V-code: ???

The Operational Amplifier Abstraction

Lecture 17
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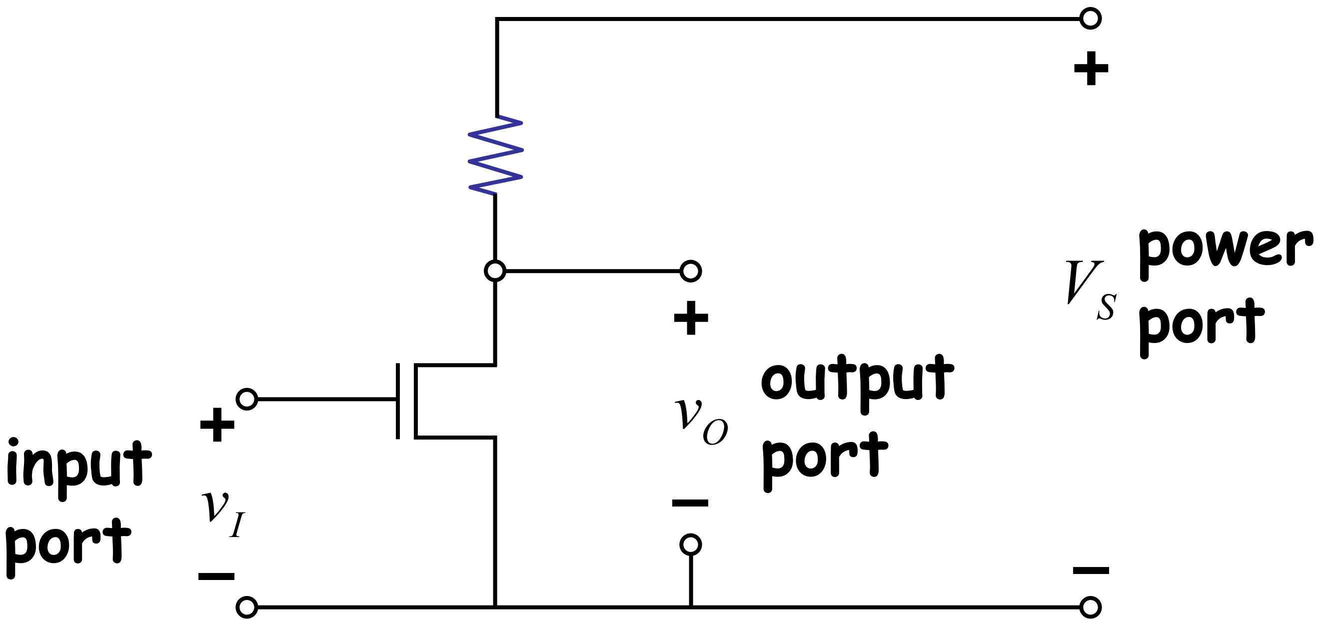
***Slide credits**: Prof. Anant Agarwal at MIT*

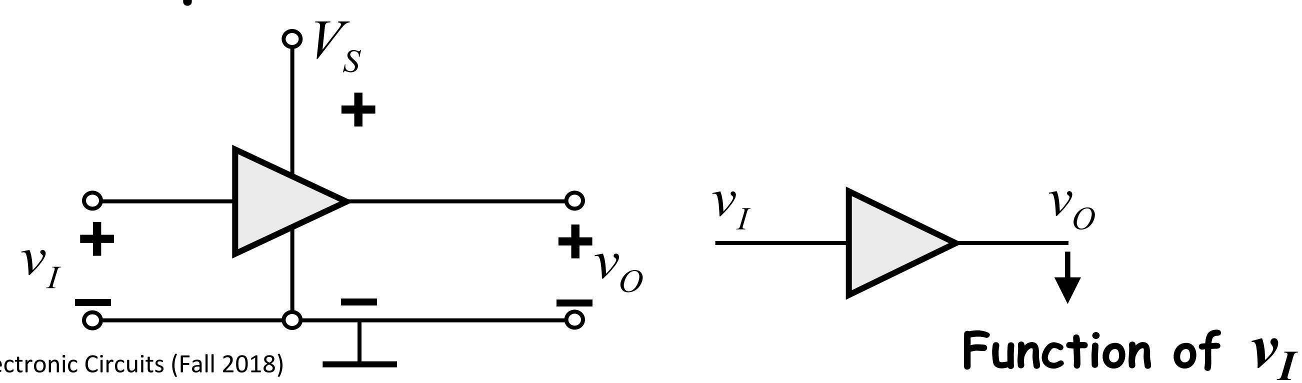
V-code: ???

Review

- MOSFET amplifier — 3 ports

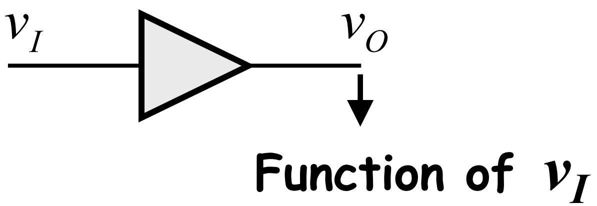


- Amplifier abstraction



V-code: ???

Review



- Can use as an abstract building block for more complex circuits (of course, need to be careful about input and output).
- Today
  Introduce a more powerful amplifier abstraction and use it to build more complex circuits.

V-code: ???

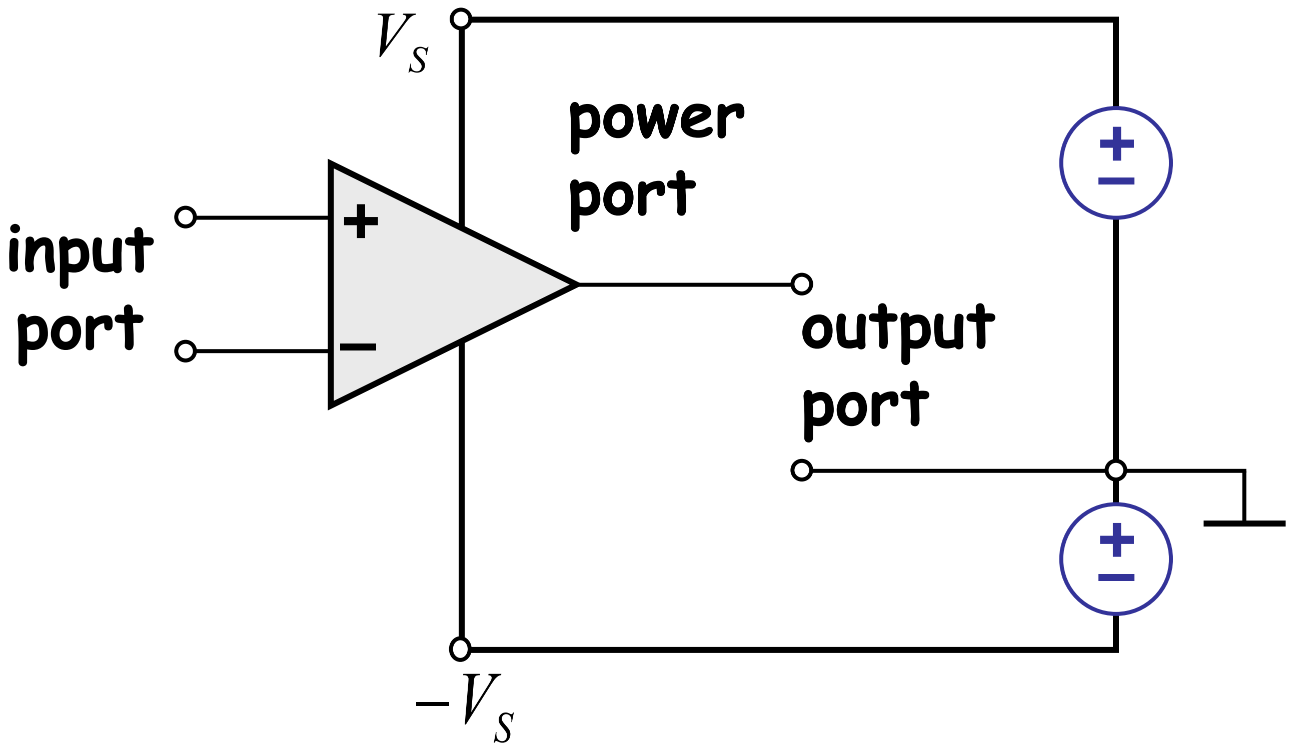
Outline

Textbook: 15.1, 15.2, 15.3, 15.5, 15.6, 15.8

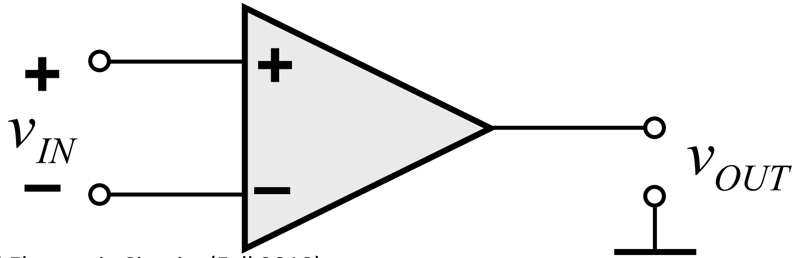
- **Device Properties of the Operational Amplifier**
- Simple Op Amp Circuits
- Op Amp RC Circuits
- Positive Feedback

V-code: ???

Operational Amplifier (Op Amp)



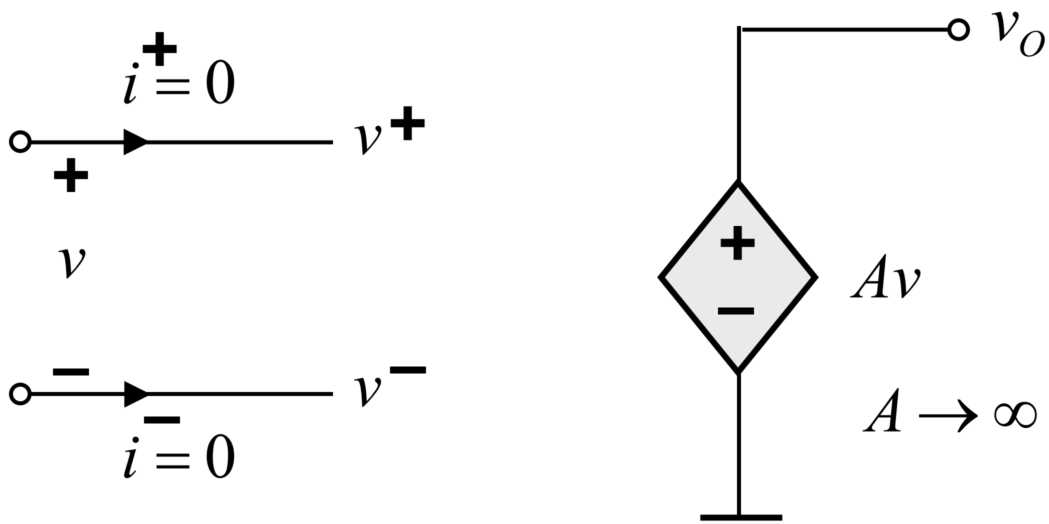
More abstract representation:



V-code: ???

