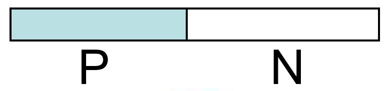
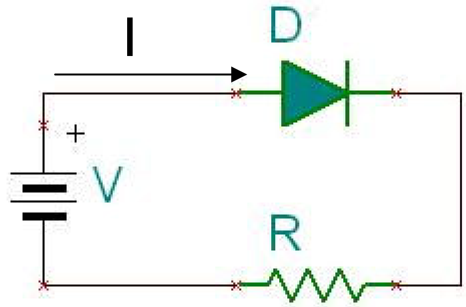
Lecture 4

Integrated Electronics

DIODES -> Recitifier

P, N is the “doping” of silicon to carry P (+) or N (-) charge)

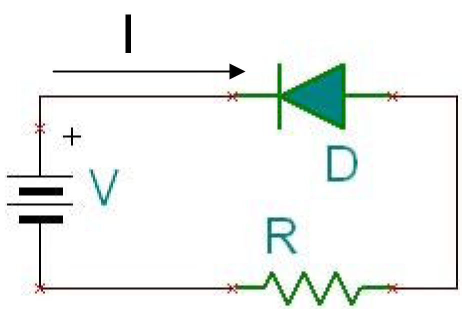




Forward bias, conducting

If V > V_{ON} of diode, $$I = \frac{V - V_{ON}}{R}$$

Von ~ 0.6 V



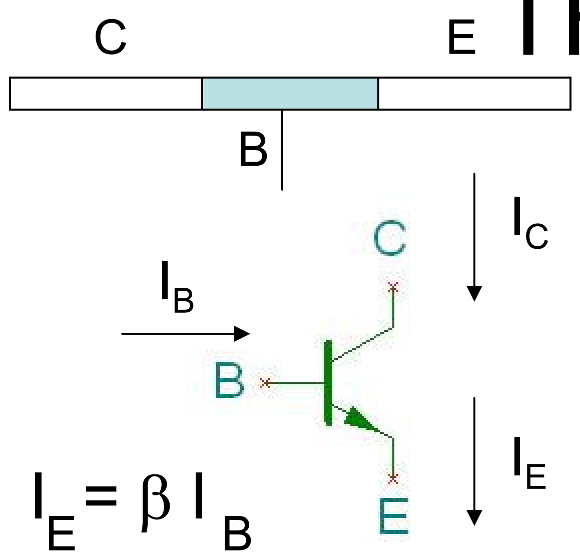
Reverse bias, non conducting

$$I = 0$$

<u>Example</u>: convert “ac” voltage into dc voltage; e.g. use a transformer, capacitor and a diode.

Diodes are silicon based semiconductor devices with P and N junctions. They carry current through electrons or holes (+ charges) in *one direction*.

BIPOLAR JUNCTION TRANSISTORS



Base, Emitter, Collector

$$I_E = I_B + I_C$$

$$V_{BE} = 0.060\log\left(\frac{I_C}{10^{-13}}\right) \quad \text{at } 27°\text{C}$$

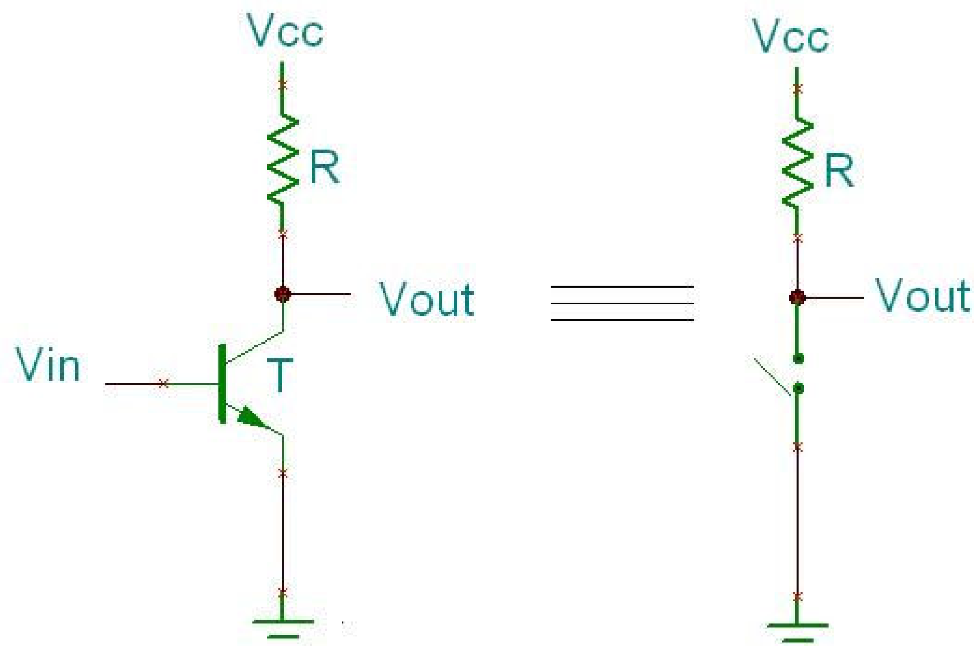
$I_E = \beta\, I_B$

Amplifying effect! => small change in base current IB has a large amplifying effect on currents IC and IE

Transistors are active components with the *ability to amplify electrical signal*. Small current at the base B is amplified to produce large current at collector C and emitter E. Transistors are made typically from Silicon (Si) and they come in different categories:

- bipolar (typically analog, range of currents, voltages, frequencies
- field effect (both analog and digital; high impedance
- MOS or CMOS (digital, high speed and low power, respectively)

TRANSISTOR AS A SWITCH



If V_{in} is high, T is ON, switch is closed and V_{out} is low. Digital “0”

If V_{in} is low, T is OFF, switch is open and V_{out} is high. Digital “1”

Switch function occurs when high base voltage (>0.7 V)saturates the transistor and it fully conducts current in the C-E path resulting in Vout =0.

or when the the base voltage is negative. Then it cuts off the current in the C-E path and Vout =Vcc.

