Operational Amplifiers: Basic Concepts

Prof. Greg Kovacs

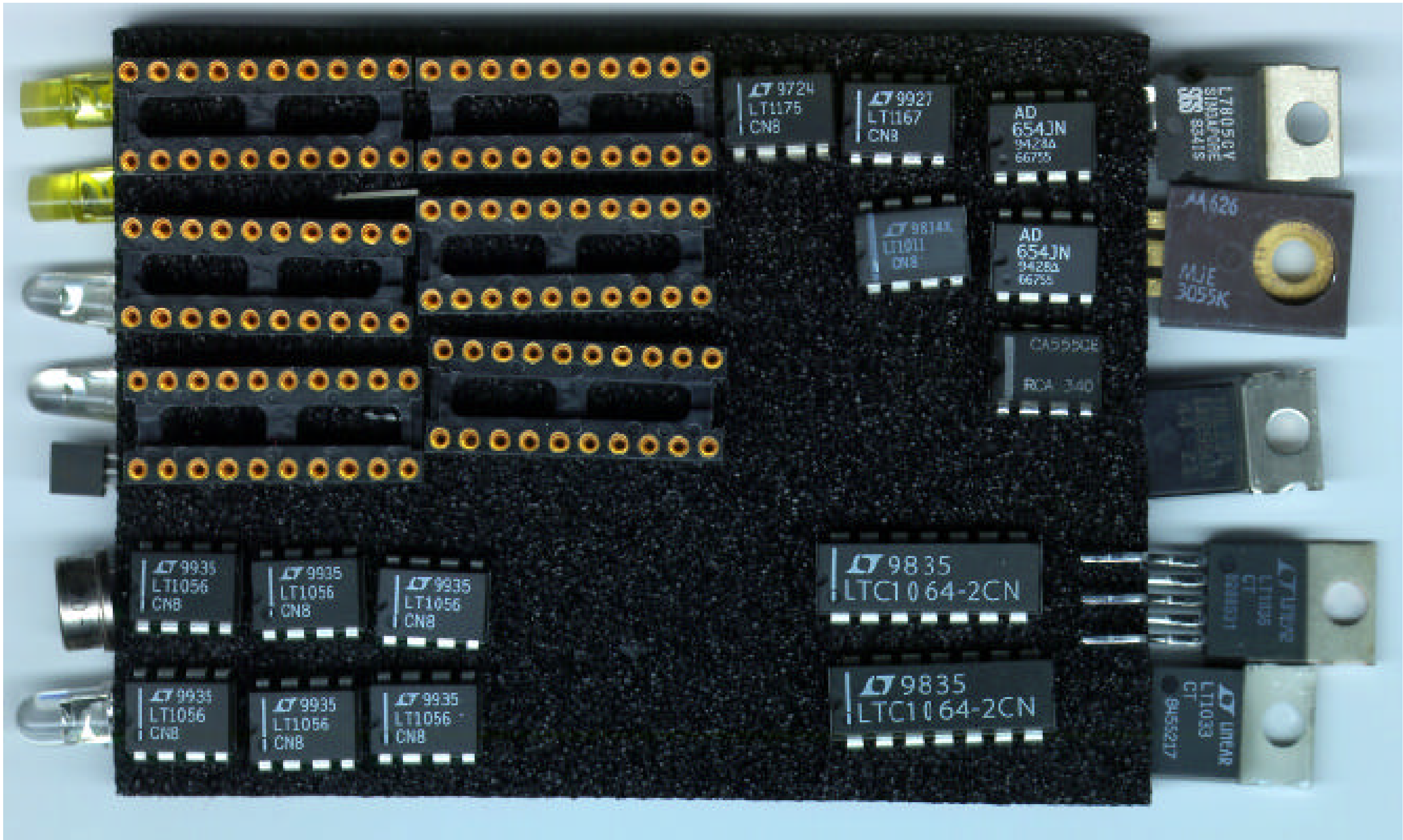
Department of Electrical Engineering

Stanford University

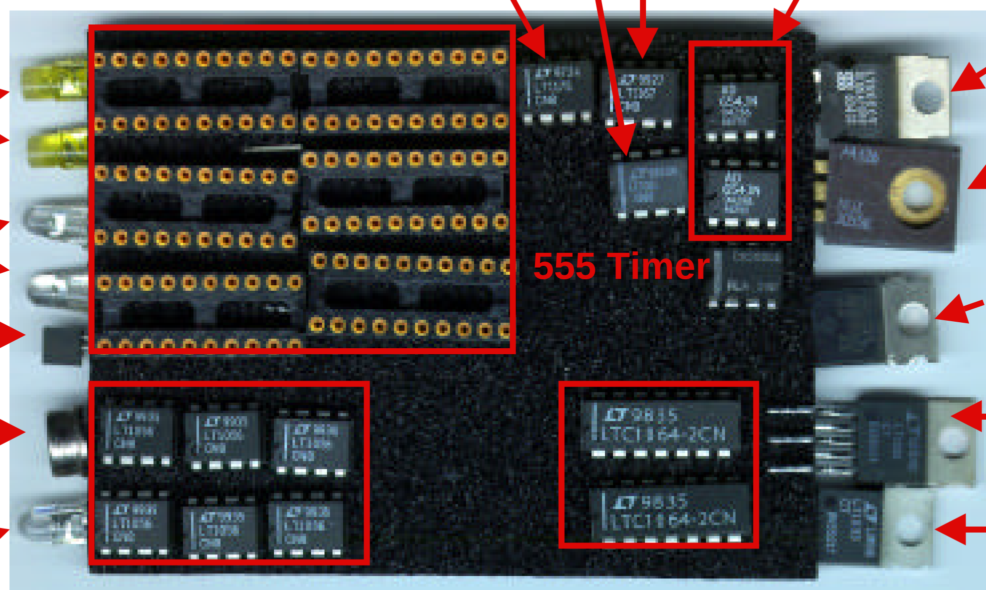
Design Note: The Design Process

- Definition of function - what you want.
- Block diagram - translate into circuit functions.
- First Design Review.
- Circuit design - the details of how functions are accomplished.
  - Component selection
  - Schematic
  - Simulation
  - Prototyping of critical sections
- Second Design Review.
- Fabrication and Testing.

EE122 Parts Kit

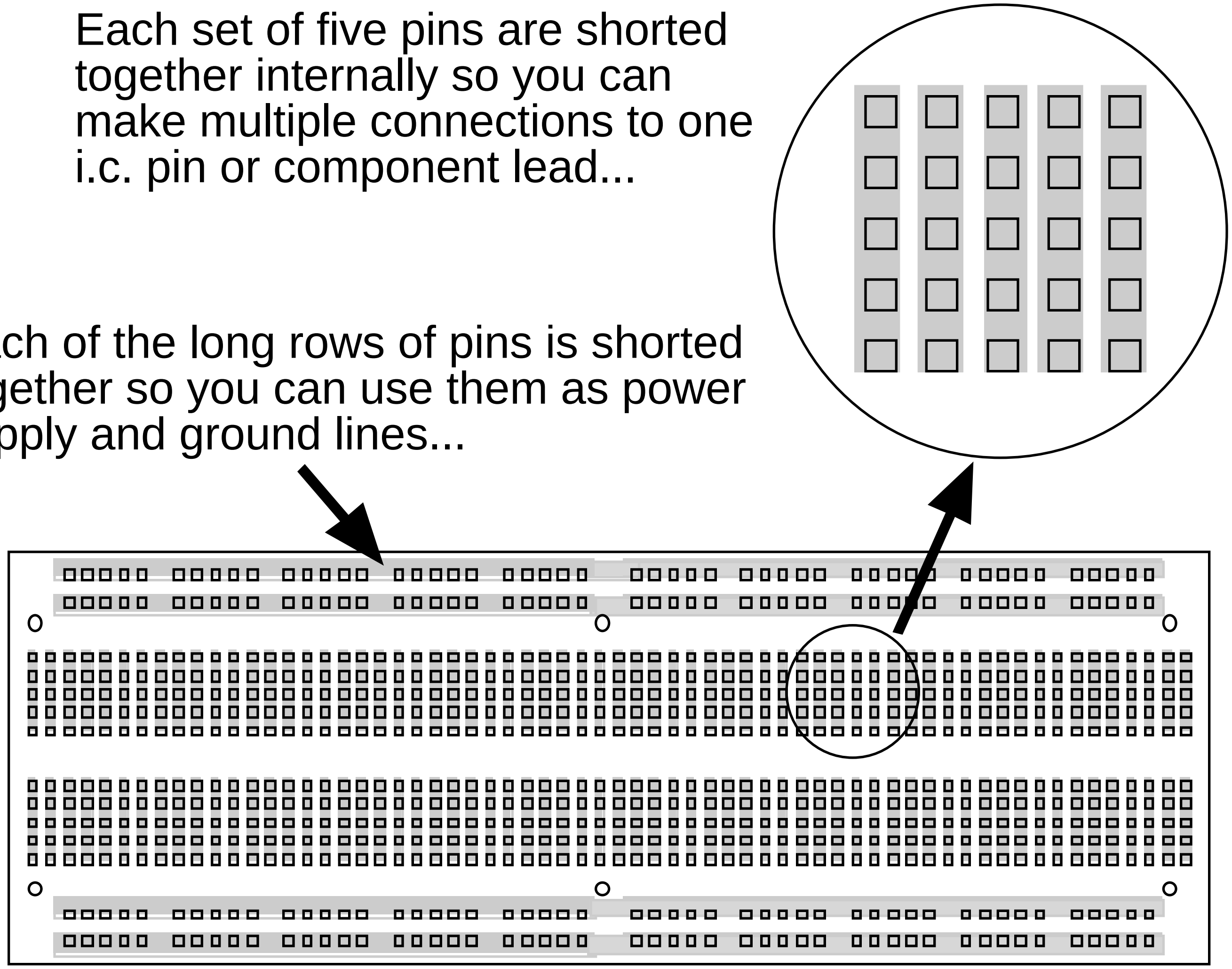


Parts Kit Guide



Each set of five pins are shorted together internally so you can make multiple connections to one i.c. pin or component lead...

Each of the long rows of pins is shorted together so you can use them as power supply and ground lines...