Operational Amplifier (Op Amp)

Circuit model (ideal):

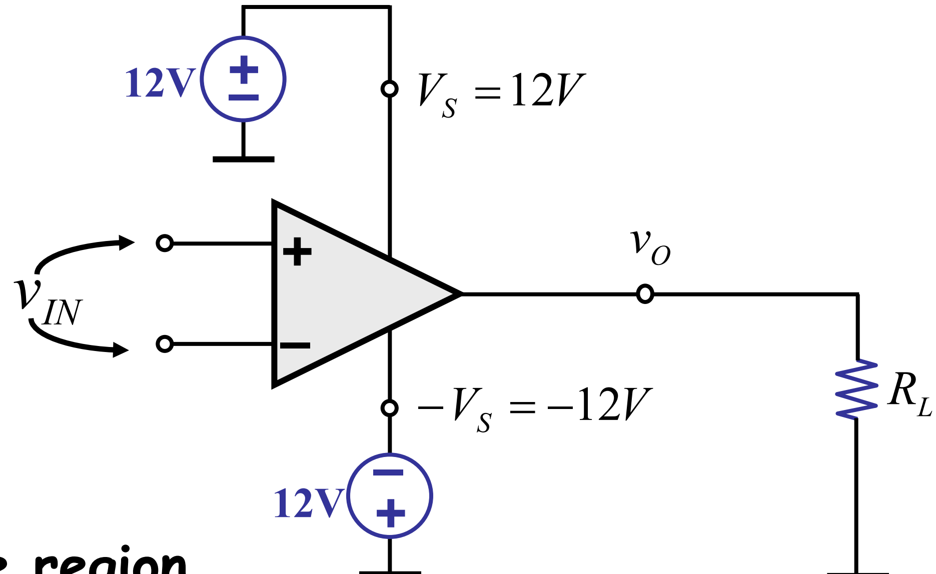


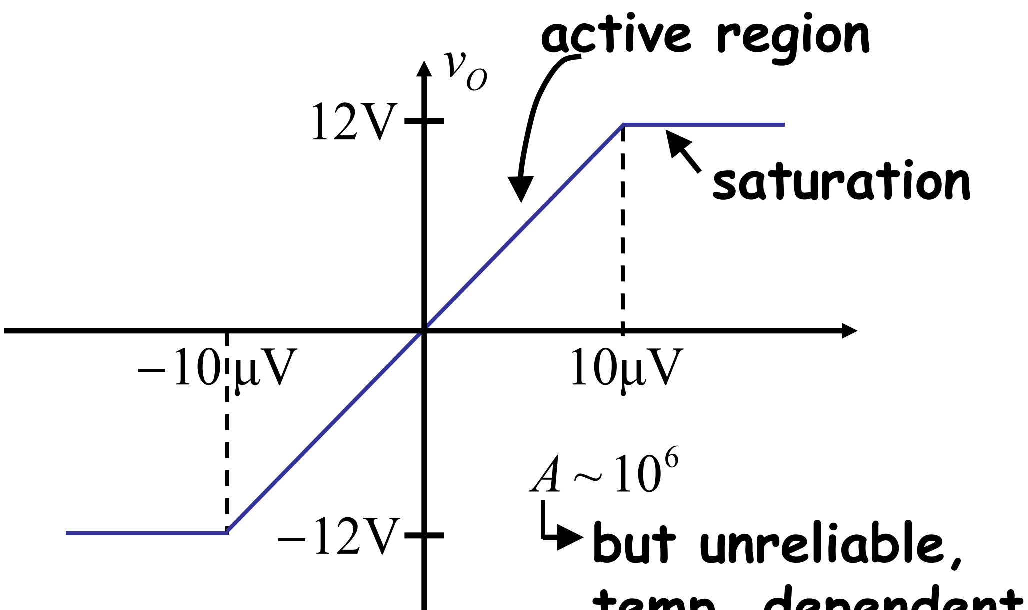
i.e.
- ♦ ∞ input resistance
- ♦ *0* output resistance
- ♦ "*A*" virtually ∞
- ♦ No saturation

V-code: ???

Operational Amplifier (Op Amp)

Using it…





(Note: possible confusion with MOSFET saturation!)

V-code: ???

Outline

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- **Simple Op Amp Circuits**
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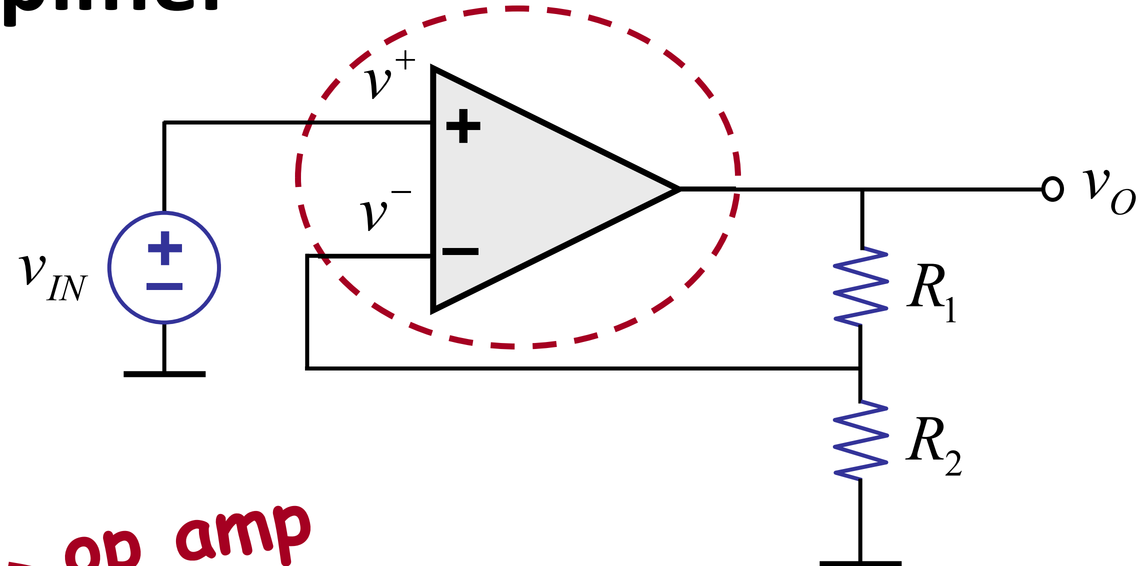
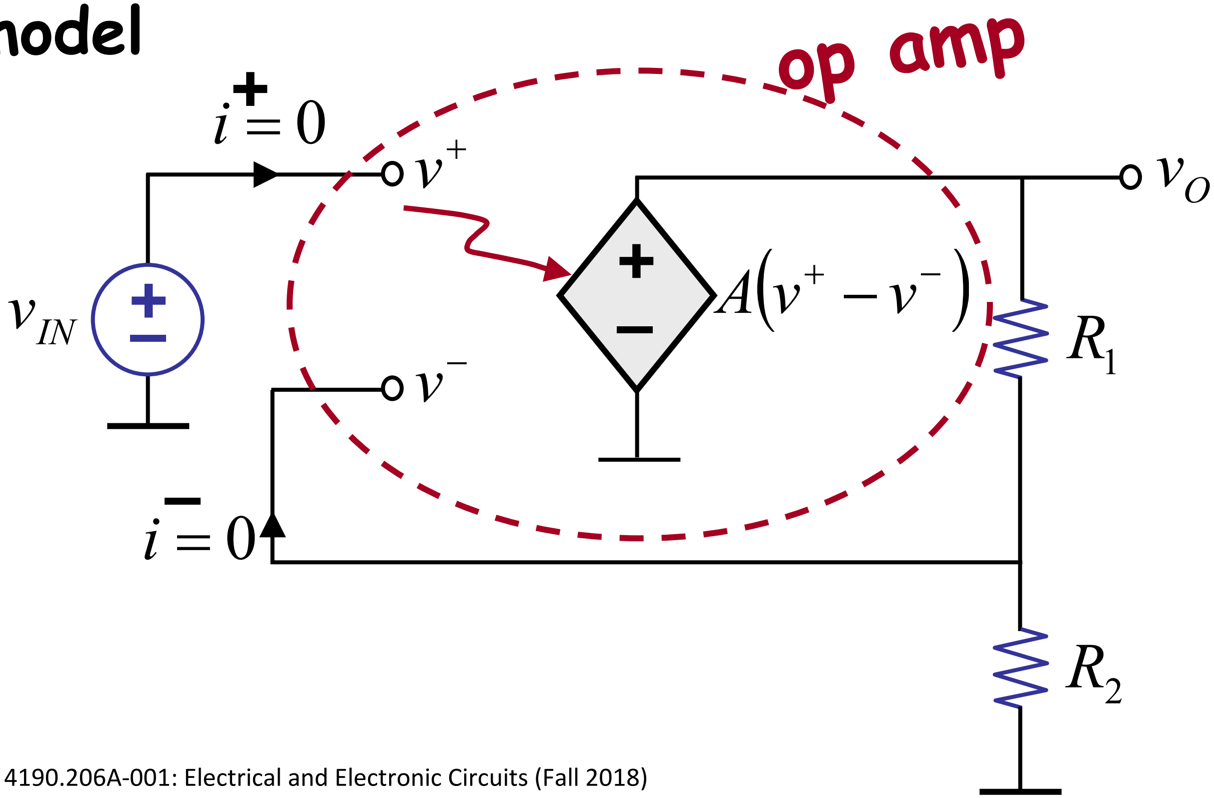
V-code: ???

Noninverting Amplifier



Equivalent circuit model



V-code: ???

Noninverting Amplifier

Let us analyze the circuit:

Find v_O in terms of v_{IN}, etc.

$$v_O = A\left(v^+ - v^-\right)$$

$$= A\left(v_{IN} - v_O \frac{R_2}{R_1 + R_2}\right)$$

$$v_O\left(1 + \frac{AR_2}{R_1 + R_2}\right) = Av_{IN}$$

$$v_O = \frac{Av_{IN}}{1 + \frac{AR_2}{R_1 + R_2}}$$

What happens when "A" is very large?