This is the means by which digital or on/off switching can be accomplished and forms the basis for all digital circuits (including computers)

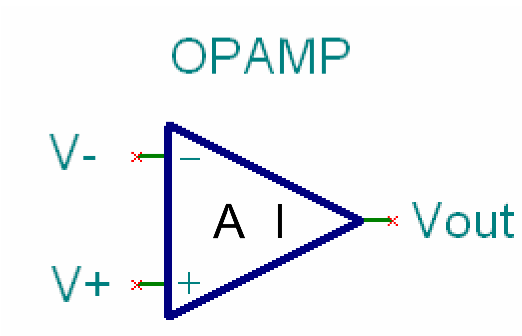
Transistors and IC’s

- Silicon transistor (bipolar junction transistor) -> high gain, bandwidth, analog amplifier
- FET (field effect transistor)-> high input impedance, analog amplifier
- MOS FET (Metal Oxide Field Effect Transistor) -> digital, fast switching (preferred in computers, microprocessors)
- CMOS (Complementary Metal Oxide Semiconductor) Transistor -> low power, digital switching and analog (preferred in low power implanted devices)

Amplifier Properties: Ideal vs. Nonideal

	Gain (open loop)	Bandwidth (frequency response Hz)	Input impedance (interfacing to sensors)	Output impedance (interfacing to load)	Noise (uV/sqrt (Hz) or uA/sqrt (Hz)	Common mode rejection (diff gain/common mode gain)
Ideal	α	α	α	0	0	α
Nonideal	10 e 6	1 M Hz	100 Mohms	100 ohms	1 uV, 1 nA	100,000
Example	Micro-phone	Ultrasound	Piezoelectric crystal	Loud speaker	EEG	ECG, EMG, EEG

Operational Amplifier (OP AMP)

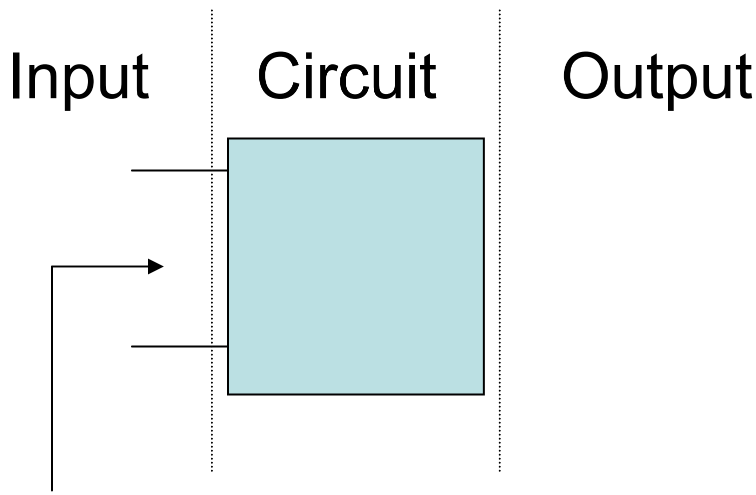


$Vo = (A V_+ \ \ -A V_-)$
$= A (V_+ - V_-)$

Basic and most common circuit building device. Ideally,

1. No current can enter terminals V_+ or V_-. Called *infinite input impedance*.
2. $V_{out}=A(V_+ - V_-)$ with $A \rightarrow \infty$
3. In a circuit V_+ is forced equal to V_-. This is the *virtual ground* property
4. An opamp needs two voltages to power it V_{cc} and $-V_{ee}$. These are called the *rails*.

INPUT IMPEDANCE



Impedance between input terminals = input impedance

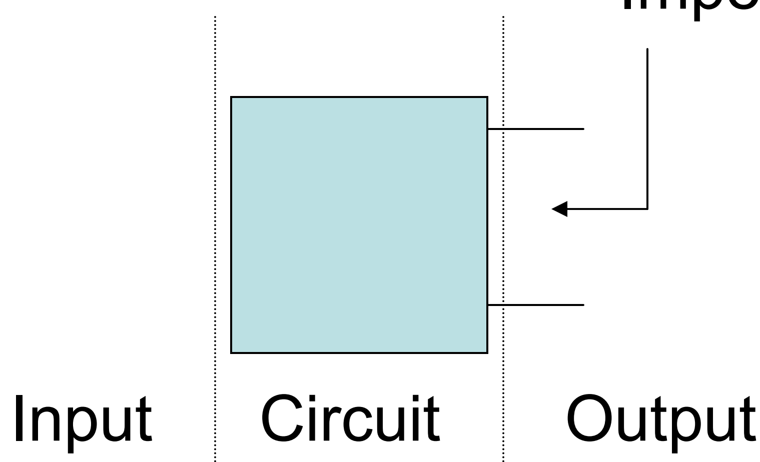
WHY?

For an instrument the Z_{IN} should be very high (ideally infinity) so it does not divert any current from the input to itself even if the input has very high resistance.

e.g. an opamp taking input from a microelectrode.

e.g. Microelectrode R=10 Mohm & therefore Rin=G Ohm!

OUTPUT IMPEDANCE



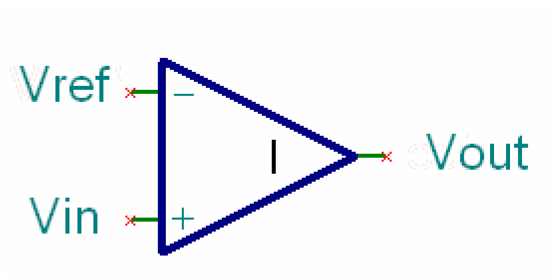
Impedance between output terminals = output impedance

WHY?

For an instrument the Z_{OUT} should be very low (ideally zero) so it can supply output even to very low resistive loads and not expend most of it on itself.

e.g. a power opamp driving a motor or a loudspeaker

OPAMP: COMPARATOR



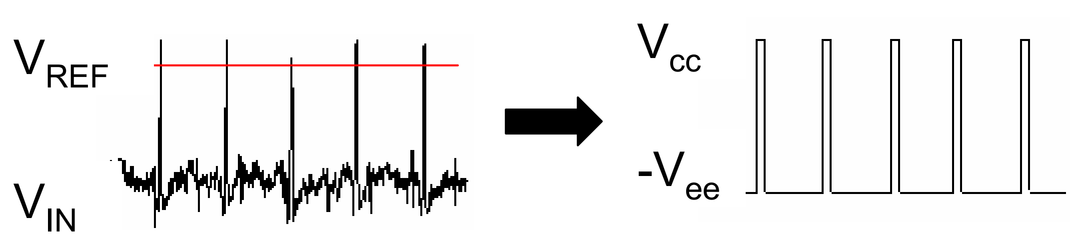
A (gain)
very high

$V_{out} = A(V_{in} - V_{ref})$

If $V_{in} > V_{ref}$, $V_{out} = +\infty$ but practically hits +ve power supply = V_{cc}

If $V_{in} < V_{ref}$, $V_{out} = -\infty$ but practically hits –ve power supply = $-V_{ee}$

Application: detection of QRS complex in ECG



OPAMP: ANALYSIS

The key to op amp analysis is simple

1. No current can enter op amp input terminals.

   => Because of infinite input impedance

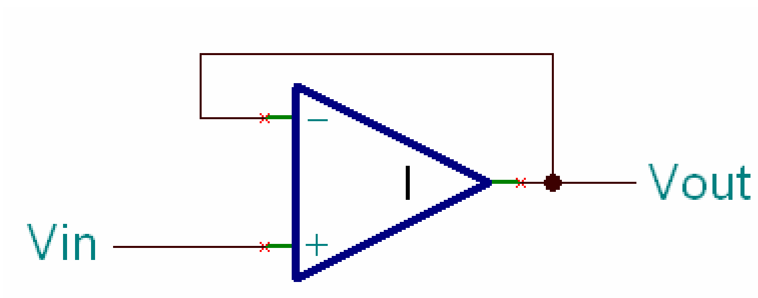
2. The +ve and –ve (non-inverting and inverting) inputs are forced to be at the same potential.