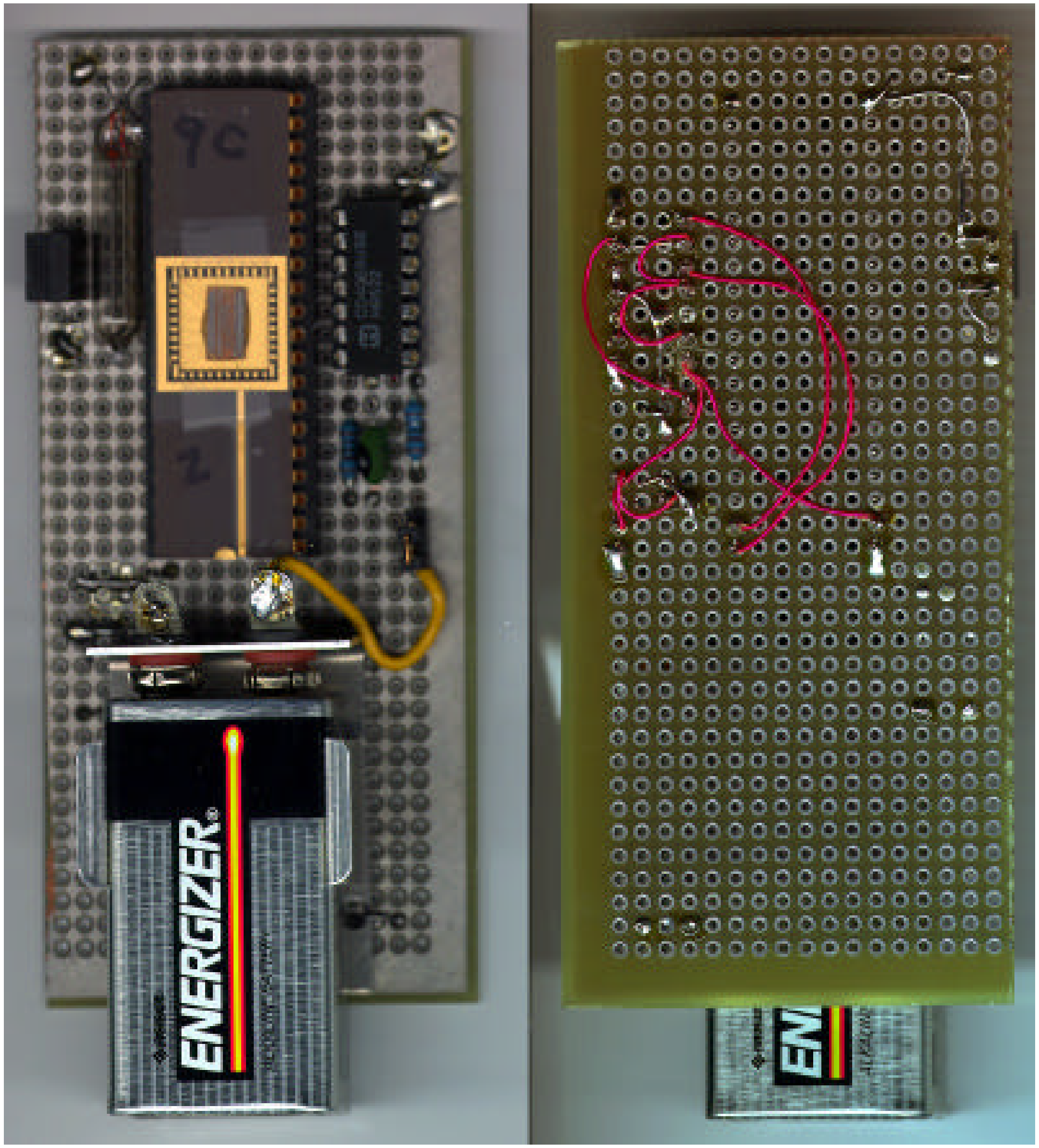


Protoboards...

USE decoupling capacitors (typically 0.1 µF) from each power supply rail to ground. This is essential to prevent unwanted oscillations.

The capacitors locally source and sink currents from the supply rails of the chips, preventing them from "talking" to each other and their own inputs!

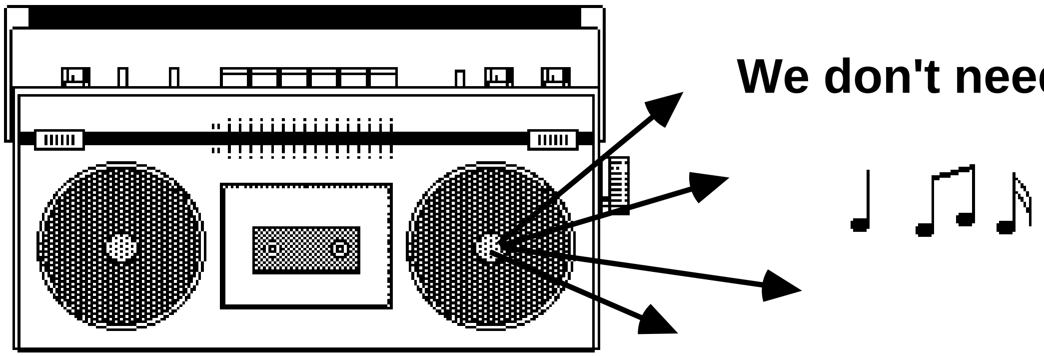
Point-To-Point Soldering On A Ground-Planed Board



What Is an Op-Amp Anyway?

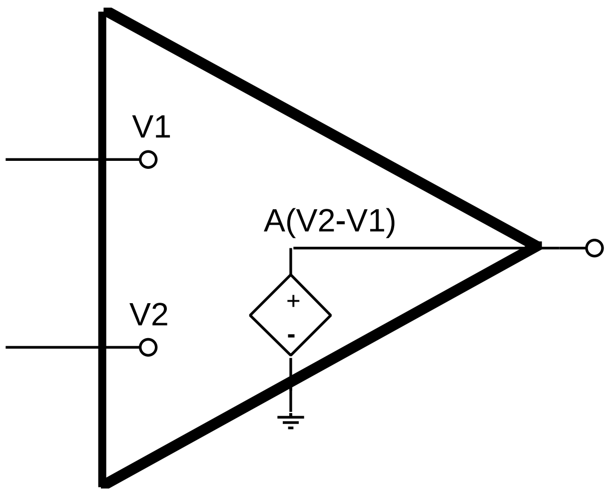
OBJECTIVES (Why am I sitting in this classroom?)

- **To obtain a practical understanding of what operational amplifiers (“op-amps”) are and some applications they can be used for.**
- **To understand the basic op-amp circuit configurations.**
- **To understand the basic characteristics (good and bad) of op-amps before measuring some of them in the lab.**
- **To keep your parents happy!**



We don't need no education....

The Ideal Op-Amp



The Op-Amp produces an output voltage that is the difference between the two input terminals, multiplied by the gain A...

1) The input impedance is infinite - i.e. no current ever flows into either input of the op-amp.

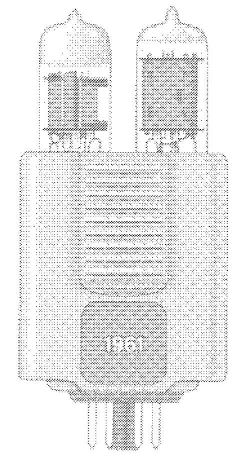
2) The output impedance is zero - i.e. the op-amp can drive any load impedance to any voltage.

3) The open-loop gain (A) is infinte.

4) The bandwidth is infinite.

5) The output voltage is zero when the input voltage difference is zero.

Types of Op-Amps



- Single
- Dual
- Quad

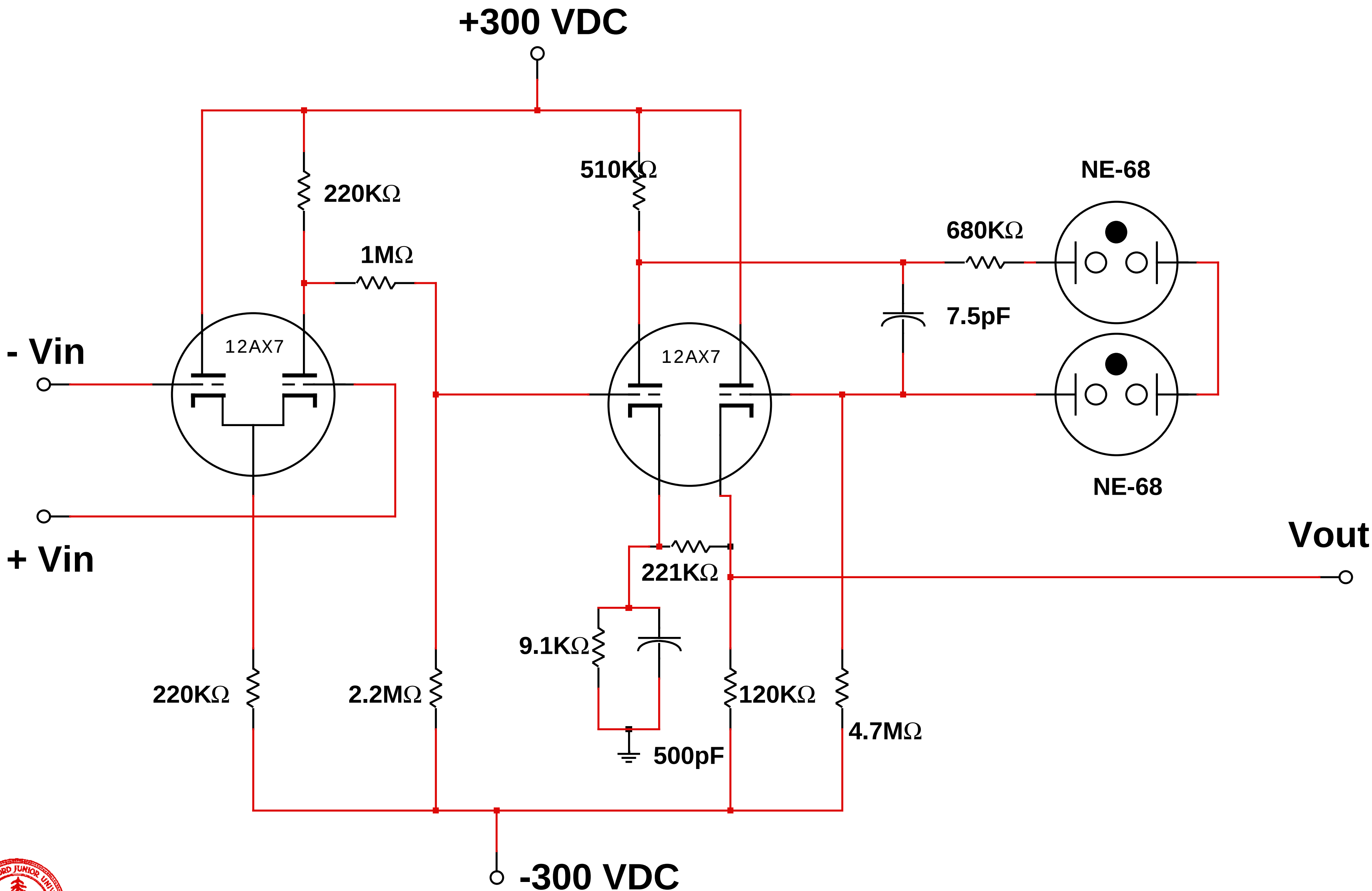
- Low power
- Low noise
- Low offset
- High power
- High voltage
- High speed

Traditional costumes of
analog circuit designers.

A Bit of History...

- The first Op-Amps were invented during the time of the Second World War...
- Dr. C. A. Lovell of Bell Telephone Laboratories introduced the Op-Amp...
- George A. Philbrick independently introduced a single vacuum tube operational amplifier in 1948.
- SO, Op-Amps are NOT new!
- The ever-popular 741 monolithic Op-Amp was designed by Dave Fullagar in 1967....

The First "Real" OpAmp -> The K2-W




K2-XA
GAP/R
MODEL
K2-XA

The K2-W Tube OpAmp

- Invented by Julie Loebe and George Philbrick (early 1950's)
- The first "mass production" OpAmp...
- Cost (in 1950's) approximately $22.00...
- Basic specifications comparison to 741 and LT1037...

Parameters	K2-W OpAmp	741 OpAmp	LT1037 OpAmp
Power Supplies	+/- 300 VDC, 6.3 VAC (filaments)	+/- 15V	+/- 15V
Open-Loop Gain	1.5×10^4	5×10^4	30×10^6
V_{out} Swing	+/- 50V	+/- 12V	+/- 13.5 V
I_{out}	+/- 1 mA	25 mA	25 mA
I_{drain}	5 mA (no load)	1.7 mA	2.7 mA
R_L(min)	50 KΩ	none (SC protect)	none (SC protect)
Slew Rate	+/- 12 V/µSec	+/- 0.5 V/µS	15 V/µS

Good Op-Amp Web Sites

- www.linear-tech.com
- www.national.com
- www.burr-brown.com
- www.maxim-ic.com
- www.intersil.com

Cool New Project/Design Website:

www.designnotes.com

Submit your favorite circuit or program. Every month the best design entry (judged by your peers), wins $100 in cash! **Monthly winners are eligible** for the $1200 Grand Prize!