V-code: ???

Noninverting Amplifier

Let's see… When A is large

$$v_O = \frac{A v_{IN}}{\cancel{1} + \frac{A R_2}{R_1 + R_2}} \approx \frac{\cancel{A} v_{IN}}{\frac{\cancel{A} R_2}{R_1 + R_2}} \approx v_{IN} \underbrace{\frac{(R_1 + R_2)}{R_2}}_{\text{gain}}$$

Suppose

$$A = 10^6$$
$$R_1 = 9R$$
$$R_2 = R$$

$$v_O = \frac{10^6 \cdot v_{IN}}{1 + \frac{10^6 R}{9R + R}}$$

$$= \frac{\cancel{10^6} \cdot v_{IN}}{\cancel{1} + \cancel{10^6} \cdot \frac{1}{10}}$$

$$\boxed{v_O \approx v_{IN} \cdot 10}$$

Gain:

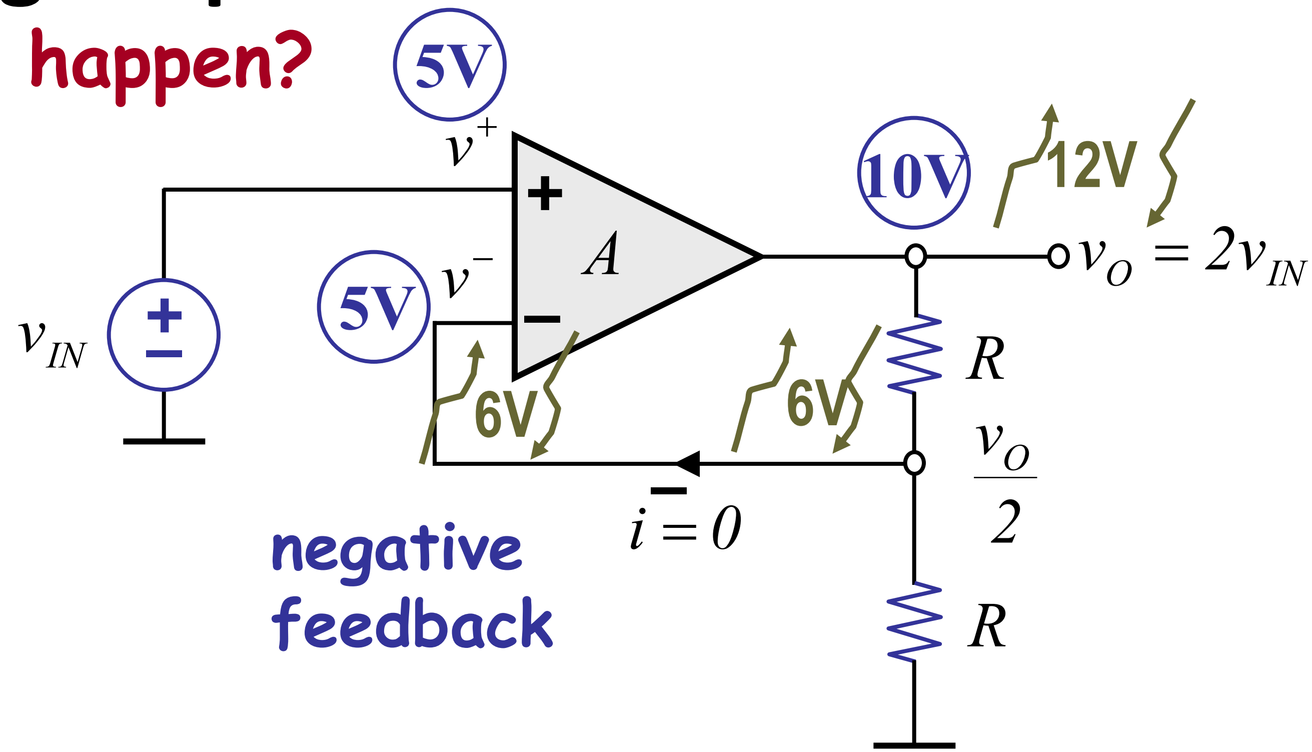
- determined by resistor ratio
- insensitive to A, temperature, fab variations

Noninverting Amplifier

V-code: ???

Why did this happen?

Insight:



e.g. $v_{IN} = 5\text{V}$

Suppose I perturb the circuit…

(e.g., force v_O momentarily to 12V somehow).

Stable point is when $v^+ \approx v^-$.

Key: neg. feedback → portion of output fed to neg input.

e.g. Car antilock brakes

→ small corrections.

Noninverting Amplifier

V-code: ???

More op amp insights:

Observe, under negative feedback,

$$v^+ - v^- = \frac{v_O}{A} = \frac{\left(\frac{R_1 + R_2}{R_1}\right) v_{IN}}{A} \rightarrow 0$$

$$v^+ \approx v^-$$

We also know

$$i^+ \approx 0$$
$$i^- \approx 0$$

→yields an easier analysis method (under negative feedback).

Noninverting Amplifier

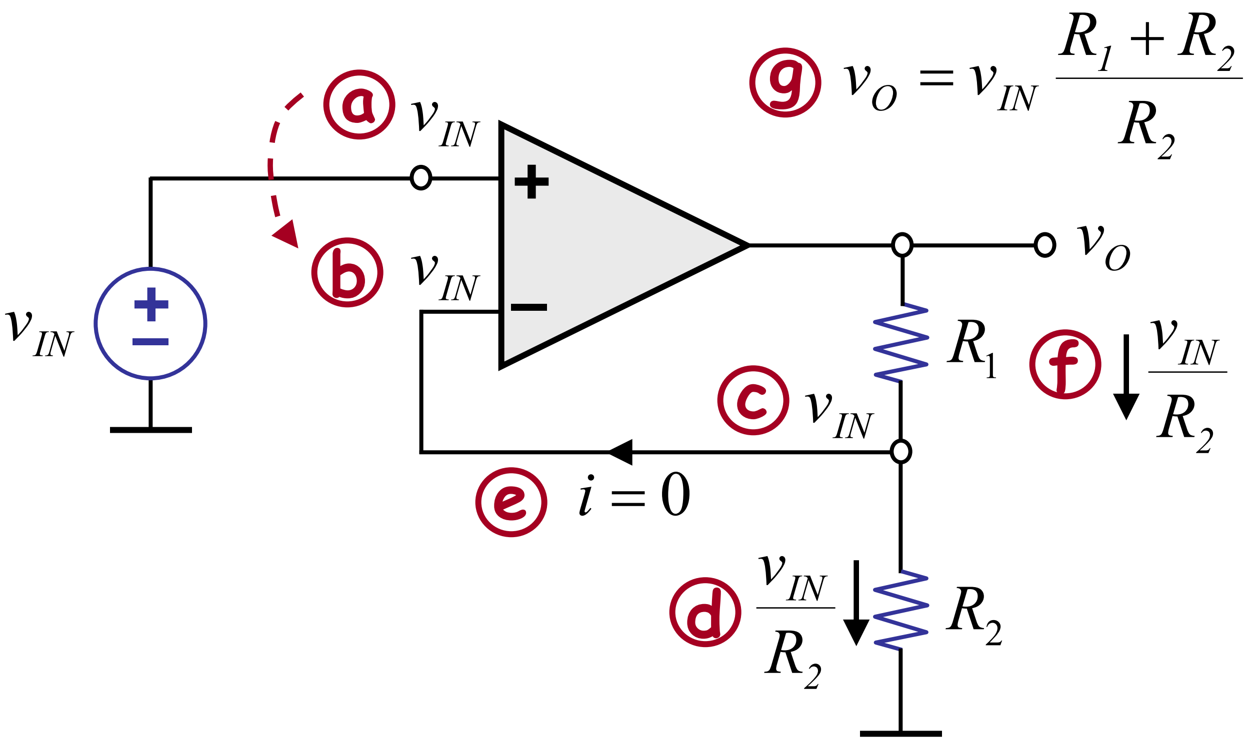
V-code: ???

Insightful analysis method under negative feedback

$$v^+ \approx v^-$$

$$i^+ \approx 0$$

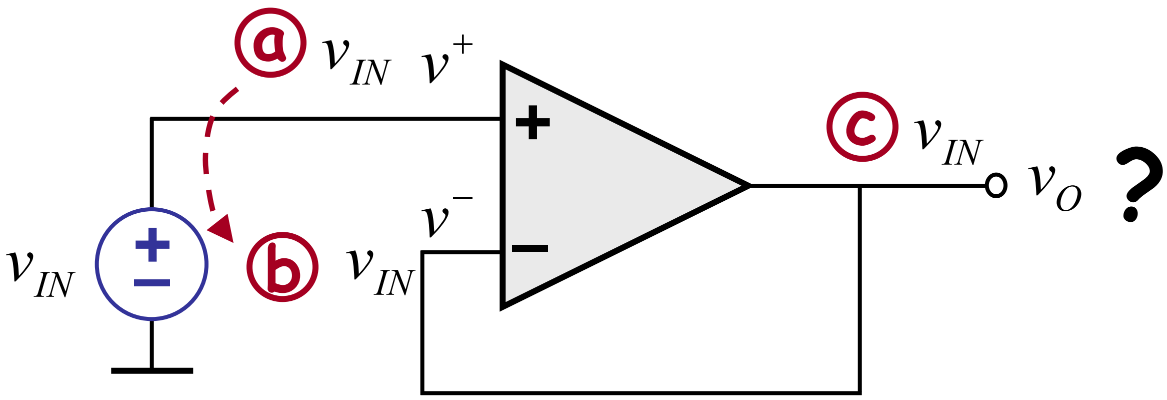
$$i^- \approx 0$$



V-code: ???

Special Case: Voltage Follower

Question:



$$v_O \approx v_{IN}$$

or $$v_O = v_{IN}\frac{R_1 + R_2}{R_2}$$

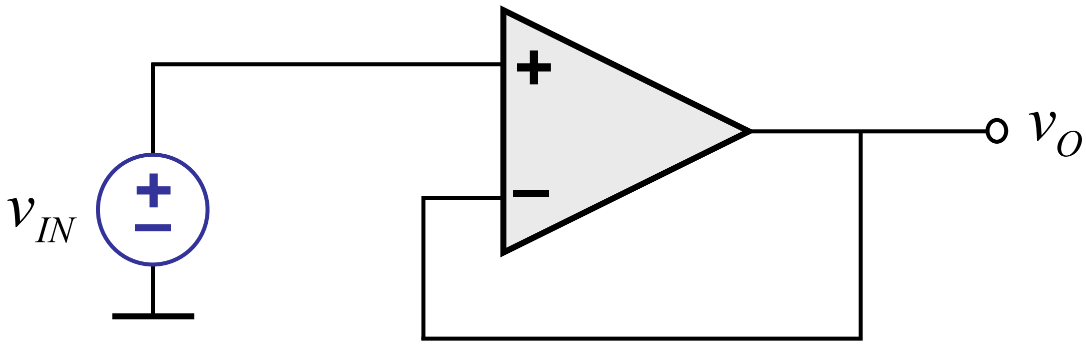
with $$R_1 = 0$$

$$R_2 = \infty$$

V-code: ???