   => Because of infinite open loop gain

3. These property is called “virtual ground”

4. Use the ideal op amp property in all your analyses

OPAMP: VOLTAGE FOLLOWER



$V_+ = V_{IN}$.

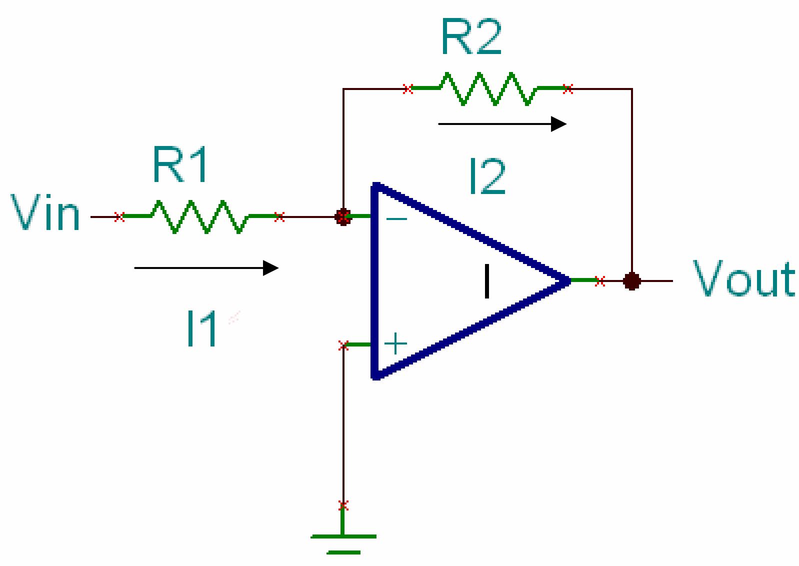
By virtual ground, $V_- = V_+$

Thus $V_{out} = V_- = V_+ = V_{IN}$!!!!

So what's the point ? The point is, due to the infinite input impedance of an op amp, no current at all can be drawn from the circuit before V_{IN}. Thus this part is effectively isolated.

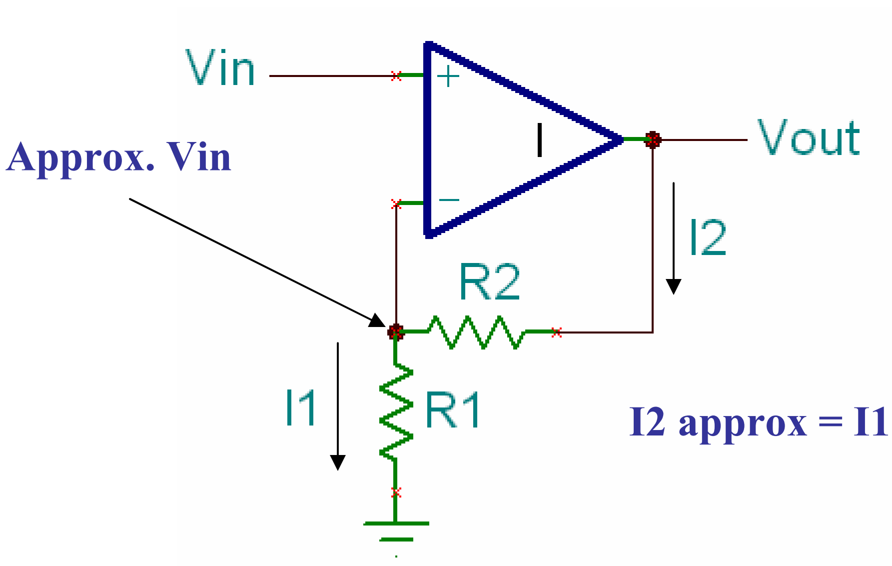
Very useful for interfacing to high impedance sensors such as microelectrode, microphone…

OPAMP: INVERTING AMPLIFIER



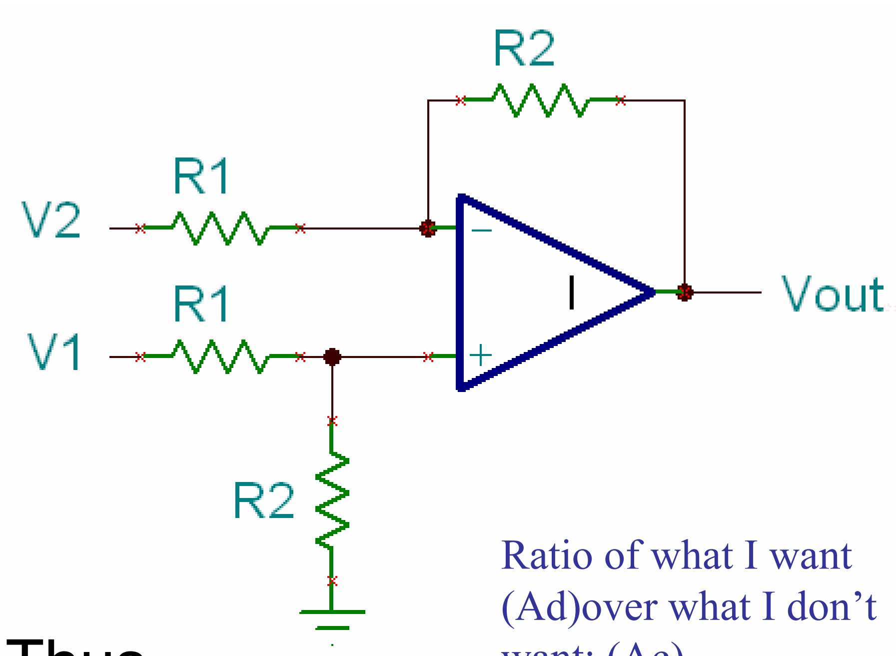
1. $V_- = V_+$
2. As $V_+ = 0$, $V_- = 0$
3. As no current can enter V_- and from Kirchoff's Ist law, $I_1 = I_2$.
4. $I_1 = (V_{IN} - V_-)/R_1 = V_{IN}/R_1$
5. $I_2 = (0 - V_{OUT})/R_2 = -V_{OUT}/R_2 \Rightarrow V_{OUT} = -I_2R_2$
6. From 3 and 5, $V_{OUT} = -I_2R_2 = -I_1R_2 = -V_{IN}(R_2/R_1)$
7. Therefore **$V_{OUT} = (-R_2/R_1)V_{IN}$**

OPAMP: NON – INVERTING AMPLIFIER



1. $V_- = V_+$
2. As $V_+ = V_{IN}$, $V_- = V_{IN}$
3. As no current can enter V_- and from Kirchoff's Ist law, $I_1 = I_2$.
4. $I_1 = V_{IN}/R_1$
5. $I_2 = (V_{OUT} - V_{IN})/R_2 \Rightarrow V_{OUT} = V_{IN} + I_2R_2$
6. $V_{OUT} = I_1R_1 + I_2R_2 = (R_1+R_2)I_1 = (R_1+R_2)V_{IN}/R_1$
7. Therefore $\mathbf{V_{OUT} = (1 + R_2/R_1)V_{IN}}$

DIFFERENTIAL AMPLIFERS



Ratio of what I want (Ad)over what I don't want: (Ac)

$V_{OUT} = (V_1 - V_2)R_2/R_1$

Amplifies a *difference*.