Courtesy Mr. Charlie Kiers.

Op-Amp Datasheets for EE122: Some Example Devices

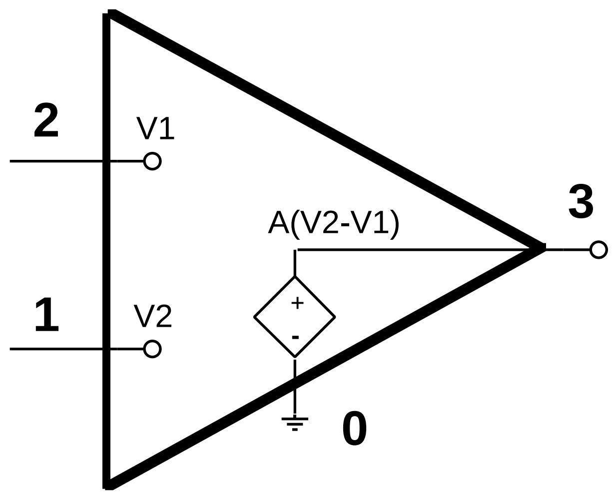
- LM741 (basic)
- LT1056 (JFET input)
- LMC660 (CMOS - low power)
- LT1220/1221 (fast)
- LM675 (medium power)
- LM12 (high power)

The Ideal Op-Amp In SPICE

Use a voltage-controlled voltage source:

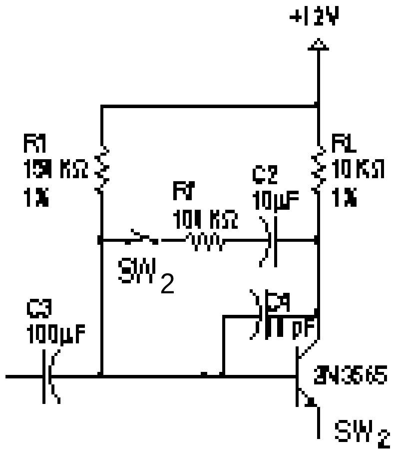
EXXXXXXX N+ N- NC+ NC- GAIN

Eout 3 0 1 2 100K

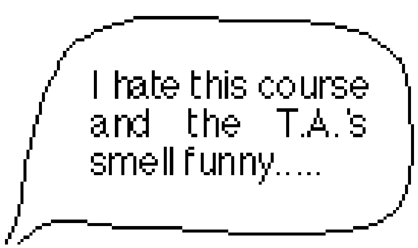


Feedback: What is it and Where Can I Get Some?

GOOD Feedback



BAD Feedback

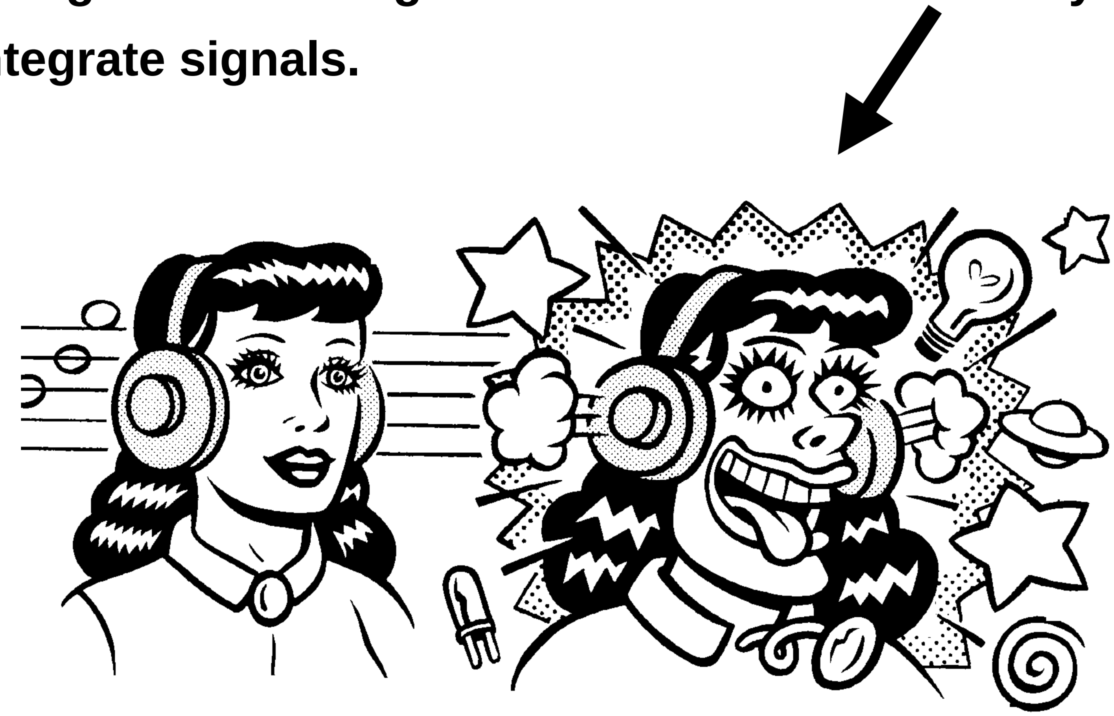


NEAT THINGS YOU CAN DO TO AN AMPLIFIER BY USING FEEDBACK (OF THE NEGATIVE KIND...)

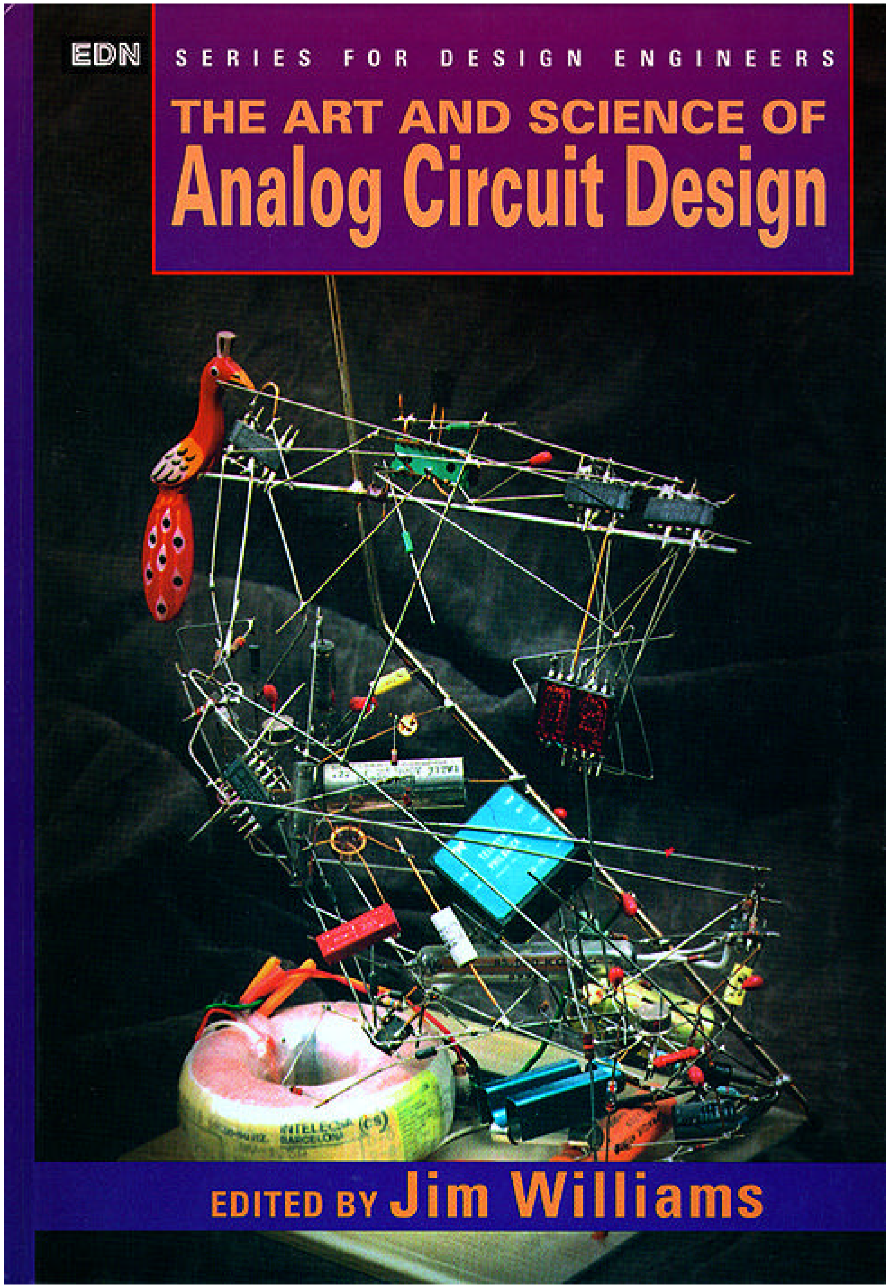
- **The gain of the circuit is made less sensitive to the values of individual components.**
- **Nonlinear distortion can be reduced.**
- **The effects of noise can be reduced.**
- **The input and output impedances of the amplifier can be modified.**
- **The bandwidth of the amplifier can be extended.**

WHAT CAN YOU DO WITH OP-AMPS?

- Feed the hungry.
- Amplify signals.
- Heal the sick.
- Buffer signals.
- End global warming.
- Integrate signals.
- Save the dolphins.
- Differentiate signals.
- Pay off the deficit.
- Sum multiple signals.
- Make music very loud!



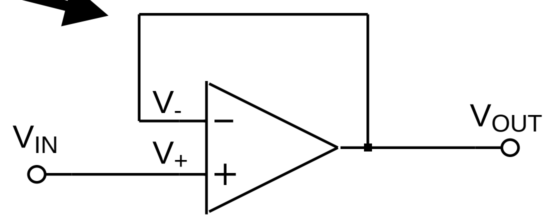
Jim Williams



Analog Hacker's Bible

THE VOLTAGE FOLLOWER

$V_- = V_{OUT}$



$$V_{OUT} = A\left(V_+ - V_-\right)$$

$$V_{OUT} = \cancelto{1}{\frac{A}{\left(1 + A\right)}} V_+$$

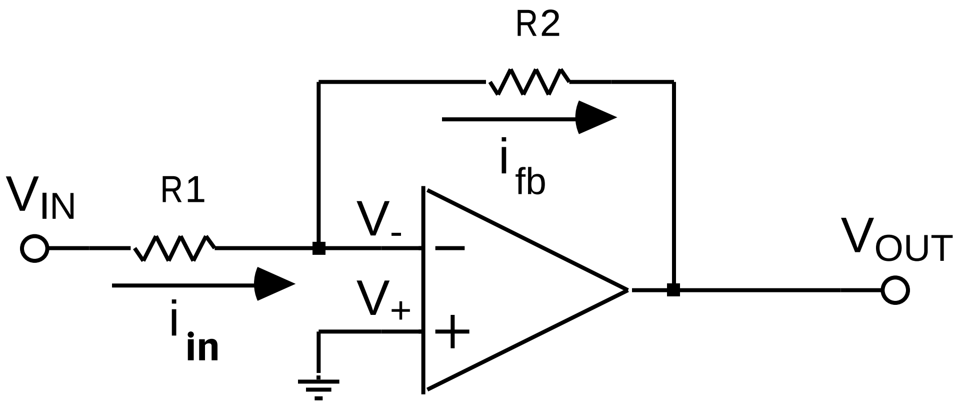
What is it good for?