Special Case: Voltage Follower

Why is this circuit useful?



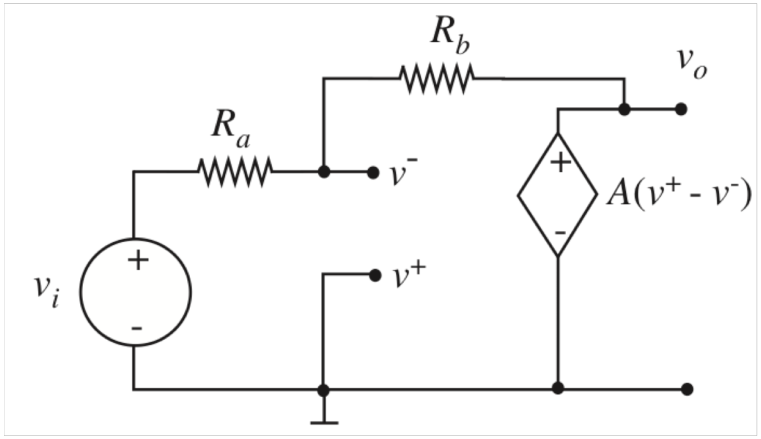
$v_O \approx v_{IN}$

Buffer: isolate the input and the output circuits

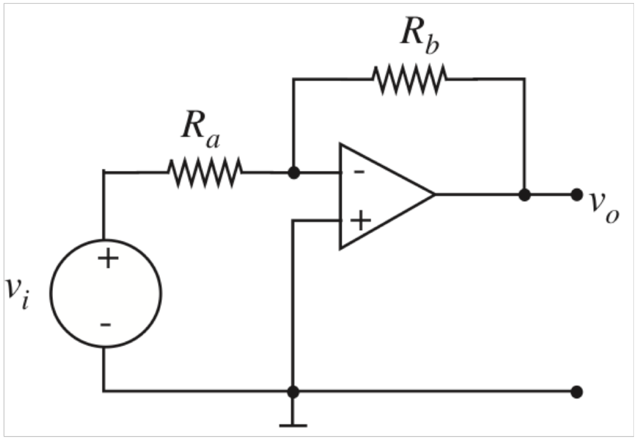
voltage gain = *1*
input impedance = ∞
output impedance = *0*
current gain = ∞
power gain = ∞

V-code: ???

Inverting Amplifier



Equivalent circuit model



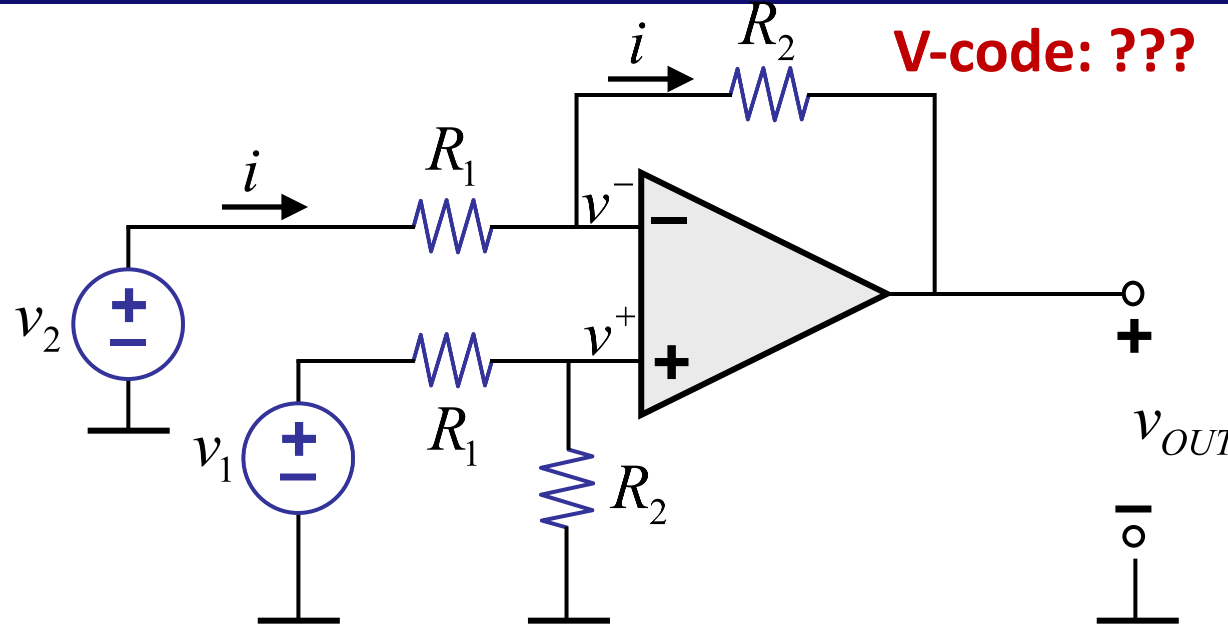
Inverting amplifier (note the input)

$v_o =$

V-code: ???

Subtracter

Consider this circuit:



$$v^+ = v_1 \frac{R_2}{R_1 + R_2}$$

$$\approx v^-$$

$$i = \frac{v_2 - v^-}{R_1}$$

$$v_{OUT} = v^- - iR_2$$

$$= v^- - \frac{v_2 - v^-}{R_1} \cdot R_2$$

$$= v^- \left[1 + \frac{R_2}{R_1} \right] - v_2 \frac{R_2}{R_1}$$

subtracts!

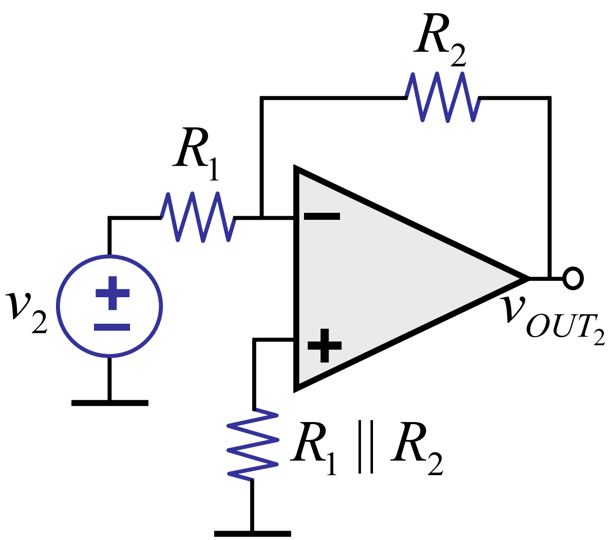
$$= v_1 \frac{R_2}{\cancel{R_1 + R_2}} \cdot \frac{\cancel{R_1 + R_2}}{R_1} - v_2 \frac{R_2}{R_1} \boxed{= \frac{R_2}{R_1}(v_1 - v_2)}$$

V-code: ???

Subtracter

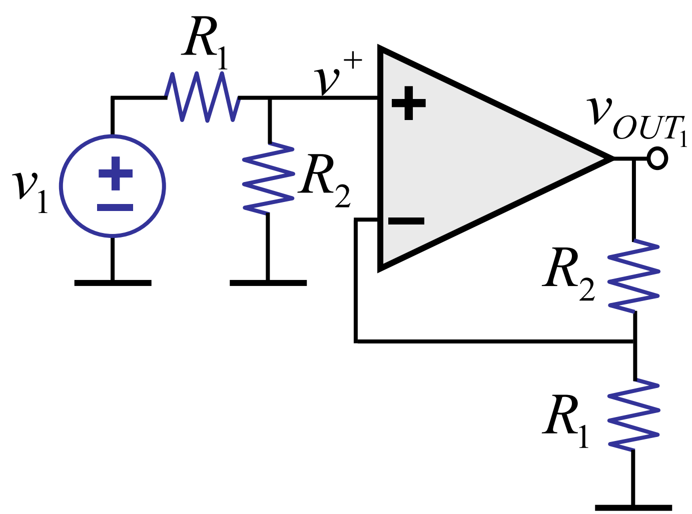
Another way of solving — use superposition

$v_1 \to 0$



$$v_{OUT_2} = -\frac{R_2}{R_1} v_2$$

$v_2 \to 0$



$$v_{OUT_1} = v^+ \cdot \frac{R_1 + R_2}{R_1} = \frac{v_1 \cdot R_2}{R_1 + R_2} \cdot \frac{R_1 + R_2}{R_1}$$

$$= v_1 \frac{R_2}{R_1}$$

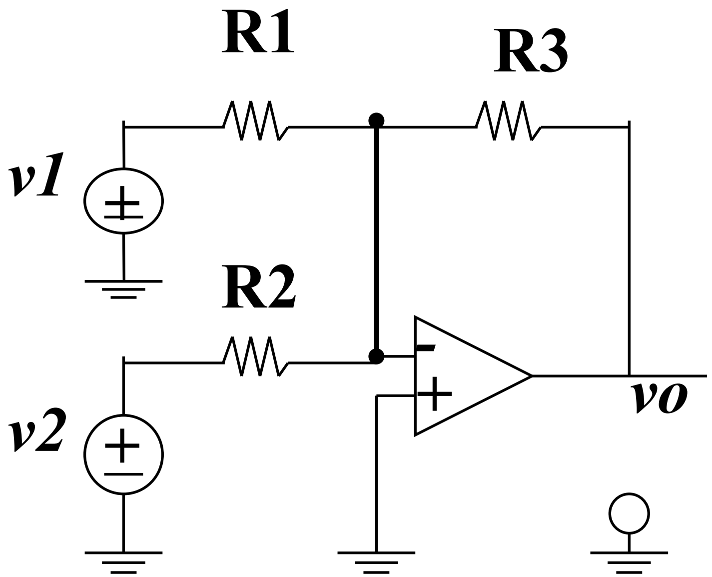
$$v_{OUT} = v_{OUT_1} + v_{OUT_2}$$

$$= \frac{R_2}{R_1}(v_1 - v_2)$$

Still subtracts!

V-code: ???

Adder



$v_o =$

V-code: ???