Common noise sources add symmetrically to an opamp. Thus there is a differential (V1 – V2) and a common mode (V1 + V2) component to the input.

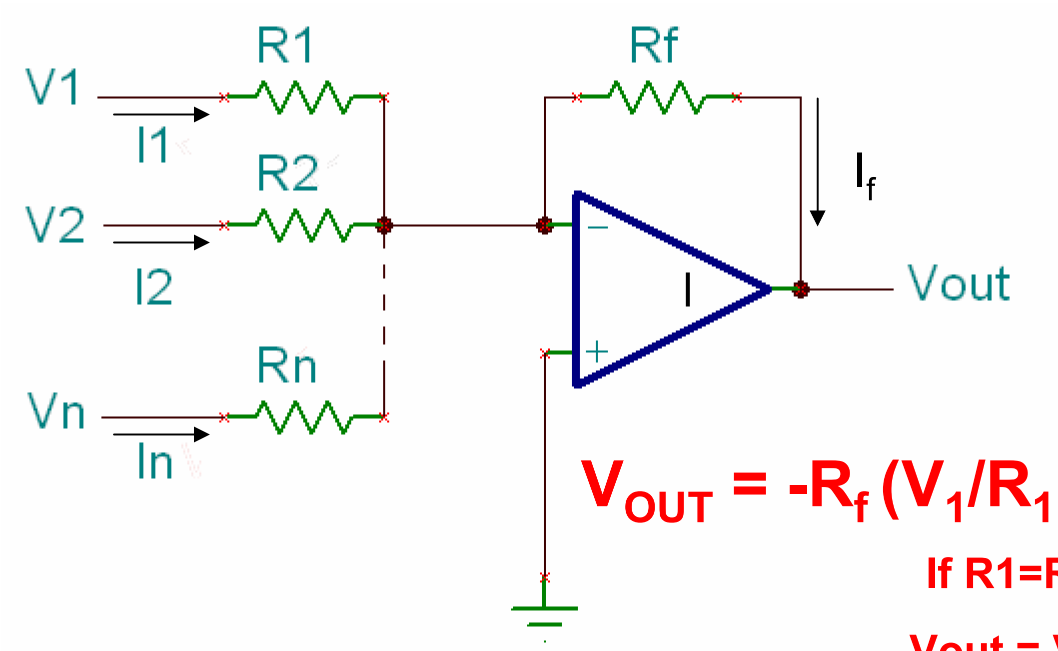
Thus ,

$V_{OUT} = A_C(V_1 + V_2) + A_D(V_1 - V_2)$

A_D:differential (signal) gain, A_C:common mode (noise) gain.

The ratio A_D/A_C (*Common Mode Rejection Ratio – CMRR*) is a very important parameter. Ideally CMRR $\rightarrow \infty$

SUMMING AMPLIFIER



Recall inverting amplifier and

$I_f = I_1 + I_2 + \ldots + I_n$

$$V_{OUT} = -R_f\,(V_1/R_1 + V_2/R_2 + \ldots + V_n/R_n)$$

If R1=R2=…=Rf, then

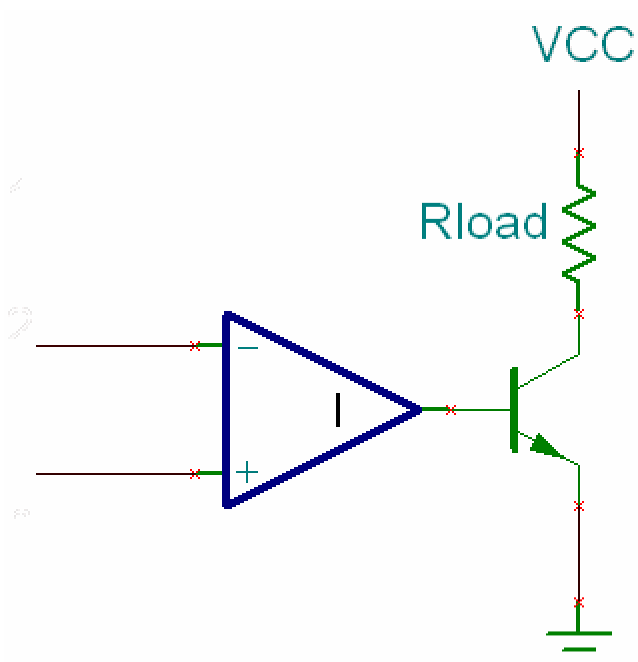
Vout = V1 + V2 +…+Vn

Summing amplifier is a good example of analog circuits serving as analog computing amplifiers (analog computers)!

Note: analog circuits can add, subtract, multiply/divide (using logarithmic components, differentiat and integrate – in real time and continuously.

DRIVING OPAMPS

•For certain applications (e.g. driving a motor or a speaker), the amplifier needs to supply high current. Op amps can't handle this so we modify them thus



Irrespective of the opamp circuit, the small current it sources can switch ON the BJT giving orders of magnitude higher current in the load.

