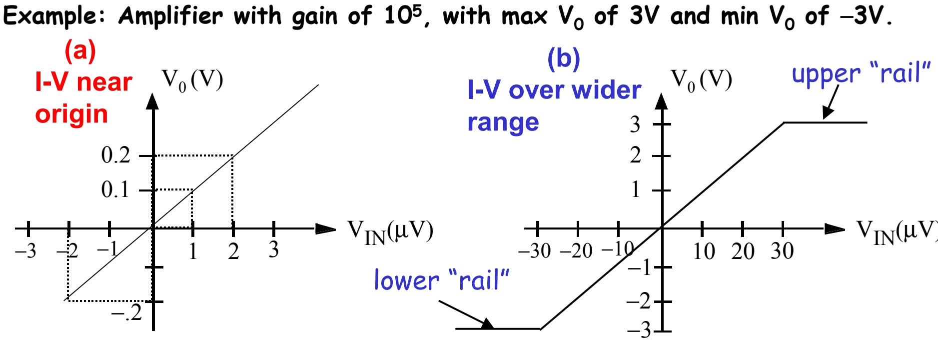
## OP-AMP I-V CHARACTERISTICS WITH RAILS



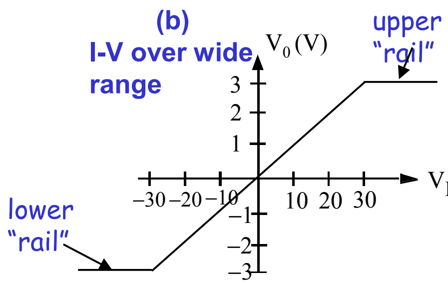

- Circuit model (ideal op-amp) gives the essential linear part
- But $V_0$ cannot rise above some physical voltage related to the positive power supply $V_{CC}$ (" upper rail") $V_0 < V_{+RAIL}$
- And $V_0$ cannot go below most negative power supply, $V_{EE}$ i.e., limited by lower "rail" $V_0 > V_{-RAIL}$

**Example: Amplifier with gain of $10^5$, with max $V_0$ of 3V and min $V_0$ of –3V.**

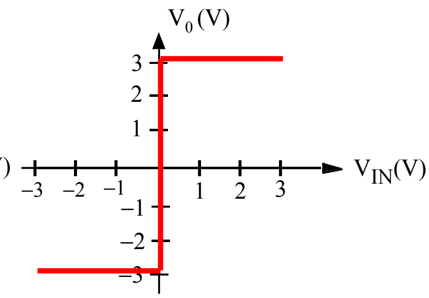


## OP-AMP I-V CHARACTERISTICS WITH RAILS (cont.)

**Example: Amplifier with gain of $10^5$, with upper rail of 3V and lower rail of –3V. We plot the $V_0$ vs $V_{IN}$ characteristics on two different scales**



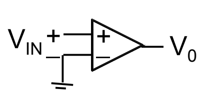

(c)
Same $V_0$ vs $V_{IN}$ over even wider range



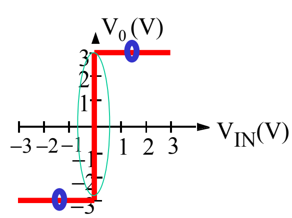





## SIMPLE A/D CONVERTER




I-V with equal X and Y axes

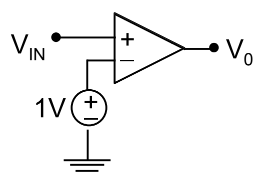


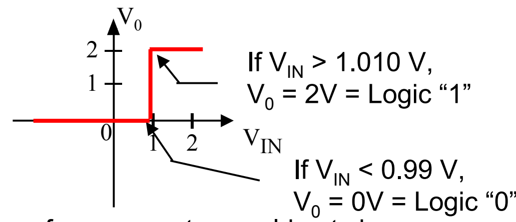

Note:

- (a) displays linear amplifier behavior ($|V_{IN}| < 30$ μV) and stops at rails
- (b) shows comparator decision function (1 bit A/D converter centered at $V_{IN}$ = 0) where lower rail = logic "0" and upper rail = logic "1"

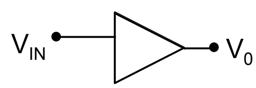
## OP-AMP USE AS COMPARATOR (A/D) MODE

Simple comparator with threshold at 1V. Design lower rail at 0V and upper rail at 2V (logic "1"). A = large (e.g. $10^2$ to$10^5$ )




NOTE: The actual diagram of a comparator would not show an amplifier with "offset" power supply as above. It would be a simple triangle, perhaps with the threshold level (here 1V) specified.

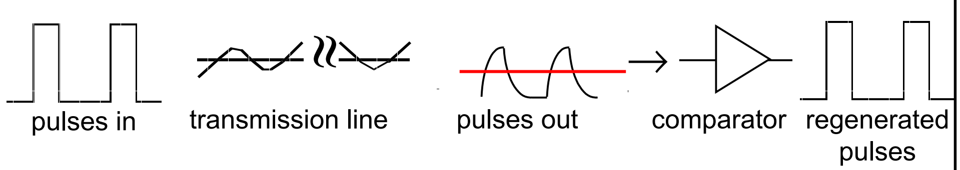



Comparator



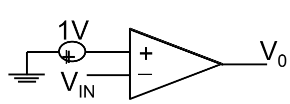


## ONE-BIT A/D CONVERSION
## REQUIRED IN DIGITAL SYSTEMS




As we saw, we set comparator threshold at a suitable value (e.g., halfway between rails) and comparator output goes to +rail if $V_{IN} > V_{THRESHOLD}$ and to –rail if $V_{IN} < V_{THRESHOLD}$.

**What would this circuit do?**




The inverse pulse shaped function is generated by applying the input voltage to V- and setting V+ to the threshold voltage.

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## D/A CONVERSION

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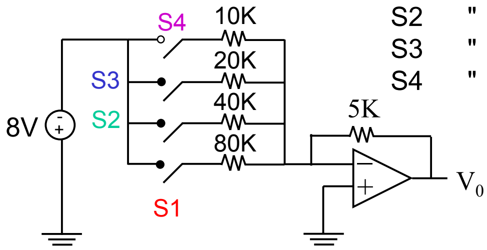
Example: Digital representation of sound to analog (so you can hear it!) → D/A conversion

The summing junction op-amp provides a simple means of D/A conversion via **weighted-adder D/A converter**

S1 closed if LSB =1
S2 " if next bit = 1
S3 " if " " = 1
S4 " if MSB = 1




4-Bit D/A

Another way (not shown) is to sum **charges** instead of current with capacitor networks

| Binary number | Analog output (volts) |
|---|---|
| 0 0 0 0 | 0 |
| 0 0 0 1 | .5 |
| 0 0 1 0 | 1 |
| 0 0 1 1 | 1.5 |
| 0 1 0 0 | 2 |
| 0 1 0 1 | 2.5 |
| 0 1 1 0 | 3 |
| 0 1 1 1 | 3.5 |
| 1 0 0 0 | 4 |
| 1 0 0 1 | 4.5 |
| 1 0 1 0 | 5 |
| 1 0 1 1 | 5.5 |
| 1 1 0 0 | 6 |
| 1 1 0 1 | 6.5 |
| 1 1 1 0 | 7 |
| 1 1 1 1 | 7.5 |

MSB LSB



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## CHARACTERISTIC OF A 4-BIT DAC