Buffering a high-impedance signal to "beat" Heisenberg... You don't load it down when you measure it...

It has the best bandwidth of any op-amp circuit.

Some op-amps need to be COMPENSATED for stable unity-gain operation (more later....).

THE INVERTING AMPLIFIER



$$A_V = -\frac{R2}{R1}$$

The V- terminal is referred to as a "virtual ground"... Why is that?

$$V_{OUT} = A(0 - V_-)$$

thus,

$$V_- = \frac{V_{OUT}}{A} \approx \frac{V_{OUT}}{\infty} = 0$$

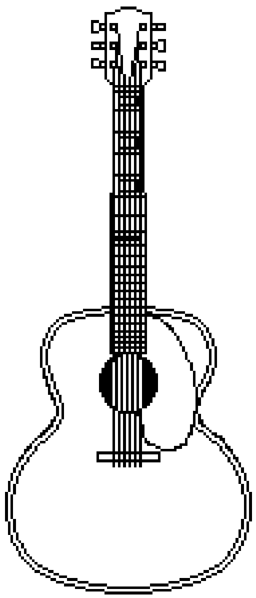
Due to NEGATIVE FEEDBACK!!!!

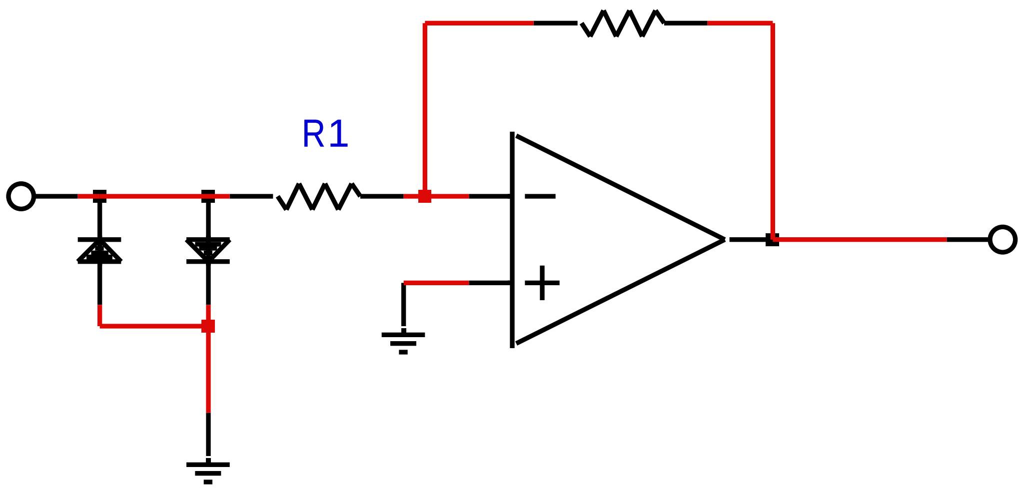
THIS IS A KEY POINT!!!

Op-Amp Application: CLIPPER (or "Fuzz Box")

Mellow Tunes

IN



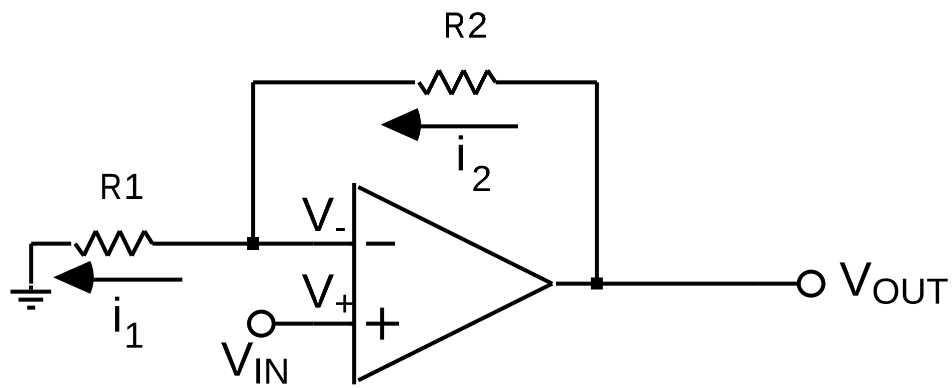


Heavy Metal

OUT

Input signal must be large enough to turn on diodes...

THE NON-INVERTING AMPLIFIER

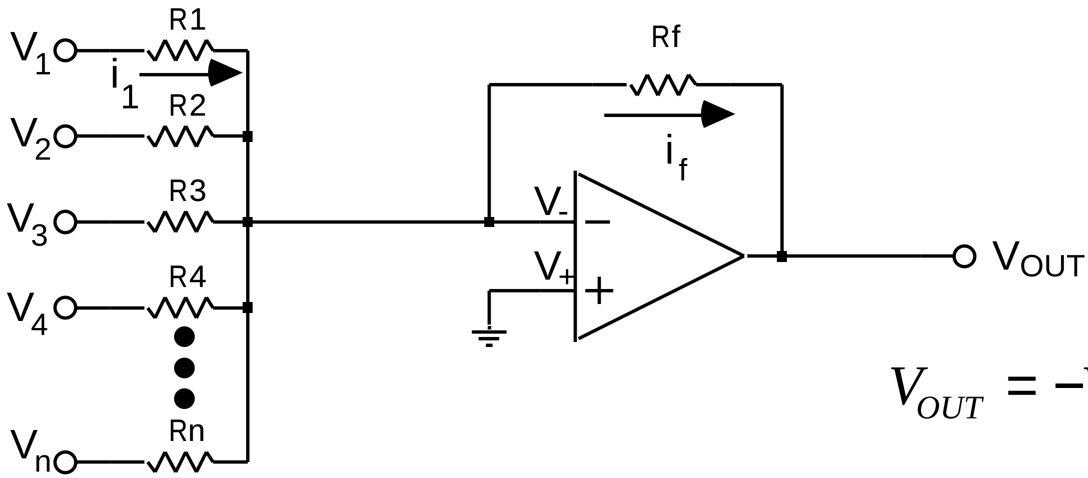


A key point to note here is that the V- node is not a virtual ground in this configuration!

The important thing to consider is that the voltage difference between V+ and V- is kept near zero. In other words, V- ≈ V_{IN}.

$$A_V = \left(1 + \frac{R2}{R1}\right)$$

THE SUMMING AMPLIFIER



$$V_{OUT} = -V_1 \frac{Rf}{R1} - V_2 \frac{Rf}{R2} - \cdots - V_N \frac{Rf}{RN}$$

$or,$

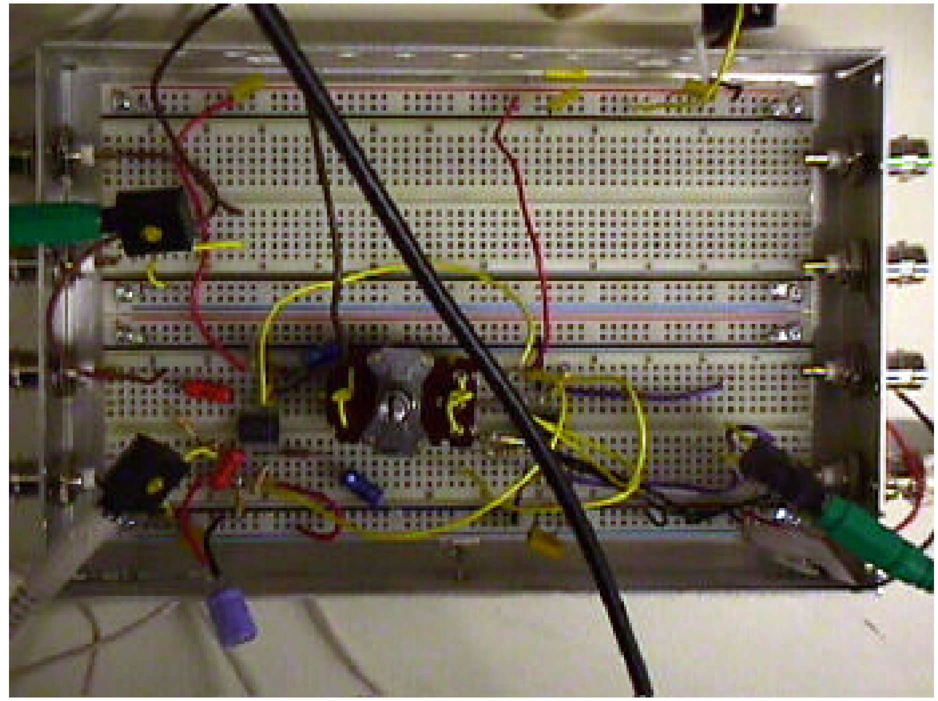
$$V_{OUT} = -Rf \sum_i \left(\frac{V_i}{Ri} \right)$$

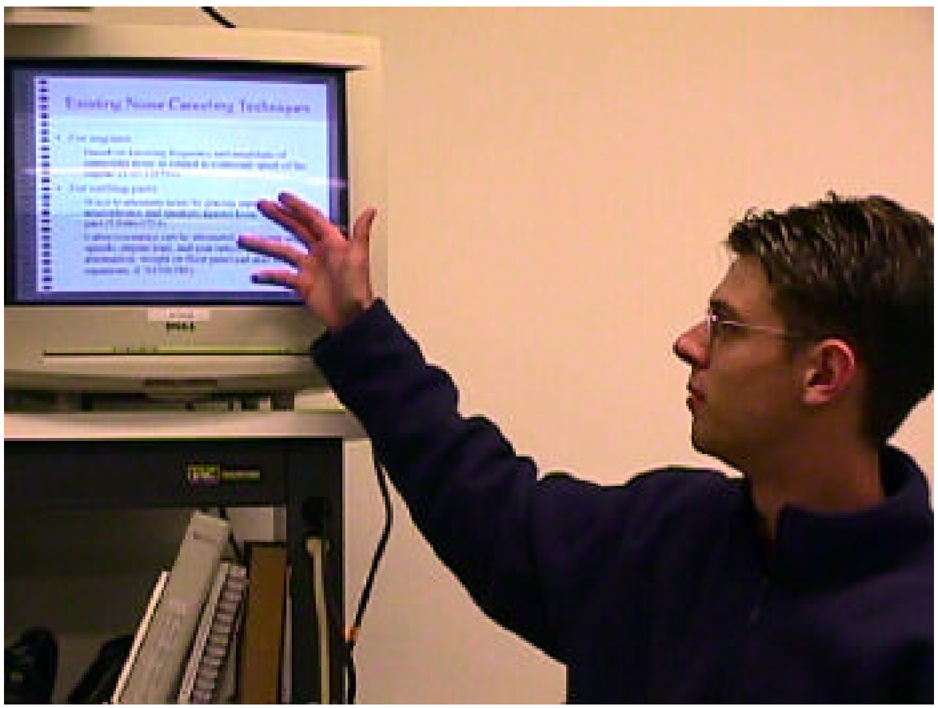
What is it good for?

Summing multiple input signals in any proportion desired (determined by the relative values of the input resistors.

Averaging signals (do you know how?).