e.g. to drive a loud speaker or a motor

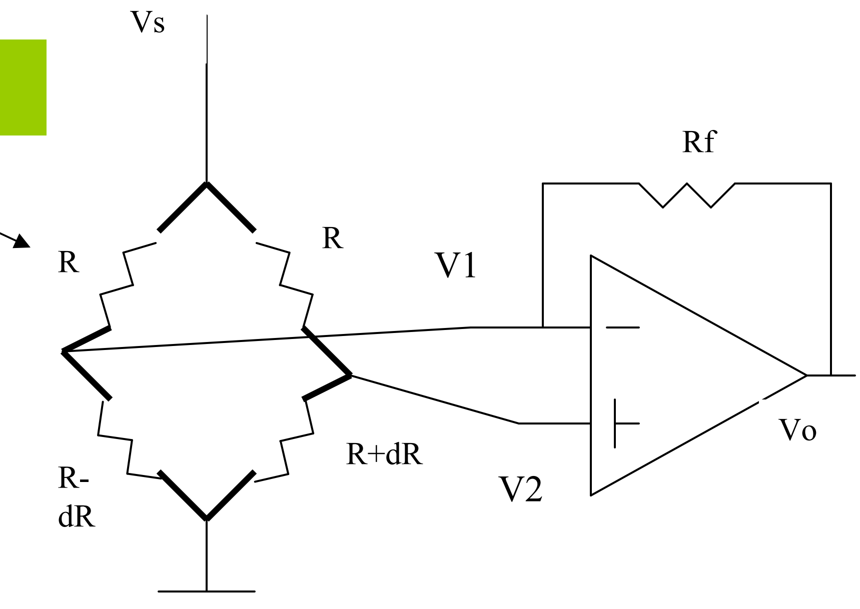
Indeed, circuits exist to boost current as well as power

APPLICATION: Interfacing Strain Gauges in a Bridge Circuit

We would like to measure small displacements or strains using strain gauges. These are variable resistances that respond to small changes in strain/stretch-contraction of the surface the sensor is mounted on. (i) suggest a suitable application. (ii) A useful design is to put the strain gauge in a bridge circuit design. Calculate the output of the following circuit for a very small dR changes with respect to the R values of the bridge elements. Hint: The output should be a relationship between V, R, dR, Rf and Vo.

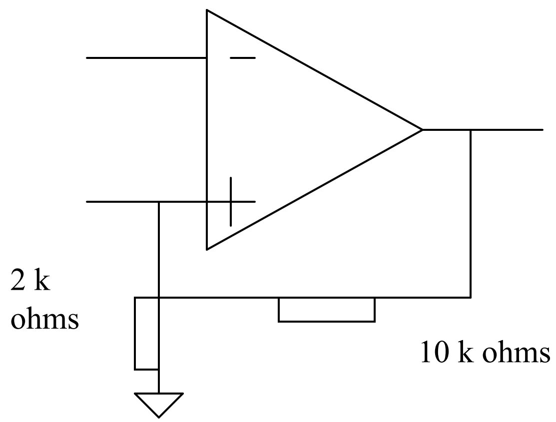
Strain Gauges

Strain gauges are restistors whose value changes with strain of the material they are mounted on



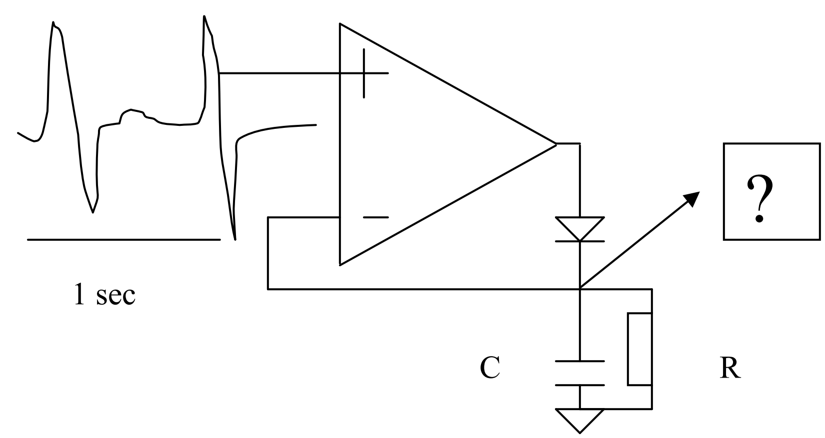
Bridge circuit **Differential amplifier**

When the bridge is balanced dR=0. When unbalanced due to strain, dR=/ 0 and hence V1-V2 gives proportional output. Then, of course, the op amp differential amplifier amplifies this small signal

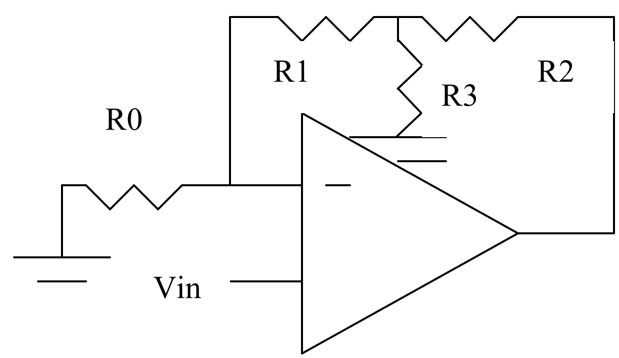


This is a circuit of a comparator (note the positive feedback). What would be the output of this circuit for the following input voltages: -5 V, -1 V, +1 V, and +5 V? The op amp is powered by ± 10 V (that would also be the maximum swing of the output).

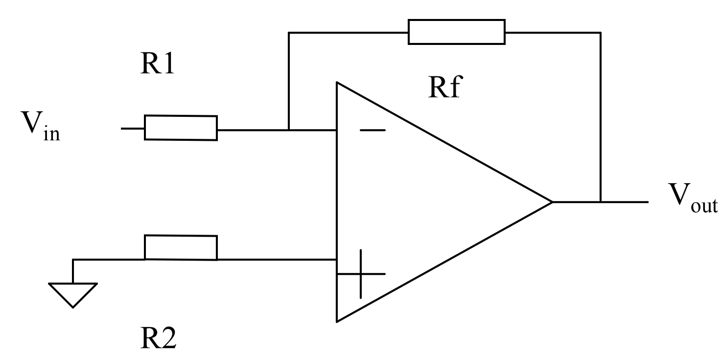
You visit a hospital and see a state of the art ECG monitoring instrument. You open up the technical manual and the following circuit is presented to you. Ostensibly, this circuit is at the output of the ECG amplifier (i.e. the amplified ECG goes to this circuit) and the output (marked ?) goes to a comparator. C= 1 uF and R=330Kohm. Draw the signal you expect to see at the point marked by a question mark.



For the following circuit, what is the input impedance and the output impedance. Now, calculate the closed loop gain. Use basic circuit analysis ideas using op amps to work through the analysis (Hint: identify the virtual ground, obtain currents in the input and the feedback paths, obtain input-output relationship).