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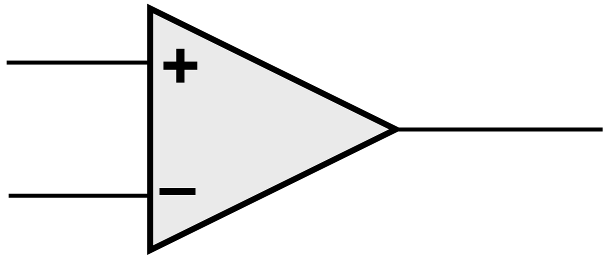
Review

V-code: ???

- Operational amplifier abstraction



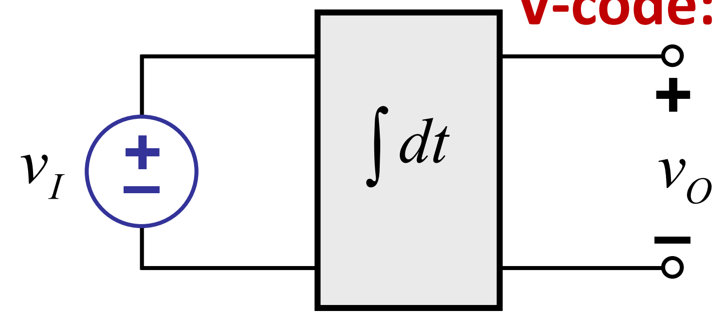
  - ♦ ∞ input resistance
  - ♦ 0 output resistance
  - ♦ Gain "A" very large

- Building block for analog systems
- We will see these examples:
  - Digital-to-analog converters
  - Filters
  - Clock generators
  - Amplifiers
  - Adders
  - Integrators & Differentiators

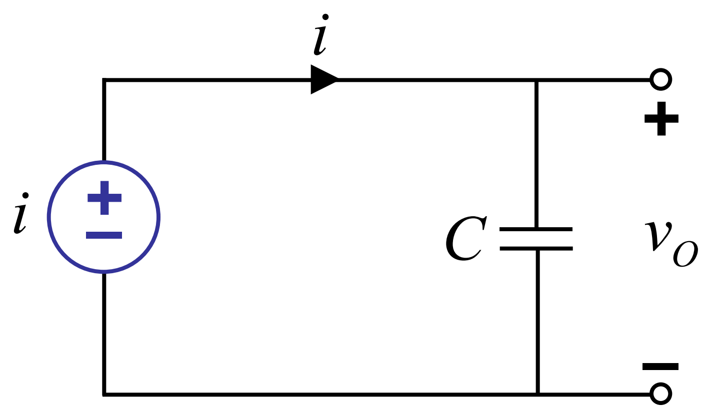
V-code: ???

Integrator

Let's build an integrator…



Let's start with the following insight:



$$v_O = \frac{1}{C}\int_{-\infty}^{t} i\,dt$$

v_O **is related to** $\int i\,dt$

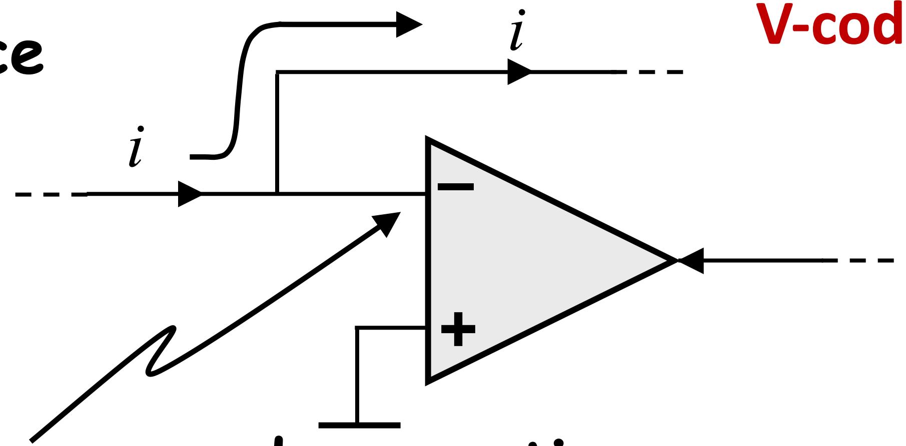
But we need to somehow convert voltage v_I to current.

V-code: ???

Integrator

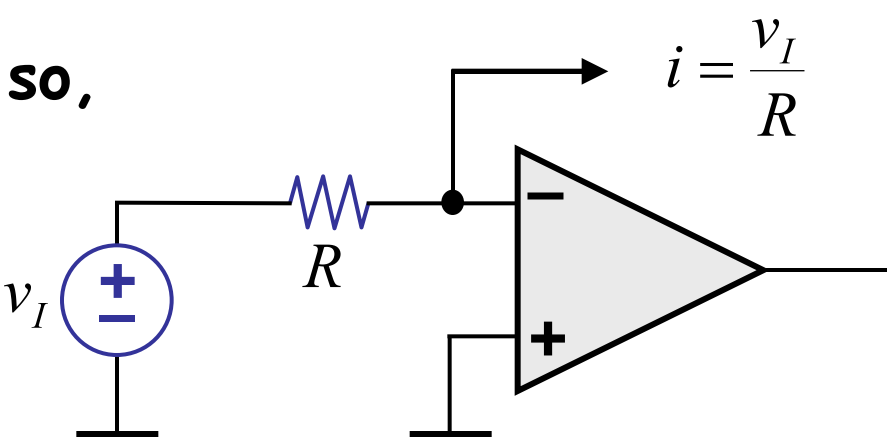
Using Op Amp!

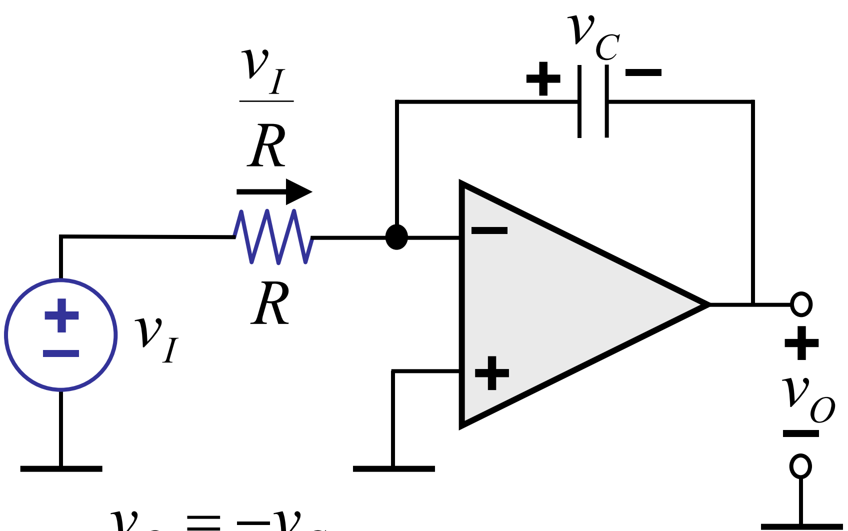
Notice



$v^- \approx 0V$ under negative feedback

so,





$$v_O = -v_C$$

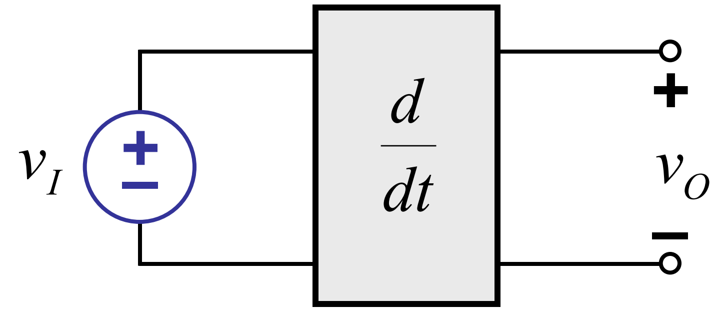
$$v_O = -\frac{1}{C}\int_{-\infty}^{t} \frac{v_I}{R} dt$$

We have our integrator.

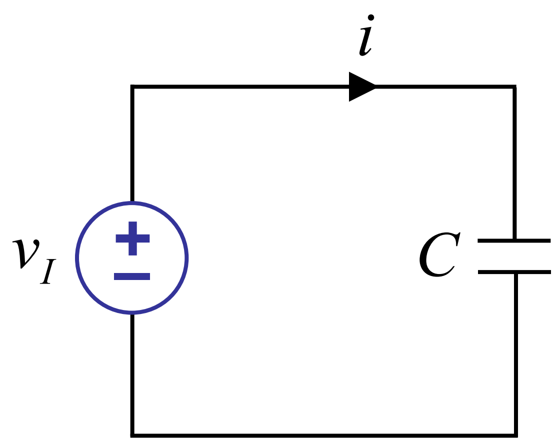
V-code: ???

Differentiator

Now, let's build a differentiator…



Let's start with the following insights:



$$i = C\frac{dv_I}{dt}$$

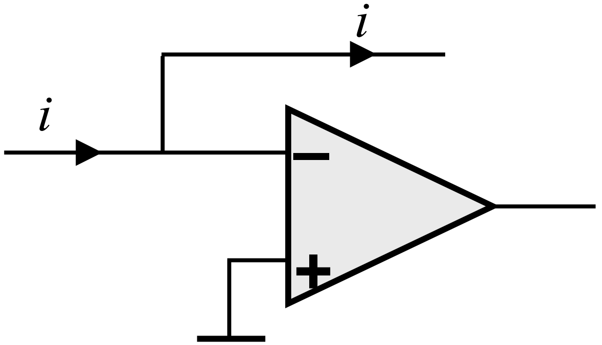
i is related to $\frac{dv_I}{dt}$

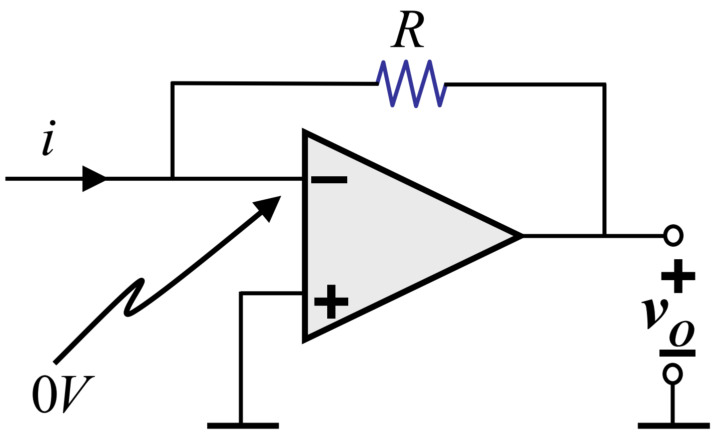
But we need to somehow convert current to voltage.