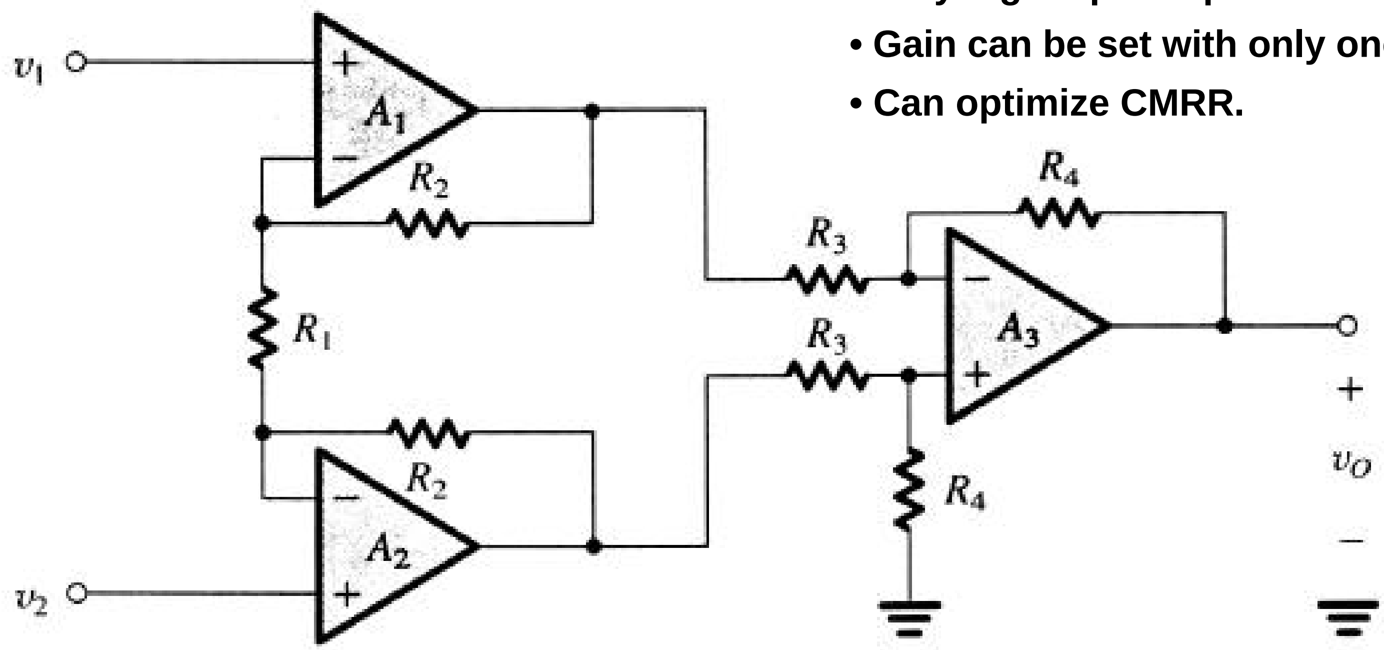
Noise Canceling Circuit





Instrumentation Amplifier

- Very high input impedance.
- Gain can be set with only one resistor.
- Can optimize CMRR.



$$A_V = -\frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)$$

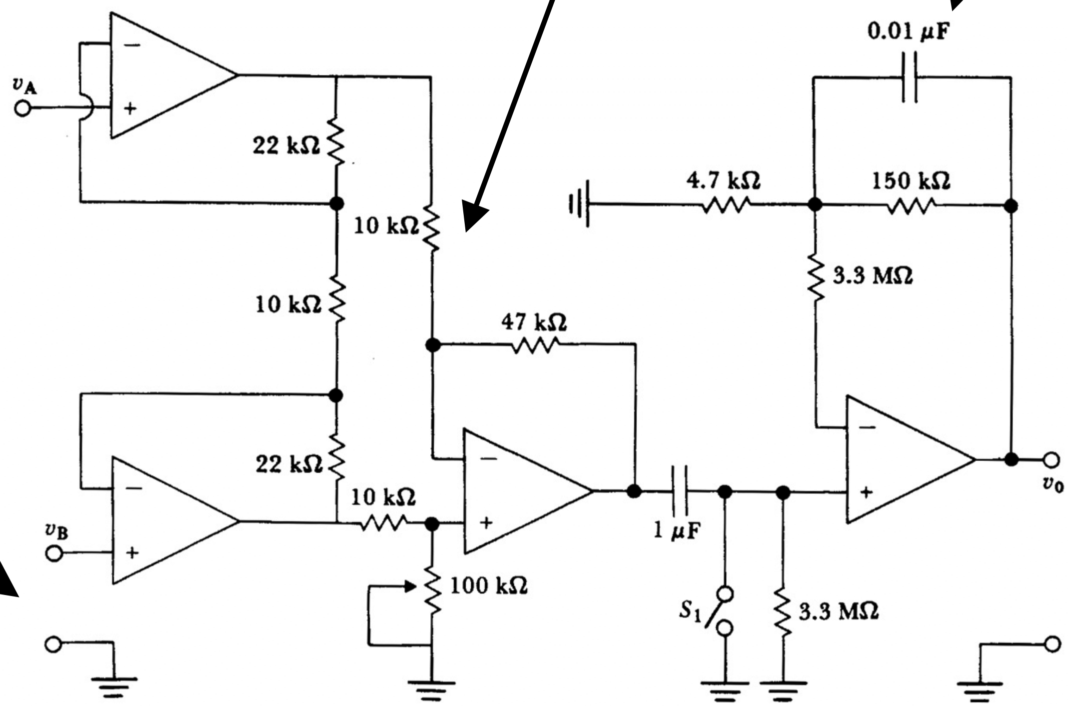
Source: Sedra, A. S., and Smith, K. C., "Microelectronic Circuits," Oxford, 1998.

For one-resistor gain adjust, set $R_4 = R_3$ and fix R_2.

Op-Amp Application: EKG

Filter (0.04 - 150 Hz)

Instrumentation Amplifier



Source: Webster, J. G., "Medical Instrumentation: Application and Design," Houghton Mifflin, 1978.

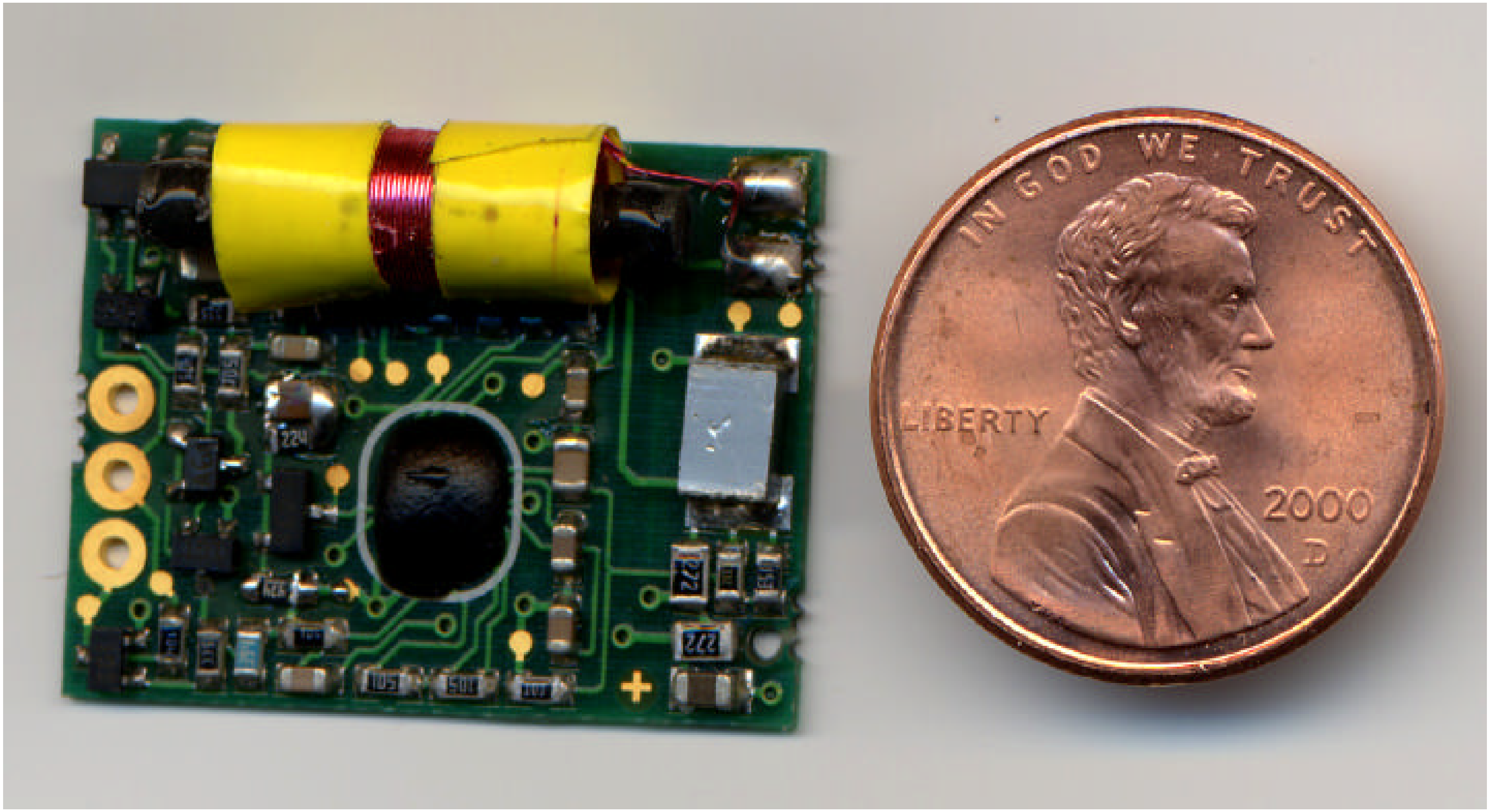
Figure 6.22 This ECG amplifier has a gain of 25 in the dc-coupled stages. The high-pass filter feeds a follower-with-gain stage having a gain of 32. The total gain is 25 × 32 = 800. Using μA 776 op amps, the circuit was found to have a CMRR of 86 dB at 100 Hz and noise level of 40 mV peak to peak at the output. The frequency response was 0.04 to 150 Hz for ± 3 dB and was flat over 4 to 40 Hz.

A Safe Heart Signal Interface

Polar™ heart-rate transmitter - provides magnetically coupled bursts of ≈ 5 kHz energy that mark the start of each heartbeat (i.e., you don't get the actual waveform).

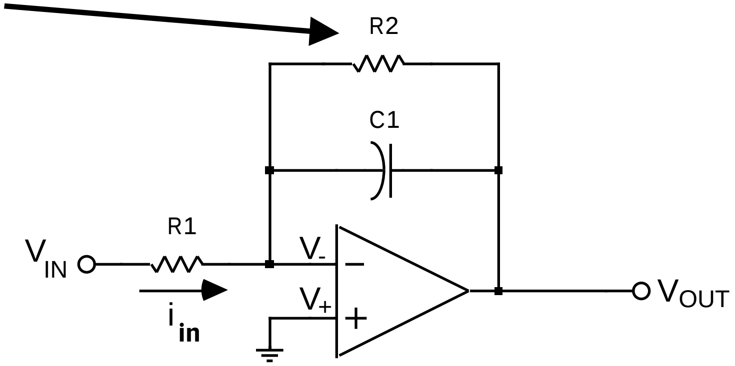
www.polarusa.com

Polar™ OEM Receiver



THE INTEGRATOR

Need R2 to make the integrator "leaky"... Otherwise small DC offsets would charge it up (and up, and up!!!!).



For DC inputs:

$$\frac{V_{OUT}}{V_{IN}} = -\frac{R2}{R1}$$

For AC inputs:

$$i_{in} = i_{fb}$$

$$\frac{v_{in}}{R1} = -C1\frac{dv_{out}}{dt}$$

$$v_{out} = -\frac{1}{(R1)(C1)}\int v_{in}dt$$

What is it good for?

Triangle wave generation.