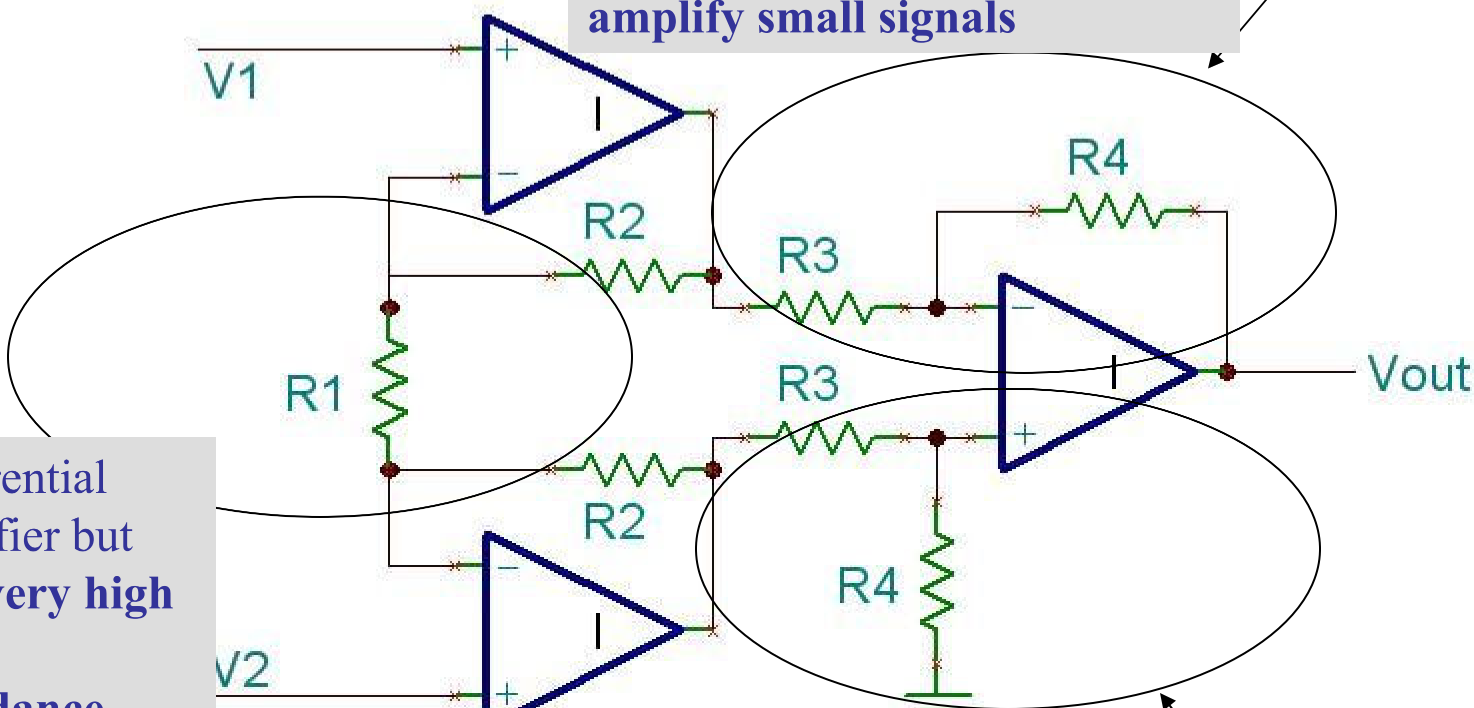
For the following circuit, calculate the input resistance. (i) First, calculate input resistance for an ideal amplifier. (ii) Next, calculate the input resistance of a non-ideal amplifier. Note that the input resistance of the op amp is R_{in} (not shown, but your can assume such a resistance going to ground from each of the – and + inputs).



INSTRUMENTATION AMPLIFIER

Inverting amplifier

Gain in the multiple stages: i.e. **High Gain – so, you can amplify small signals**



As a bonus, put some **lowpass and high pass filters!**

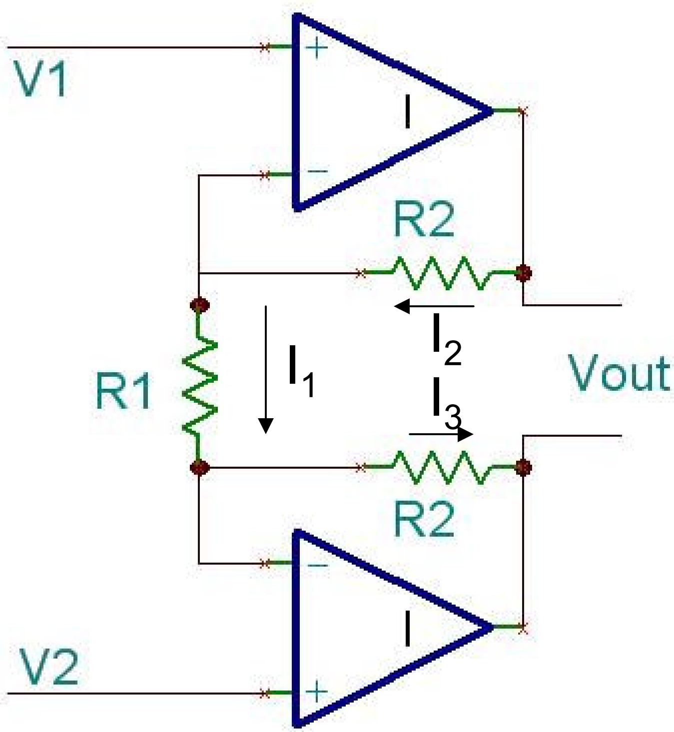
Differential amplifier but with **very high input impedance**

- So, you can connect to sensors

Differential amplifier -> **it rejects common-mode interference -> so you can reject noise**