V-code: ???

Differentiator

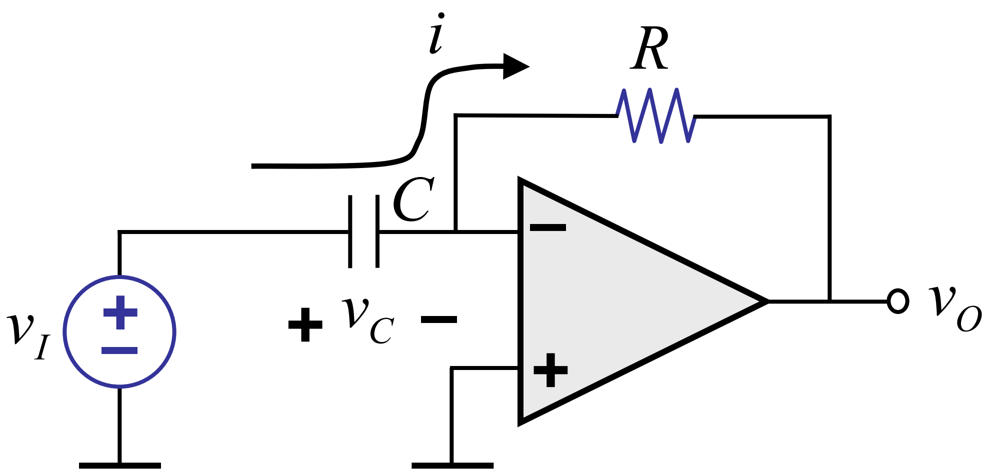
Recall





$v_O = -iR$

current to voltage



$$v_I = v_C$$

$$i = C\frac{dv_I}{dt}$$

$$v_O = -RC\frac{dv_I}{dt}$$

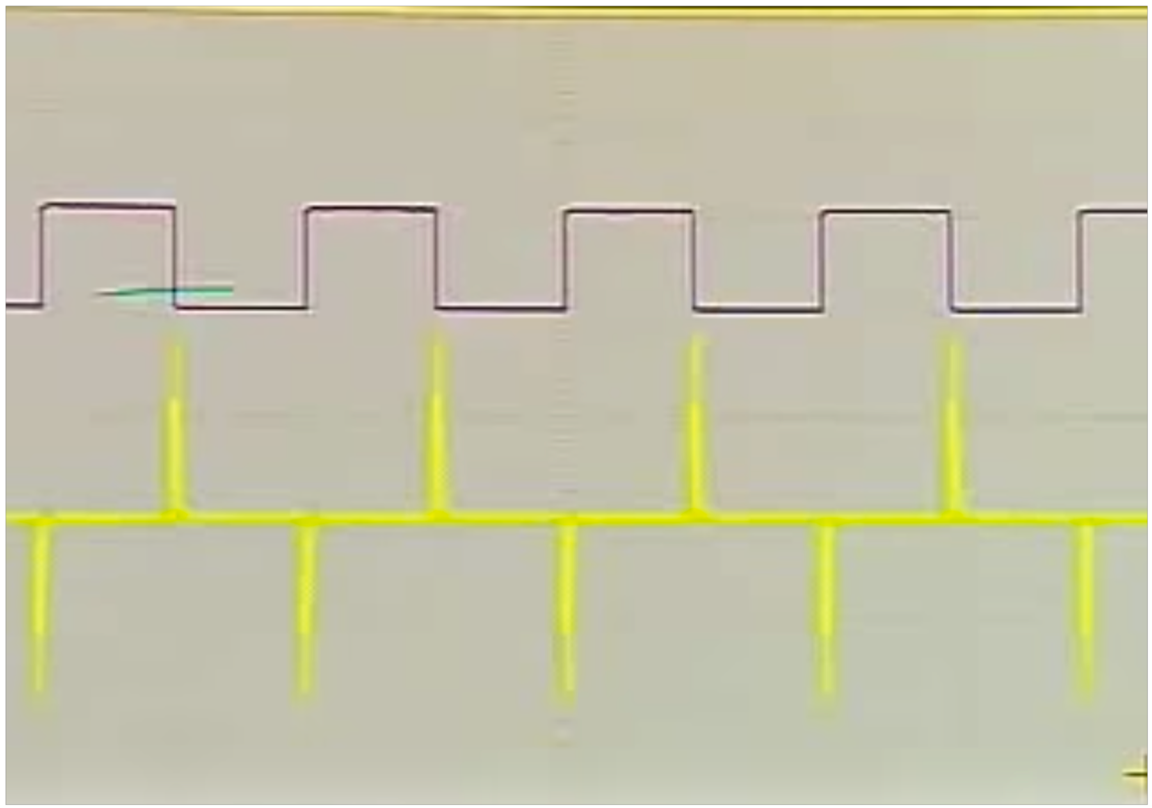
V-code: ???

Differentiator

Demo

v_I

v_O



Source: https://www.youtube.com/watch?v=2SwT6JnfCq8&itct=CAoQpDAYCCITCK6-sL2M2dcCFRajAwodSm0ApjIHcmVsYXRlZEi0y462romQuccB

V-code: ???

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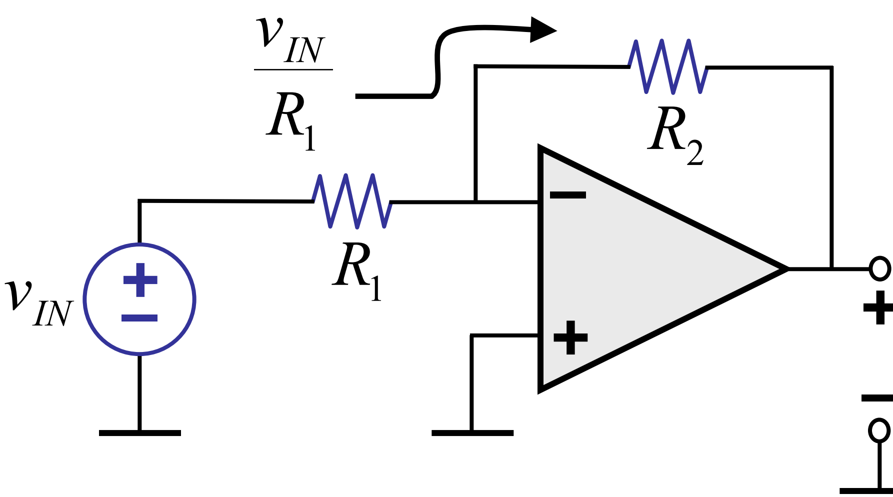
- **Positive Feedback**

V-code: ???

Negative vs. Positive Feedback

Consider this circuit — *negative feedback*



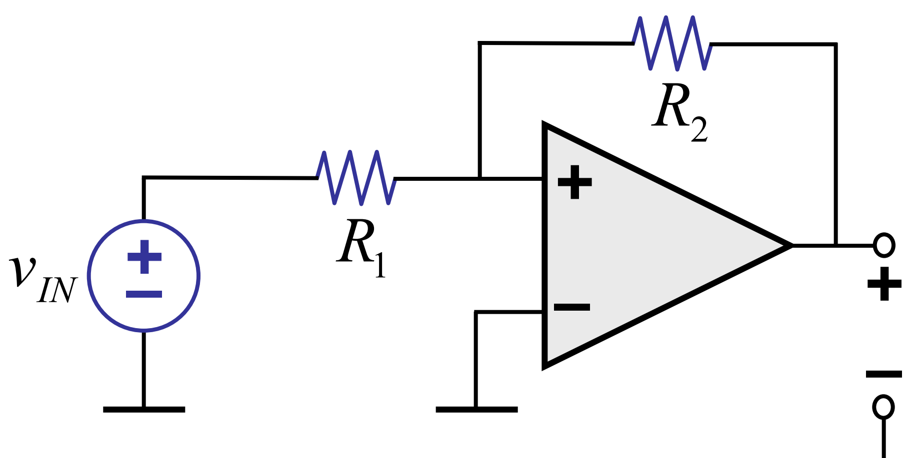
$$v_{OUT} = -\frac{R_2}{R_1} v_{IN}$$

What's the difference?

Consider what happens when there is a pertubation…

Positive feedback drives op amp into saturation: $v_{OUT} \to \pm V_S$

and this — *positive feedback*

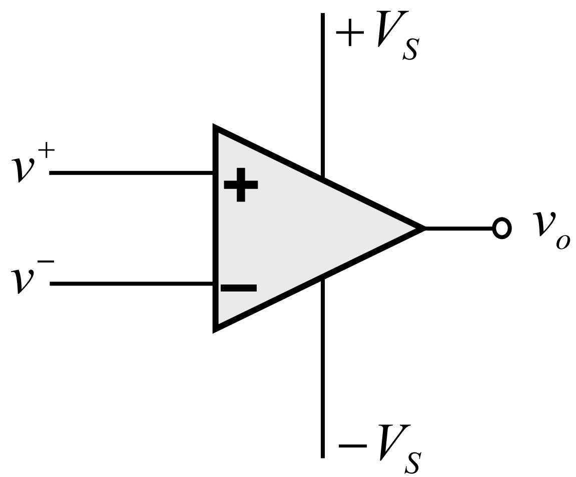


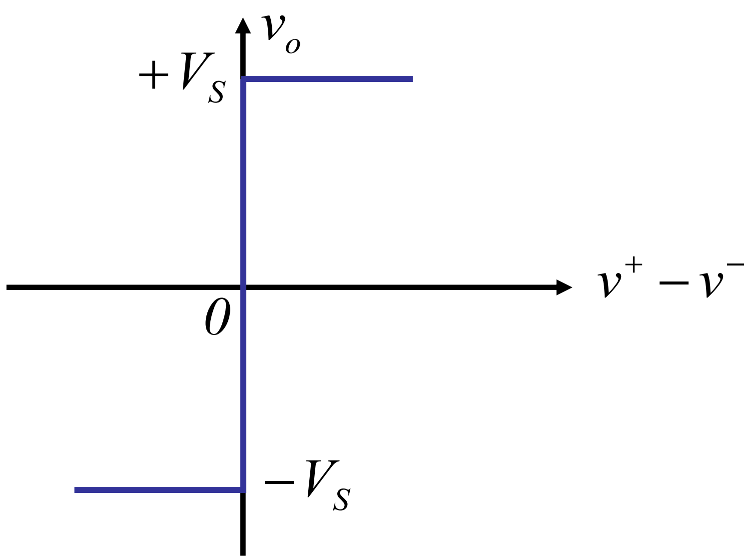
$$v_{OUT} = -\frac{R_2}{R_1} v_{IN}$$

V-code: ???