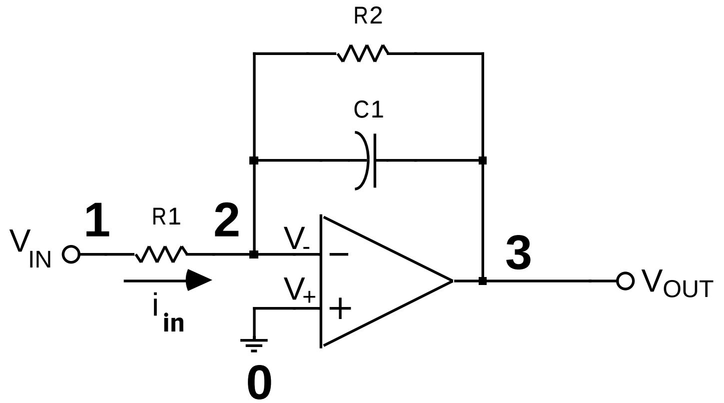
Ramp generation ('scopes!).

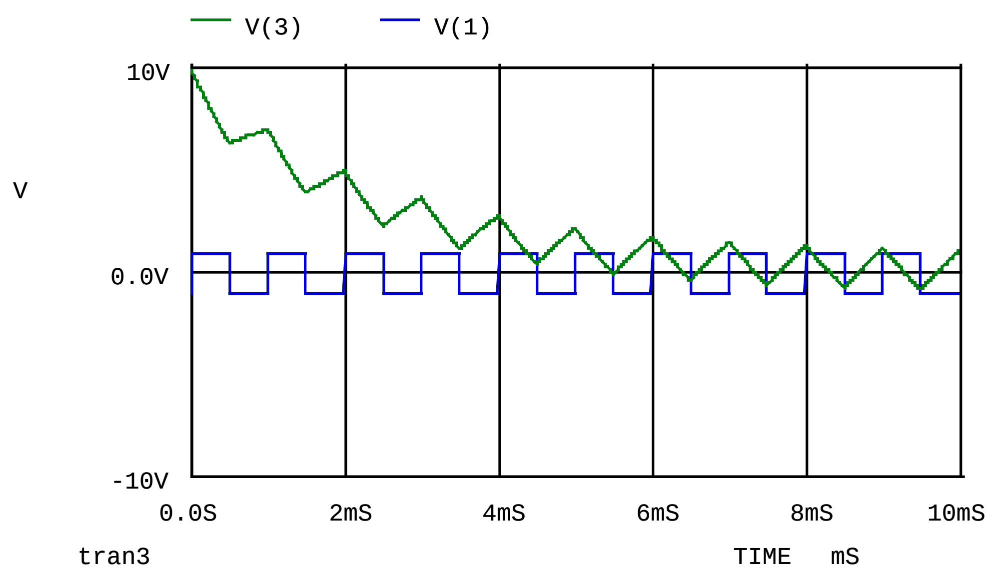
Math (yuk) as it used to be done!

What kind of filter is this?

OP-AMP INTEGRATOR SIMULATION

Op-Amp Integrator Simulation
***YOU fill in the component values!**
R1 1 2 ?
CI2 2 3 ?
R2 2 3 ?
E1 3 0 0 2 100K
Vin 1 0 pulse(-1 1 0 5nS 5nS 500uS 1mS)
.TRAN 100uS 10mS
.probe
.end

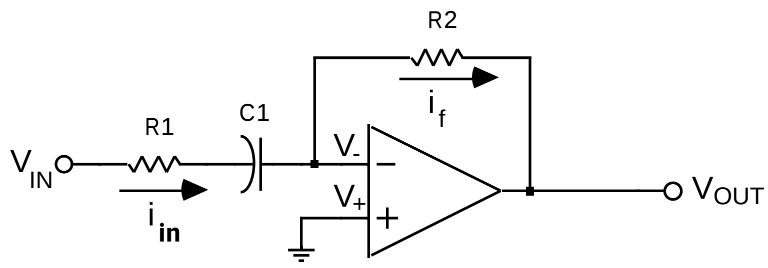




Insect Larva Containing Candy

THE DIFFERENTIATOR

R1 is needed to limit the high-frequency gain (noise may be small, but it can have a very large derivative!).



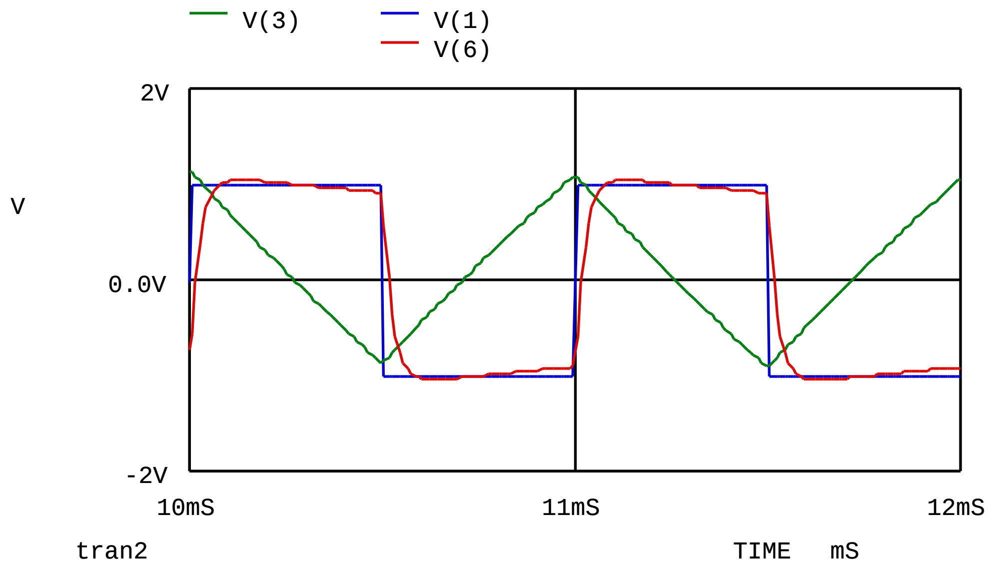
$$v_{out} = -(R2)(C1)\frac{dv_{in}}{dt}$$

Design the circuit to be used below this frequency

$$f_{max} = \frac{1}{2\pi(R1)(C1)}$$

What kind of filter is this?

INTEGRATOR/DIFFERENTIATOR SIMULATION



Why don't you get out what you put in?

"REAL" OP-AMPS DO EAT QUICHE

What You WANT

1) The input impedance is infinite - i.e. no current ever flows into either input of the op-amp.
2) The output impedance is zero - i.e. the op-amp can drive any load impedance to any voltage.
3) The open-loop gain (A) is infinte.
4) The bandwidth is infinite.
5) The output voltage is zero when the input voltage difference is zero.

What You GET

NO, but it is often GIGA or TERA Ω!

NO, but is can be a few ohms in many cases!

NO, but it is usually several million!

NO, usually several MHz.

NO, offset voltages exist, but can be trimmed.

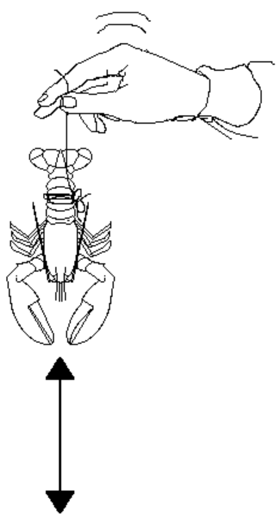
SLEW RATE

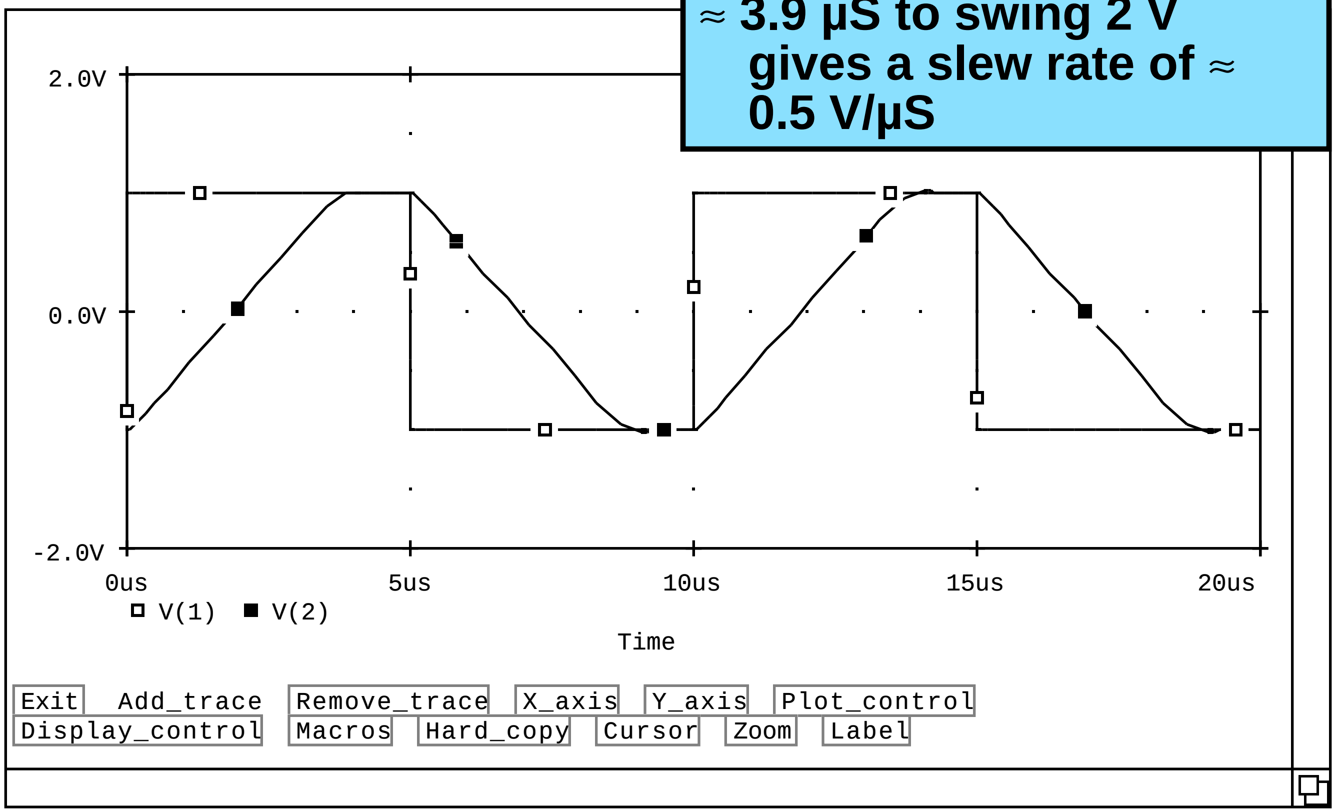
Op-Amps can only swing their outputs so fast...

If you try an make them go faster, they try, but you get a limiting rate of change, the SLEW RATE!