Non-inverting amplifier

INSTRUMENTATION AMPLIFIER: STAGE 1



Recall virtual ground of opamps

$I_1 = (V_1 – V_2)/R_1$

Recall no current can enter opamps and Kirchoff's current law

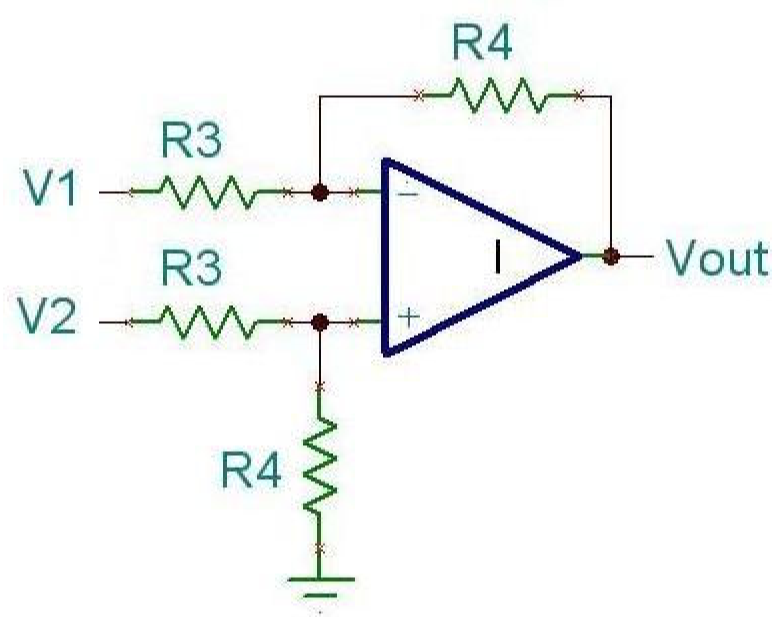
$I_2 = I_3 = I_1$

Recall Kirchoff's voltage law

$V_{OUT} = (R_1 + 2R_2)(V_1 – V_2)/R_1$

$= (V_1 – V_2)(1+2R_2/R_1)$

INSTRUMENTATION AMPLIFIER: STAGE 2



Recall virtual ground of opamps and voltage divider

$V_- = V_+ = V_2R_4/(R_3 + R_4)$

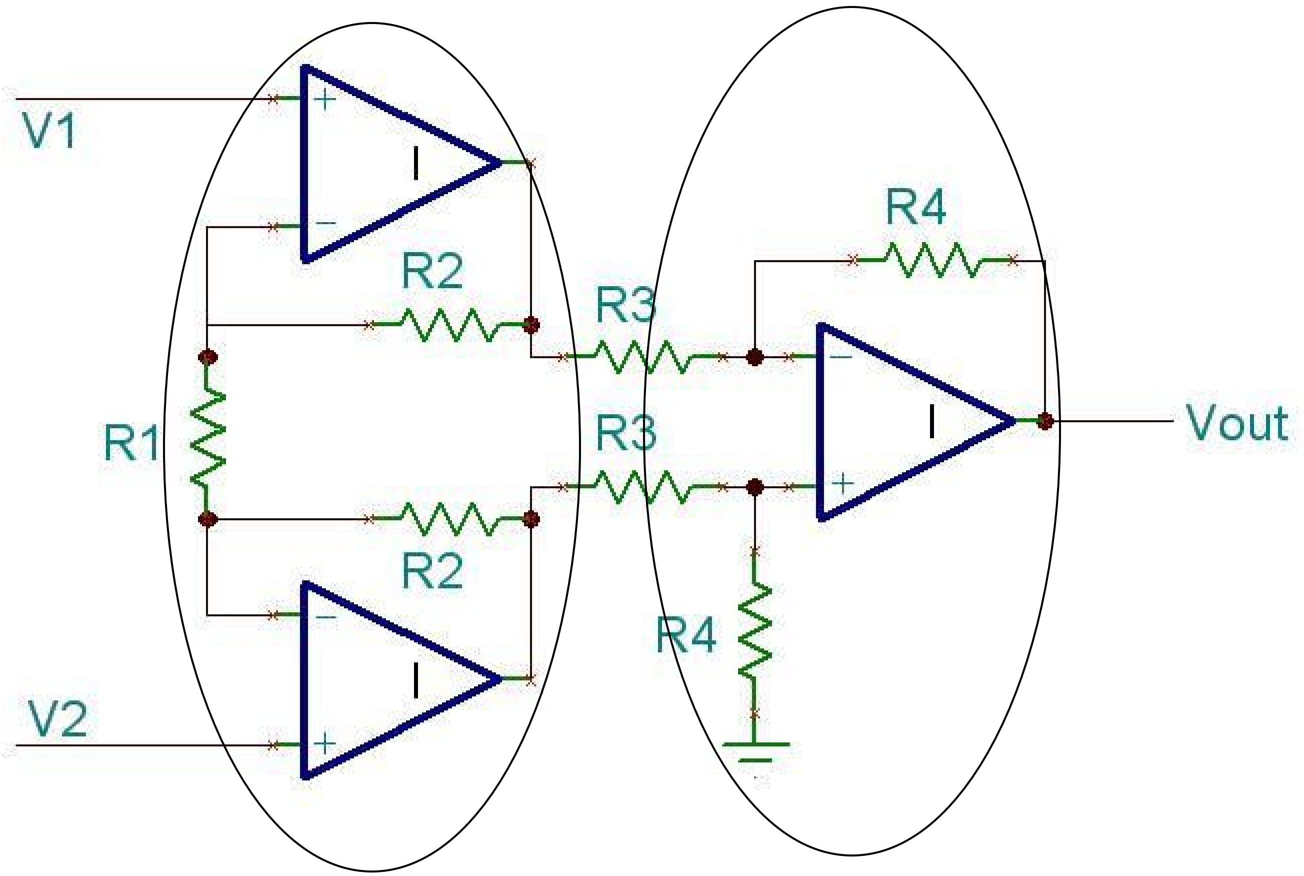
Recall no current can enter opamps

$(V_1 - V_-)/R_3 = (V_- - V_{OUT})/R_4$

Solving,

$V_{OUT} = -(V_1 - V_2)R_4/R_3$

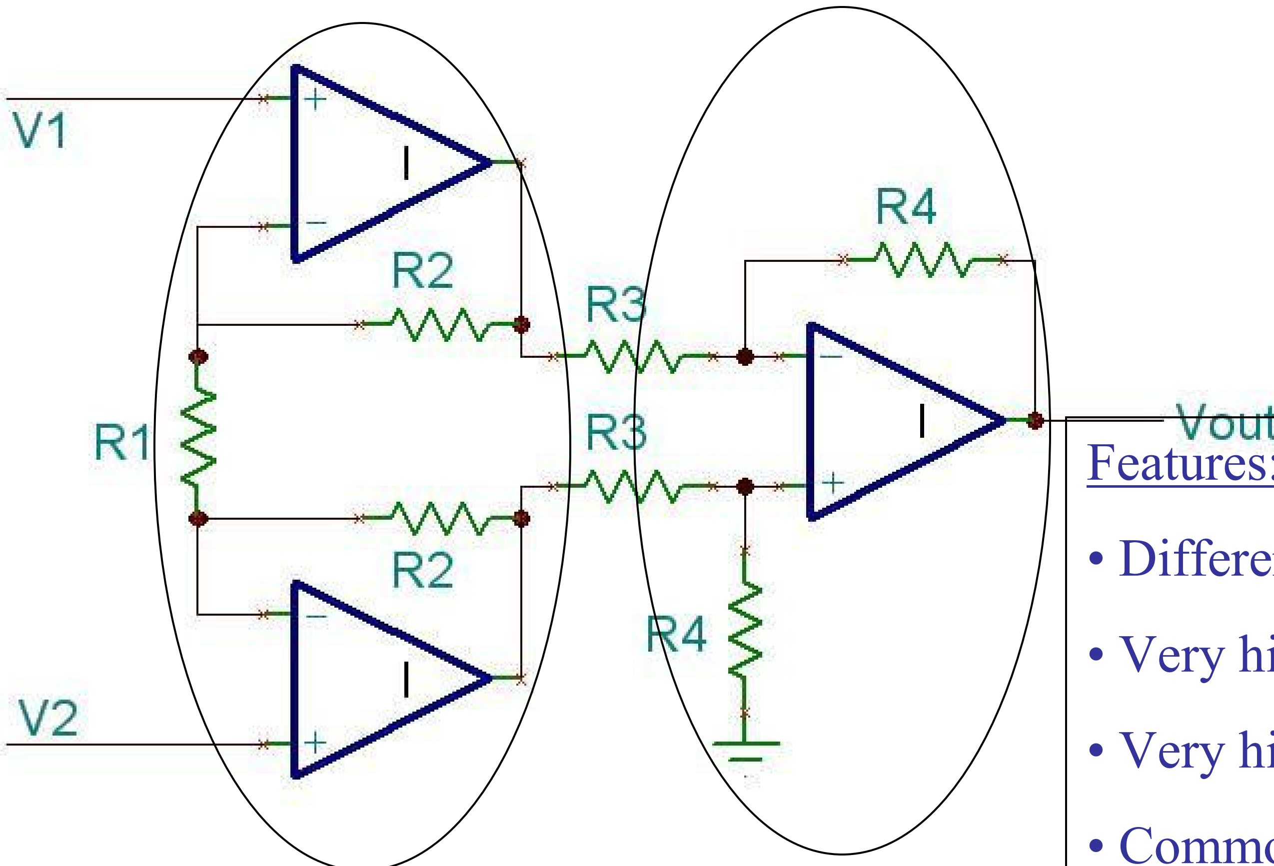
INSTRUMENTATION AMPLIFIER: COMPLETE



$$V_{OUT} = -(V_1 - V_2)(1 + 2R_2/R_1)(R_4/R_3)$$

Gain from <u>Stage I</u> and <u>Stage II</u>

INSTRUMENTATION AMPLIFIER: COMPLETE



$$V_{OUT} = -(V_1 - V_2)(1 + 2R_2/R_1)(R_4/R_3)$$

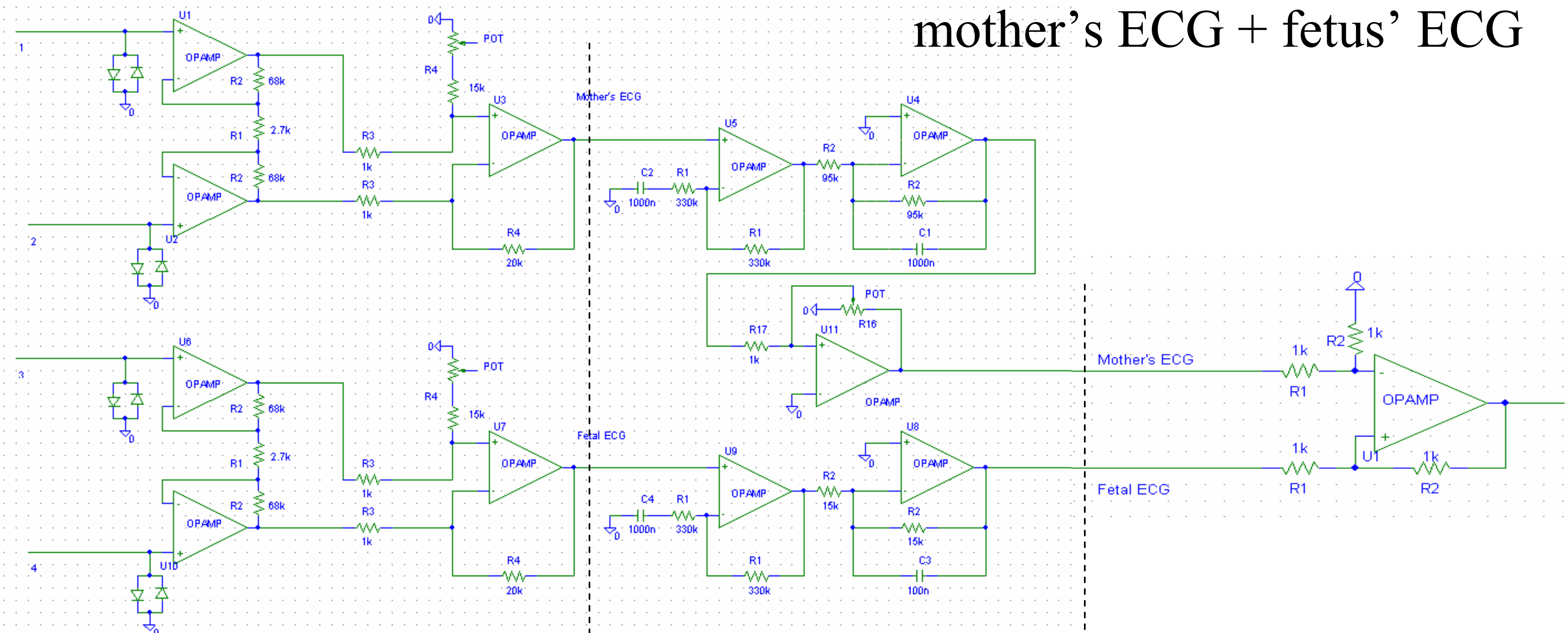
Gain from <u>Stage I</u> and <u>Stage II</u>

<u>Features:</u>

- Differential amp
- Very high gain
- Very high input R
- Common mode rejection
- (we also need filters)

APPLICATION: Fetal ECG

Problem: Recorded ECG = mother's ECG + fetus' ECG



UP: mother ECG ampl.

DN: fetus ECG ampl.

mother ECG filters

fetus ECG filters

V_{OUT} = mother's ECG – fetus' ECG

Problems

- Research commercial Op Amps – e.g. 741 op amp (try company like Analog Devices or Texas Instruments, Maxim, Siliconix, …
  - – Identify from the company catalogs op amps for specialized needs. E.g. for low noise, low power, ultra high bandwidth, ultrahigh input impedance
- Devise different applications for
  - – Integrator (e.g. charge integrator…what sensor? Biopotential measurement.) and Differentiator, Logarithmic amplifier (draw circuits or look up applications in literature)
- Next, consider an application of driving an ultrasound transducer with very high voltage. Op amps work at small voltages. How would you boost the op amp output?
  - – Look up circuits/application notes – e.g. Art of Electronics or company application notes).
- Properties of Op Amps in ideal conditions differ from the nonideal. What are the environmental considerations?
  - – E.g. How does the temperature or noise change? Look up these specifications in commercial devices.

More Problems, More Fun

- Analog Computing! How can we do it?
  - We can add
  - We can subtract
  - We can do logarithm…multiply and divide
  - Can we integrate?
  - Can we differentiate?
  - Can we compare?

IF WE CAN DO ALL THIS, WE HAVE AN **ANALOG COMPUTER!**

- Is Analog Computer or Digital Computer better?
  - What components (i.e. circuit components, chips) do you use for analog vs. digital computers?
  - What are the limitations of analog/digital computers
  - What one or two application each is best suited for?