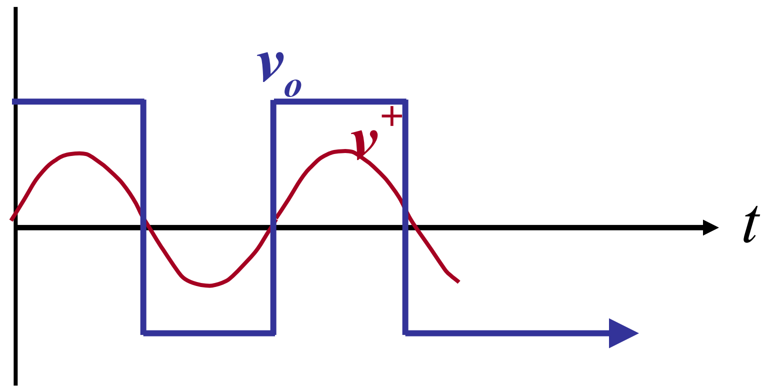
Comparator

One use for instability: Build on the basic op amp as a comparator





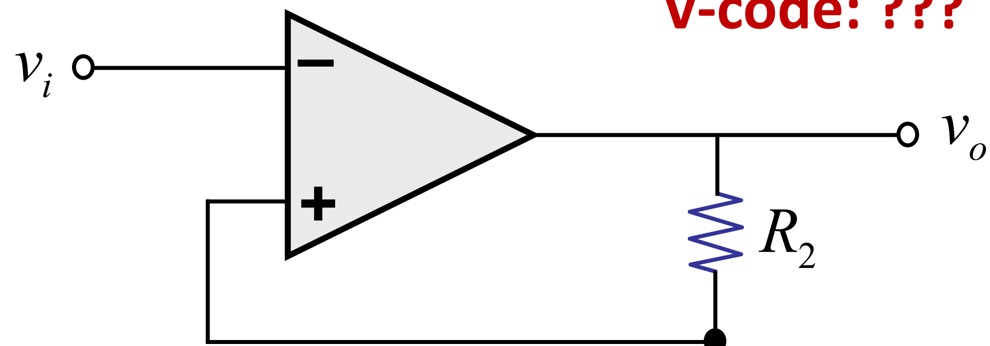
$v^- \to 0$



V-code: ???

Comparator

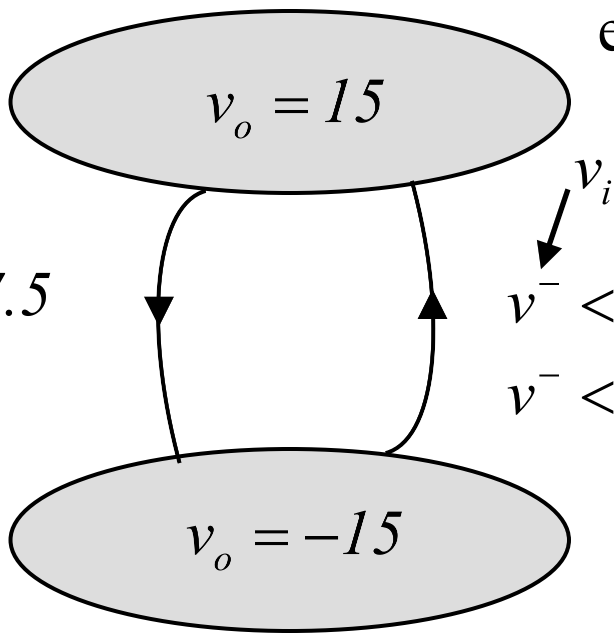
Now, use positive feedback



$$v^+ = \frac{v_o R_1}{R_1 + R_2}$$

e.g. $R_1 = R_2$

$V_S = 15$



$v^+ = 7.5$

$(v_i = v^-) > 7.5$

$v^- > 7.5$

$v^- < v^+$

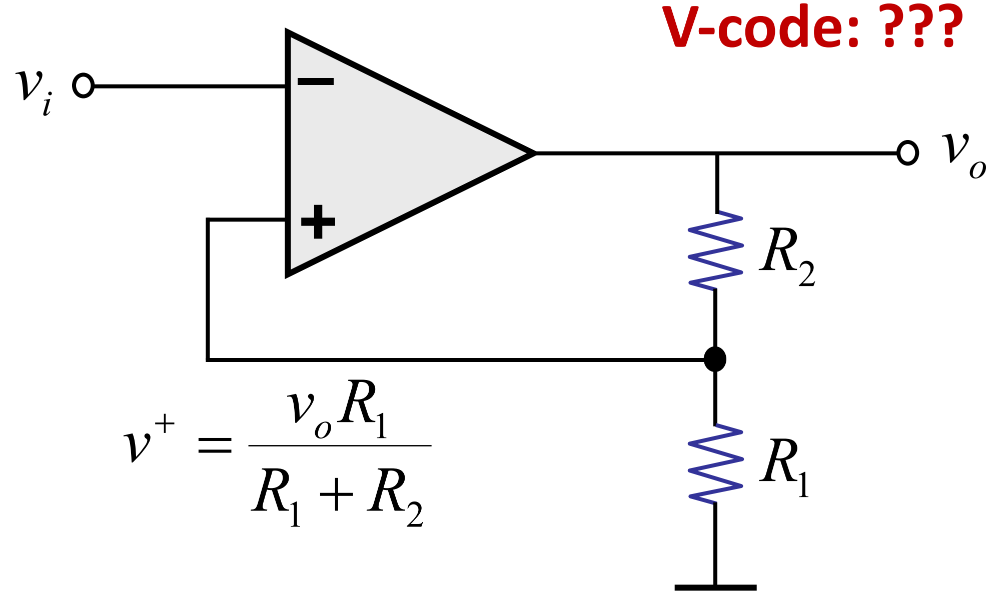
$v^- < -7.5$

$v^- = -7.5$

V-code: ???

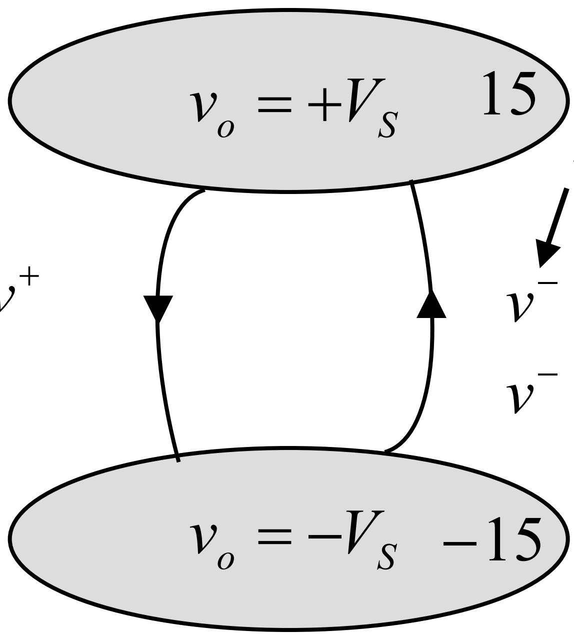
Comparator

Now, use positive feedback



$$v^+ = \frac{v_o R_1}{R_1 + R_2}$$

$$v^+ = \frac{V_S R_1}{R_1 + R_2}$$



e.g. $R_1 = R_2$

$V_S = 15$

$(v_i = v^-) > v^+$

$v^- > 7.5$

v_i

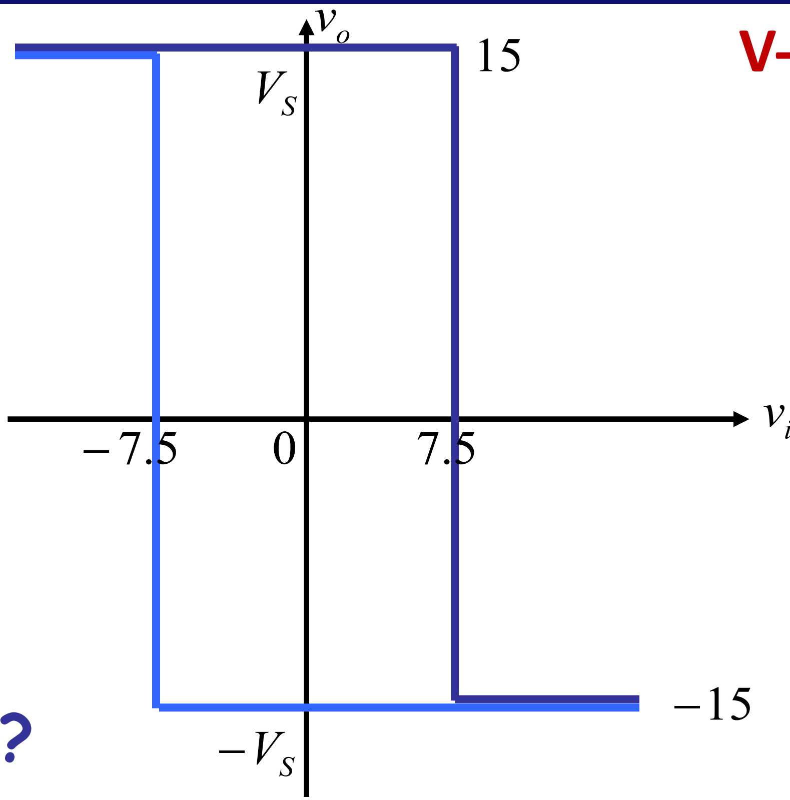
$v^- < v^+$

$v^- < -7.5$

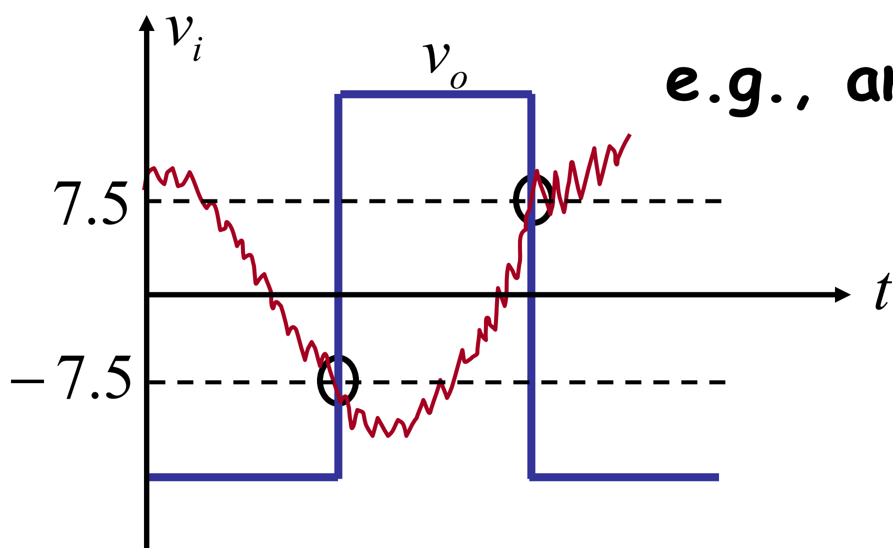
$$v^- = \frac{-V_S R_1}{R_1 + R_2}$$

V-code: ???