Simulated slew-rate-limited unity-gain amplifier with a UA741 op-amp

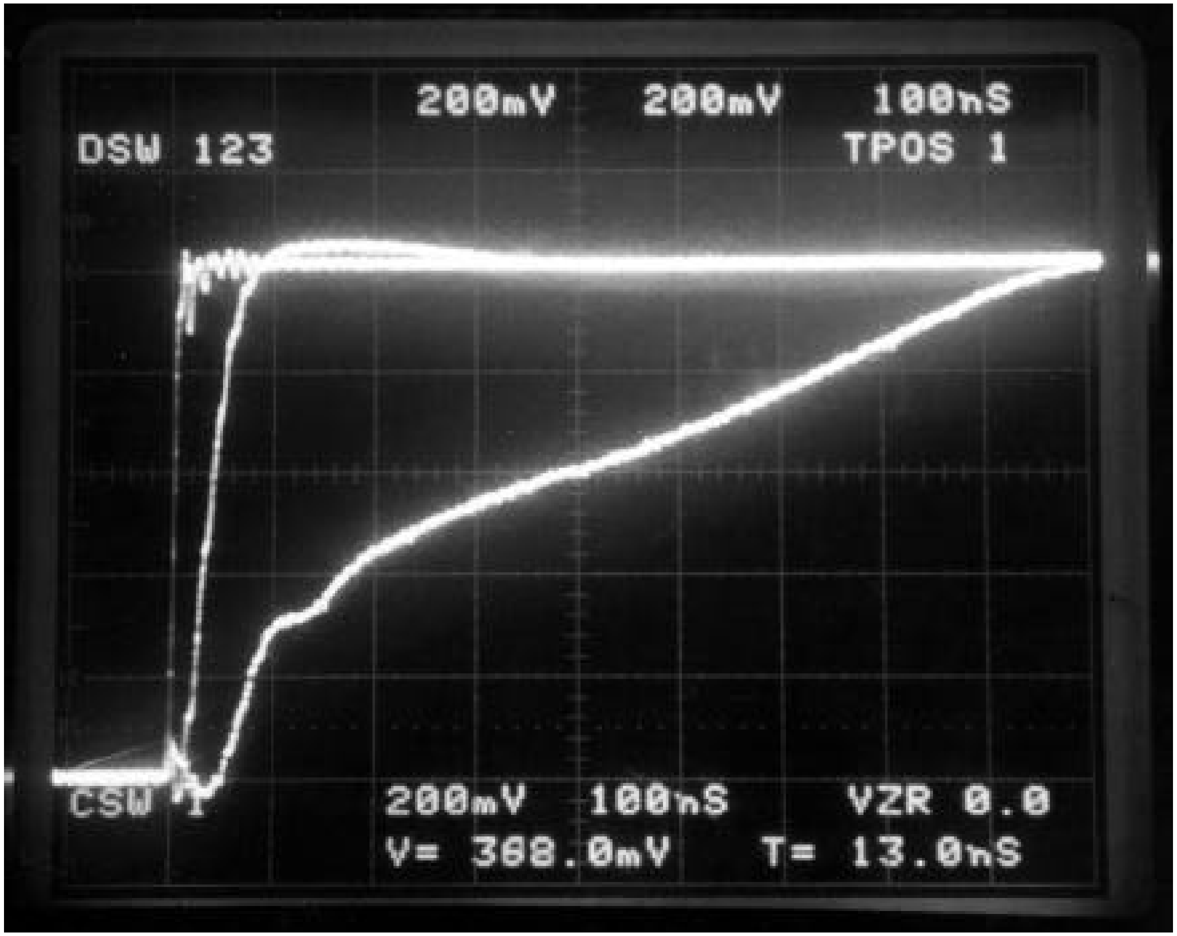
≈ 3.9 μS to swing 2 V gives a slew rate of ≈ 0.5 V/μS





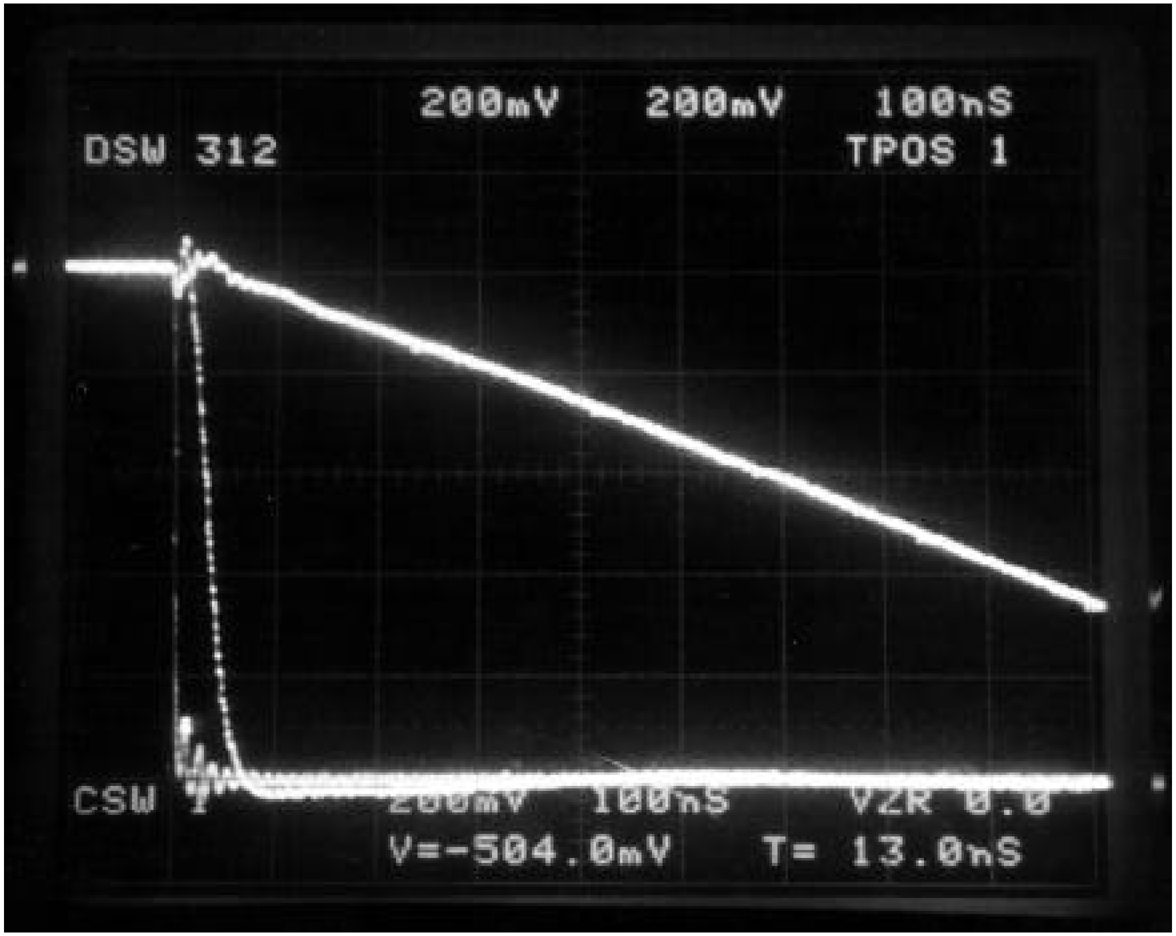
Measuring the SLEW RATE of a lobster using a piece of Bungie-cord...

Slew Rate Example - Rising



LM741 (slow) and LT1056, ±15V Supplies, 2kΩ Load, 1 VPP Squarewave Input (locally terminated into 50Ω).

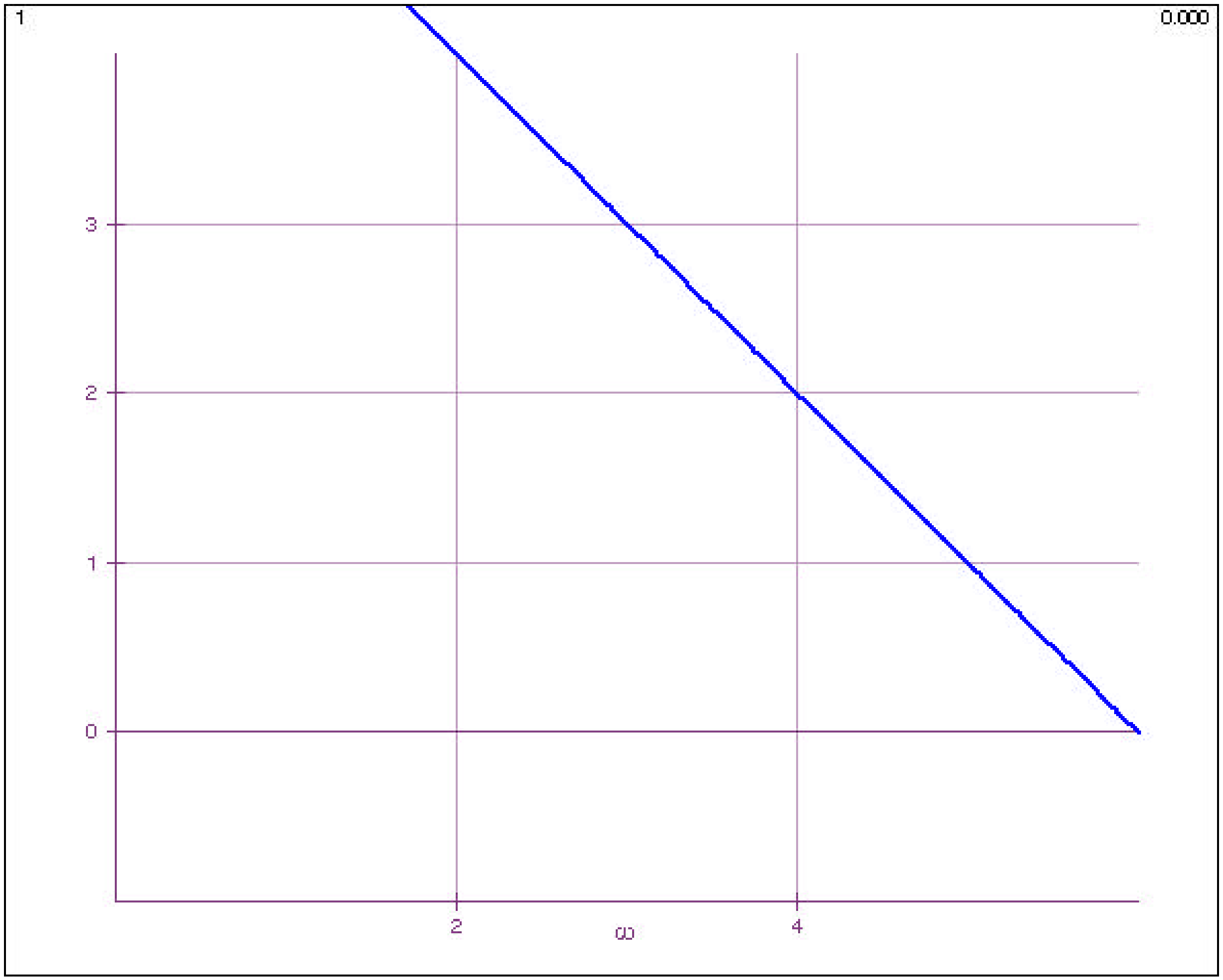
Slew Rate Example - Falling



LM741 (slow) and LT1056, ±15V Supplies, 2kΩ Load, 1 VPP Squarewave Input (locally terminated into 50Ω).

