EE122A
Operational Amplifiers: Basic Concepts

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Objectives

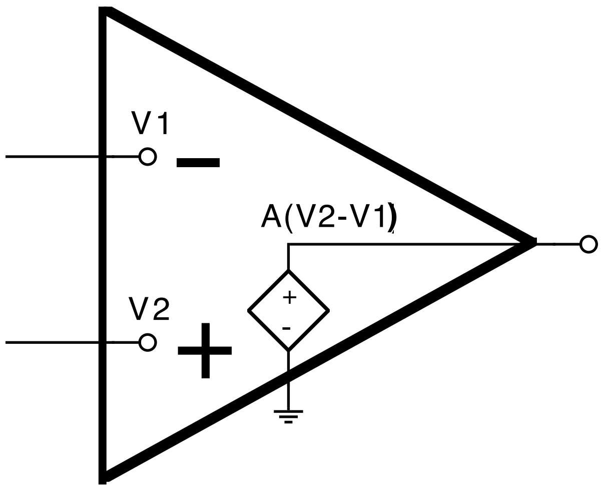
- **Obtain a practical understanding of what operational amplifiers ("op-amps") are and some applications they can be used for.**

- **Understand the basic op-amp circuit configurations.**

- **Understand the basic characteristics (good and bad) of op-amps before measuring some of them in the lab.**

- **Learn how to apply the basic "op-amp" rules to understand and analyze circuits quickly.**

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.

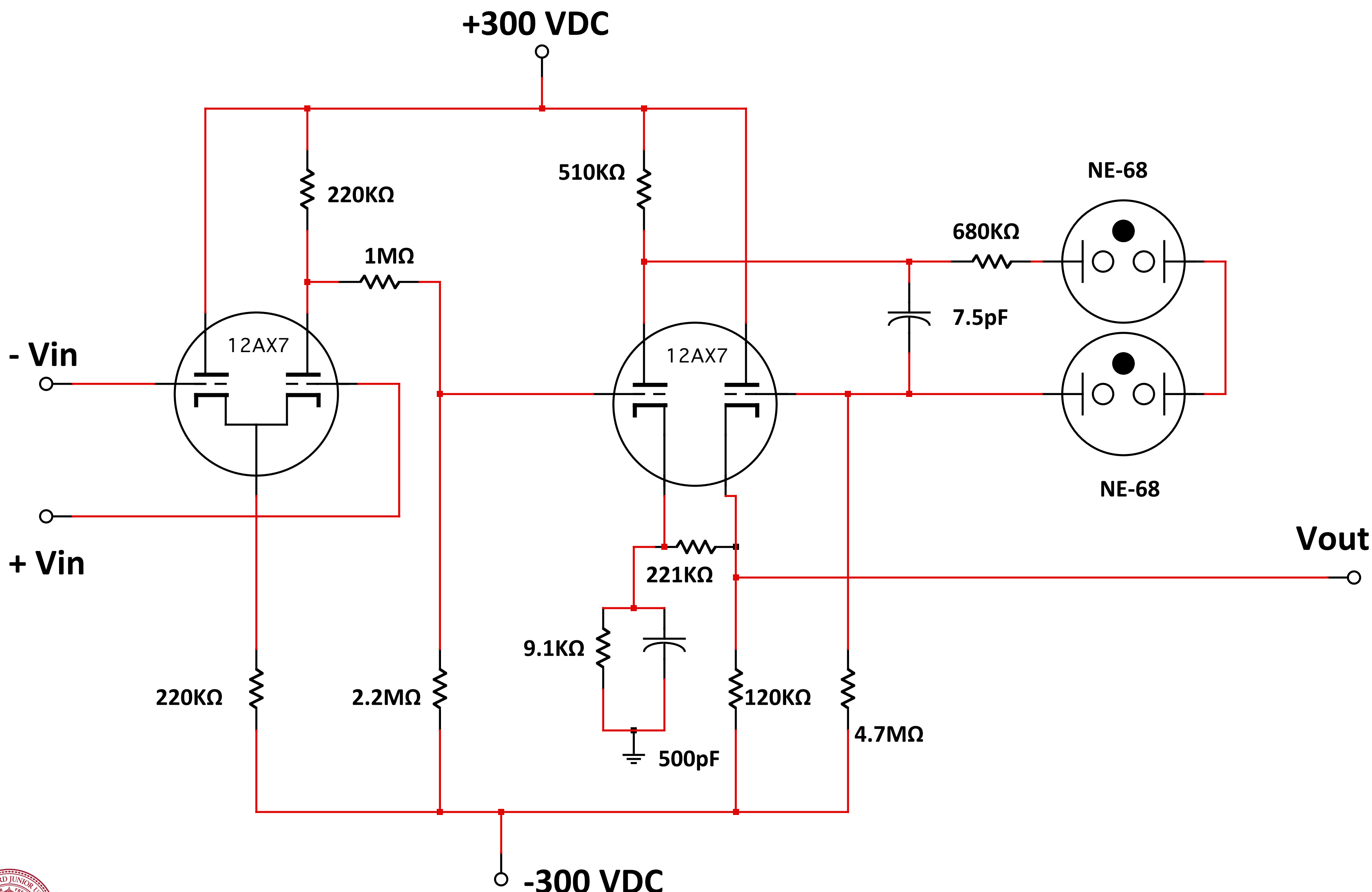
4) The bandwidth is infinite.