Comparator
hysteresis



Why is hysteresis useful?

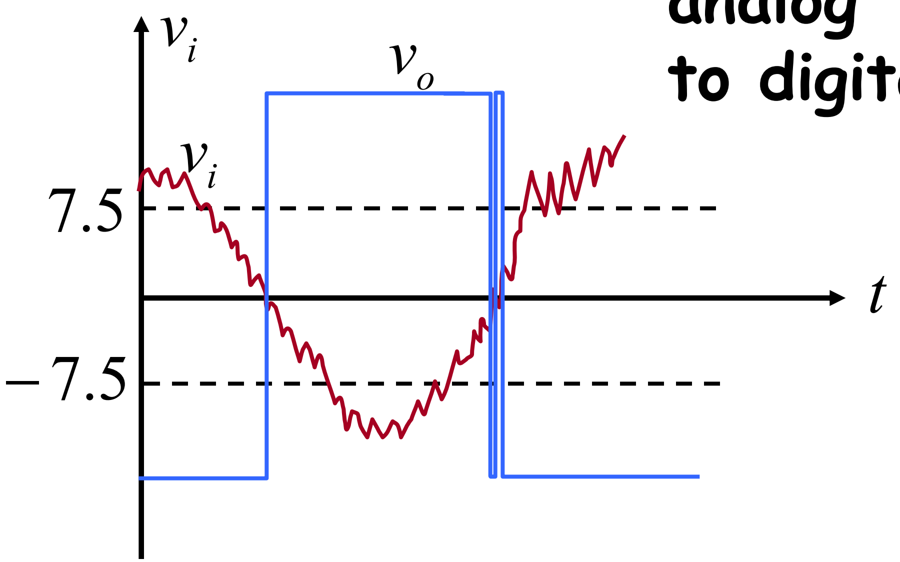


e.g., analog to digital

V-code: ???

Comparator

Without hysteresis

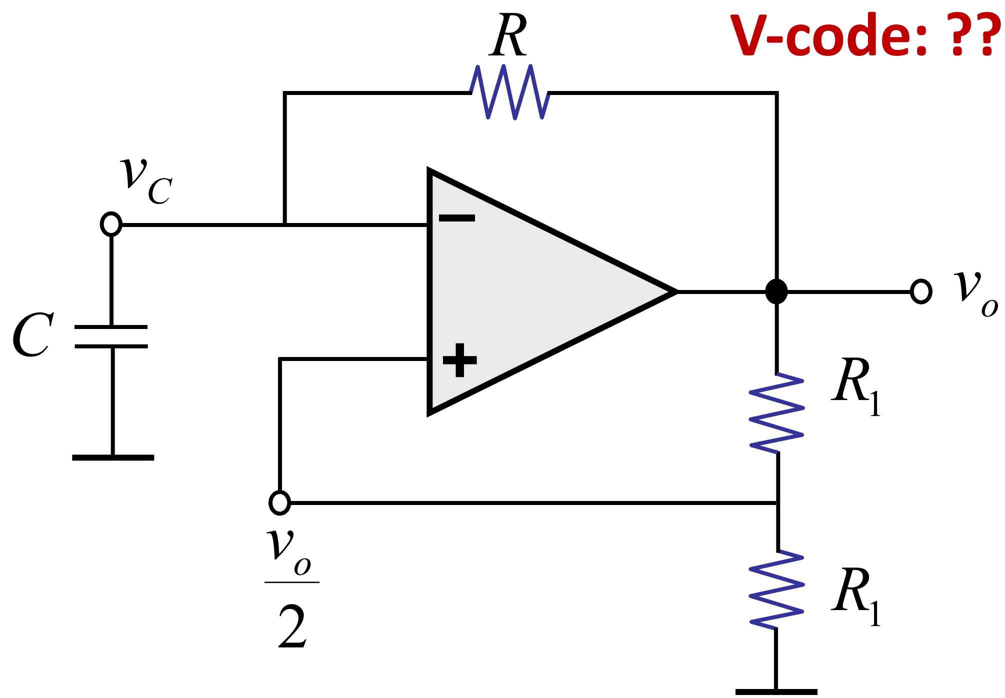


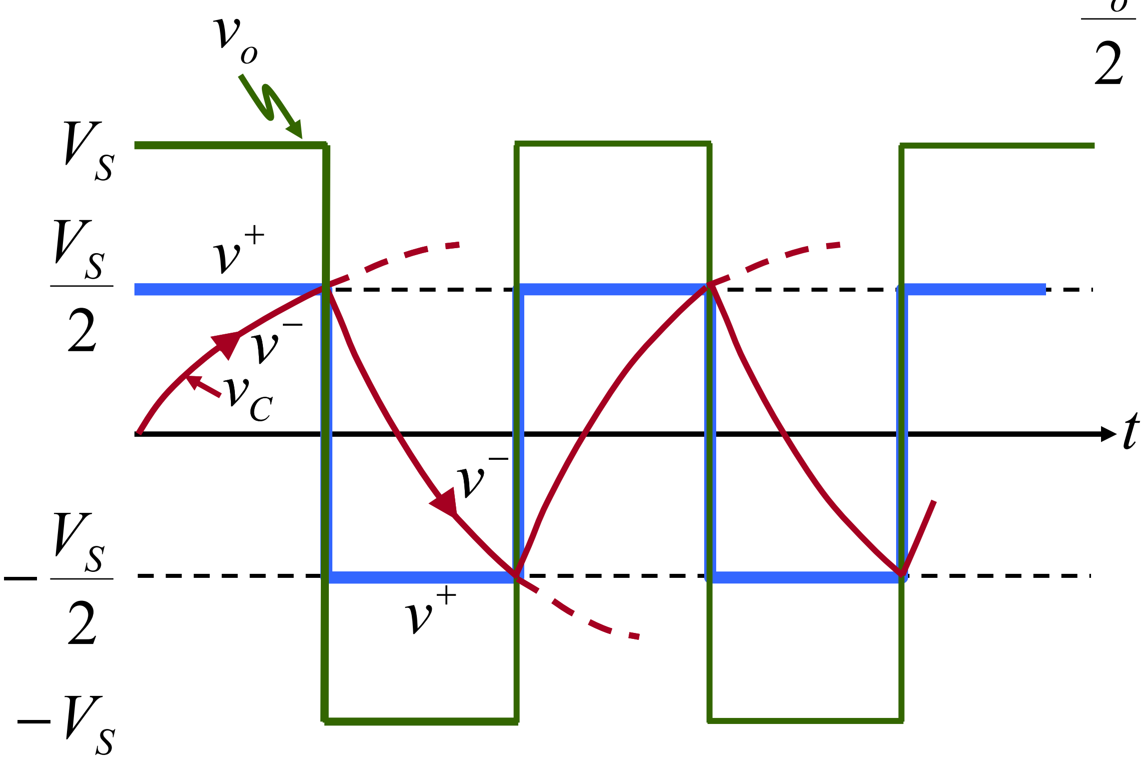
analog
to digital

V-code: ???

Oscillator

Can create a clock



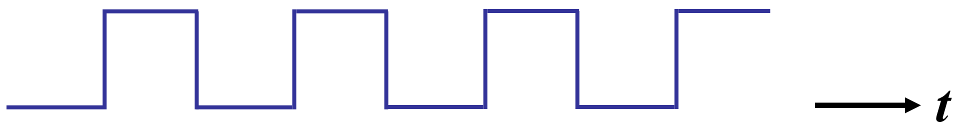


Assume $v_o = V_S$ at $t = 0$

$v_C = 0$

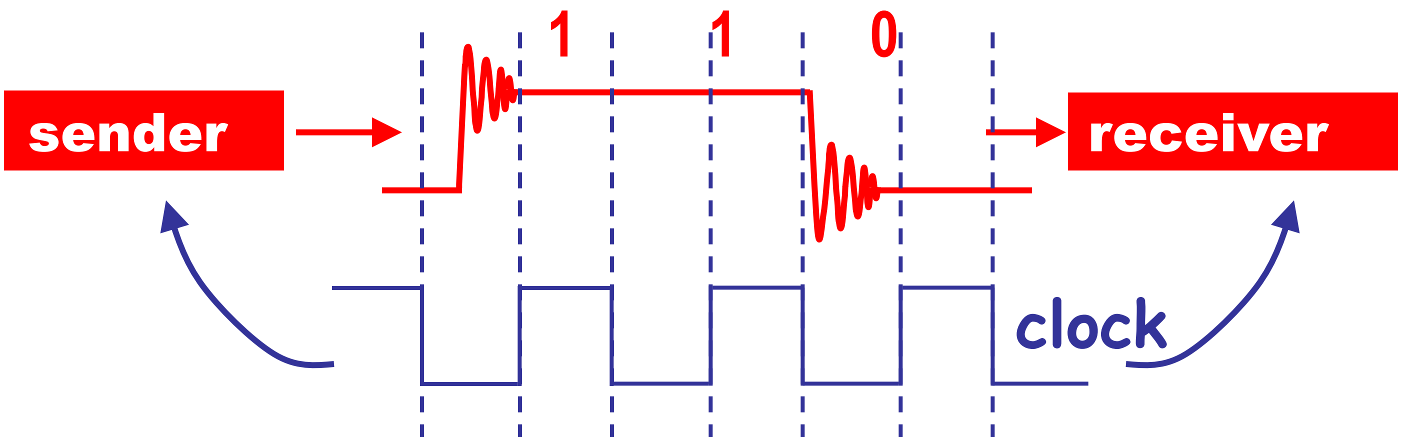
Oscillator   Clocks in Digital Systems   V-code: ???

- We built an oscillator using an op amp.



can use as a clock

- Why do we use a clock in a digital system?



ⓐ 1,1,0?

ⓑ When is the signal valid?
common timebase -- when to "look" at a signal
(e.g. whenever the clock is high)

→ Discretization of time
one bit of information associated with
an interval of time (cycle)