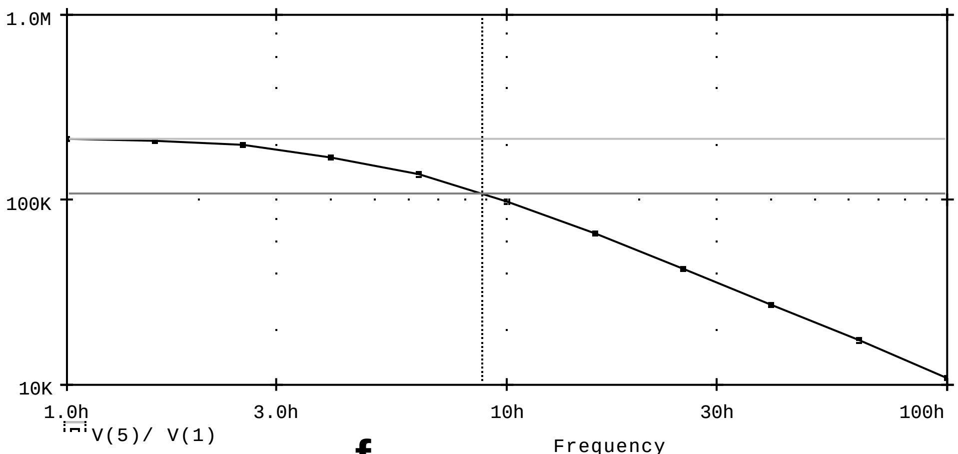
"Ultra Stealth Airplane"

Gain-Bandwidth Product is Constant

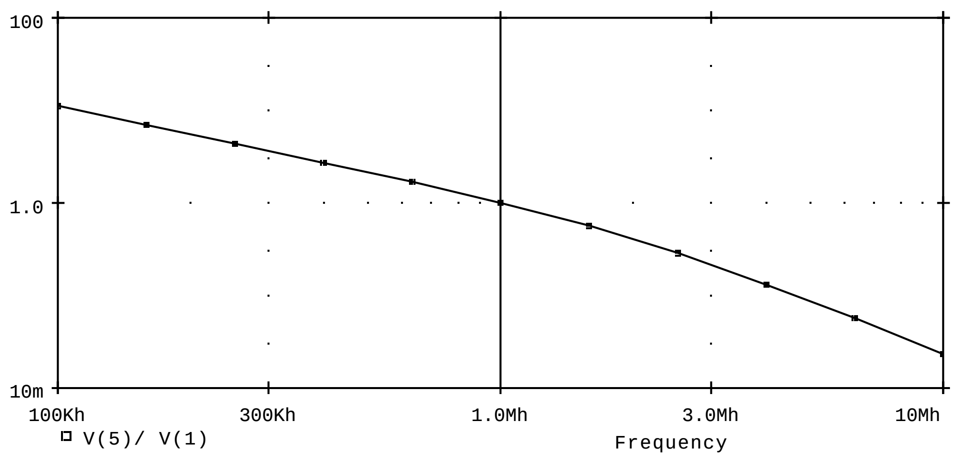


This animation shows the how the bandwidth of an op-amp in the inverting configuration increases as the gain is decreased.

OPEN-LOOP CHARACTERISTICS OF "REAL" OP-AMPS



f_u



f_T

3 dB frequency f_u is VERY LOW!

This frequency is determined by the "Dominant Pole" of the op-amp.

If negative feedback is applied, f_u may be shifted to much higher frequencies

Unity-gain frequency f_T can be VERY HIGH (many MHz)!

For unity-gain connected op-amps, f_u is the same as f_T.

For any other gain, f_T can be determined by using the GAIN-BANDWIDTH PRODUCT

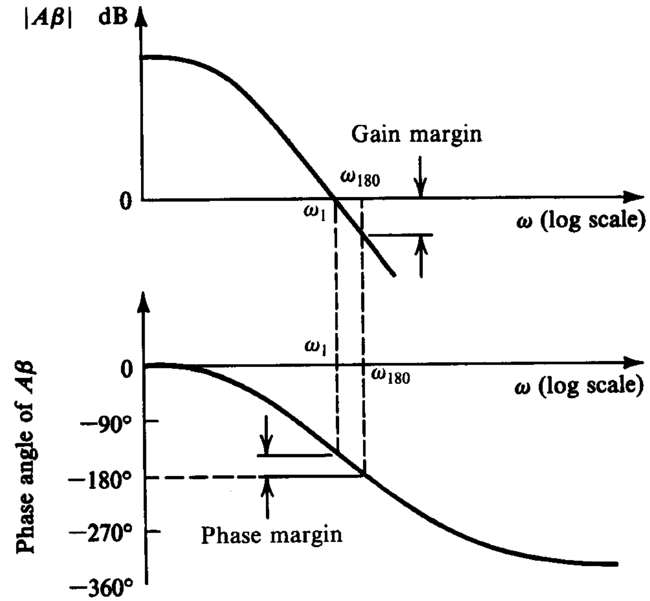
$$f_U = \frac{f_T}{Closed - Loop\_Gain}$$

STABILITY AND COMPENSATION

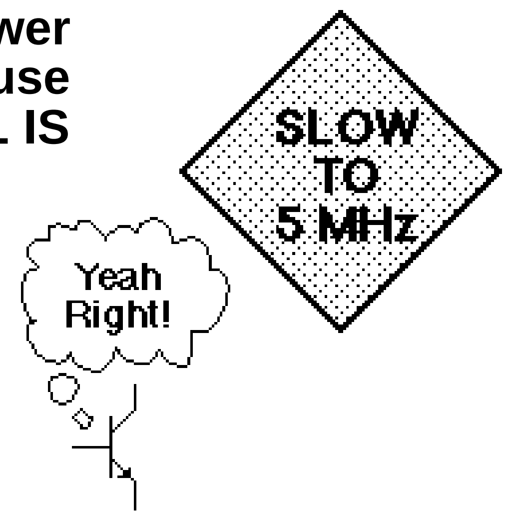
With negative feedback, if the input of the amplifier receives a -180° out-of-phase replica of the output signal (via the feedback circuit) you end up with OSCILLATIONS!!!!

All op-amps have a high-frequency roll-off determined by several poles. This means that eventually, you will hit -180° phase! The key to STABILITY is to ensure that this happens when the gain has fallen off to less than 1!

This can be accomplished by DELIBERATELY rolling off the amplifier using a COMPENSATION CAPACITOR!



This effect is worse at lower gains because MORE SIGNAL IS FED BACK!



MODELING "REAL" OP-AMPS

The WORSE the op-amp, the more work it takes to model it!

IDEAL OP-AMP:

```
Eout   3   0   1   2   100K
```

CRAPPY, OBSOLETE OP-AMP:

```
* UA741 operational amplifier "macromodel" subcircuit
* connections:  non-inverting input
*               | inverting input
*               | | positive power supply
*               | | | negative power supply
*               | | | | output
*               | | | | |
.subckt UA741  1 2 3 4 5
*
c1  11 12 4.664E-12
c2  6 7 20.00E-12
dc  5 53 dx
de  54 5 dx
dlp 90 91 dx
dln 92 90 dx
dp  4 3 dx
egnd1 98 0 3 0 0.500000
egnd2 99 98 4 0 0.500000
fb1 7 99 vb 10610000.000000
fb2 7 99 vc -10000000.000000
fb3 7 99 ve 10000000.000000
fb4 7 99 vlp 10000000.000000
fb5 7 99 vln -10000000.000000
ga 6 0 11 12 137.7E-6
gcm 0 6 10 99 2.574E-9
iee 10 4 dc 10.16E-6
hlim 90 0 vlim 1K
q1  11 2 13 qx
q2  12 1 14 qx
r2  6 9 100.0E3
rc1  3 11 7.957E3
rc2  3 12 7.957E3
re1 13 10 2.740E3
re2 14 10 2.740E3
ree 10 99 19.69E6
ro1  8 5 150
ro2  7 99 150
rp  3 4 18.11E3
vb  9 0 dc 0
vc 3 53 dc 2.600
ve  54 4 dc 2.600
vlim 7 8 dc 0
vlp 91 0 dc 25
vln  0 92 dc 25
.model dx D(Is=800.0E-18)
.model qx NPN(Is=800.0E-18 Bf=62.50)
.ends
```

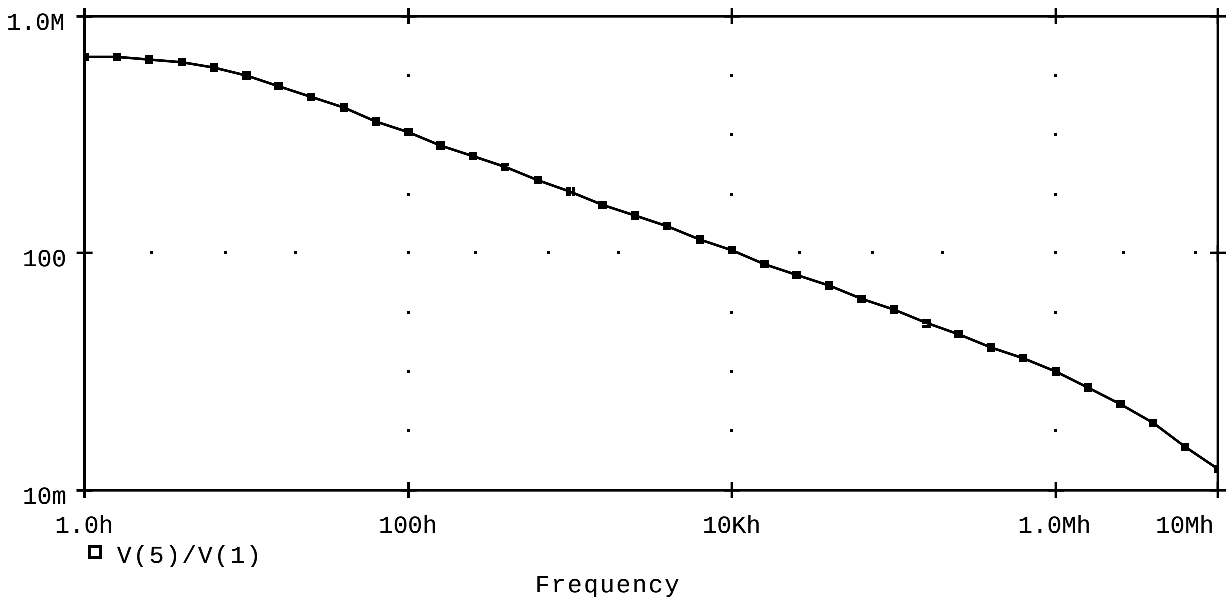
EXAMPLE OF USING A "REAL" OP-AMP MACROMODEL

```
X1 1 2 3 4 2 UA741
Vplus 3 0 15V
Vminus 0 4 15V
Vin 1 0 AC 1 0
.AC DEC 100 1hz 10MEG
.probe
.end
```

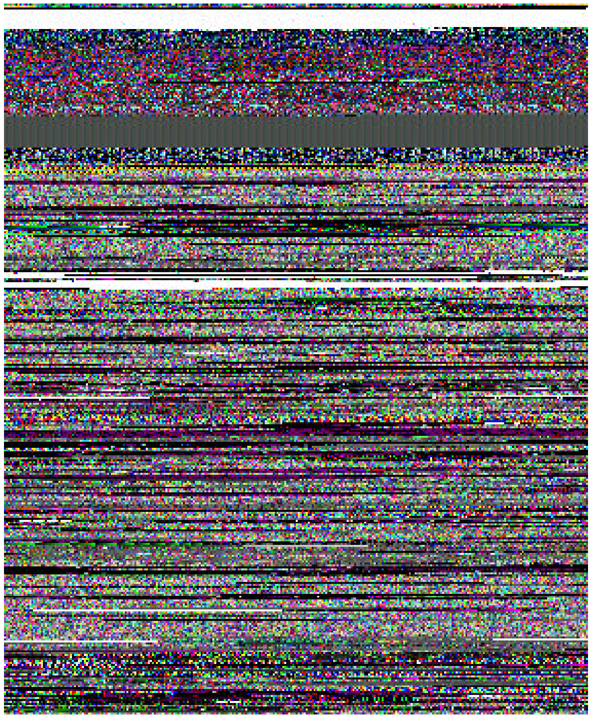
NOTE:

1) You declare an "instance" of your macromodel with a name that begins with "X"

2) You have to explicitly define the power supplies.



SPAM ZAPPED WITH PHOTONS!



CONCLUSION

- Op-Amps are useful for lots of things.
- Op-Amps deliver a lot of performance for peanuts!
- Op-Amp circuits are generally fairly intuitive if you remember the basic "rules" of op-amp operation!