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

A Bit of History...

- The first operational amplifiers (op-amps) were invented during the time of the Second World War.
- C. A. Lovell, D. Parkinson and others of Bell Telephone Laboratories introduced the op-amp for use in a gun director during that period.
- Prof. J. Ragazzino of Columbia University coined the term "operational amplifier" in 1947.
- George A. Philbrick independently introduced a single vacuum tube operational amplifier in 1948.
- The first integrated (monolithic) op-amp, the Fairchild µA702 was designed by Bob Widlar in 1963 but was not a commercial success.
- The ever-popular Fairchild µA741 monolithic op-amp was designed by Dave Fullagar in 1967 and was the first to include on on-chip compensation capacitor to make it simpler to use.
- Op-amps are not new, but the concept is fundamental and has had incredible staying power.

The First "Commercial" OpAmp: The K2-W




GAP/R
MODEL
K2-XA
K2-XA

The K2-W Tube OpAmp

- **Designed by Julie Loebe and George Philbrick (early 1950's).**
- **The first "mass production" op-amp, although hand-wired inside the case.**
- **Cost (in 1950's) approximately $22.00. (about $200 in 2013 dollars).**
- **Basic specifications comparison to 741 and more modern LT1037:**

Parameters	K2-W OpAmp	741 OpAmp	LT1037 OpAmp
Power Supplies	+/- 300 VDC, 6.3 VAC (filaments)	+/- 15V	+/- 15V
Open-Loop Gain	$1.5X10^4$	$5X10^4$	$30X10^6$
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

Types of Modern Op-Amps

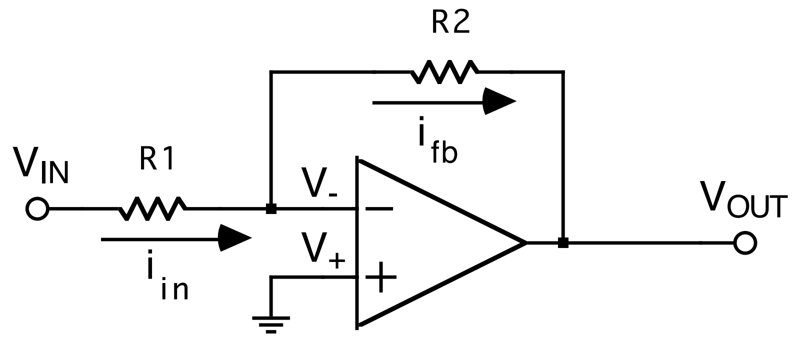
- Single
- Dual
- Quad

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

Op-Amp Example Devices

- **LM741 (basic, classic, 0.5 MHz, 0.5Vµs slew rate)**
- **LT1056 (JFET input, 6.5MHz, 23V/µs slew rate)**
- **LMC6582 (dual, 1.2 MHz, CMOS - low power, 0.6V/µs slew)**
- **AD8052 (dual, 110MHz, 145V/µs slew rate)**
- **LM7171 (200MHz, 4,100V/µs slew rate)**
- **LM675 (medium power, 3A current, 5.5 MHz, 8V/µs)**
- **LM12 (high power: 80W, sadly obsolete)**

Feedback and Op-Amps

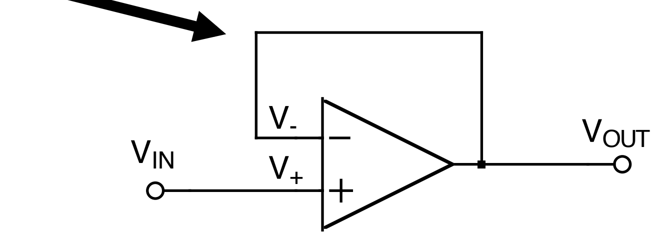


Feedback in op-amp circuits is usually *negative*, which means that some of the output signal is subtracted at the input, reducing gain, but providing other benefits. *The trading of gain for other properties is truly fundamental in electronics.*

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

THE VOLTAGE FOLLOWER

$$V_- = V_{out}$$



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

$$V_{out} = A\left(V_{in} - V_{out}\right)$$

$$V_{out} = \frac{A}{(1+A)} V_{in}$$

1

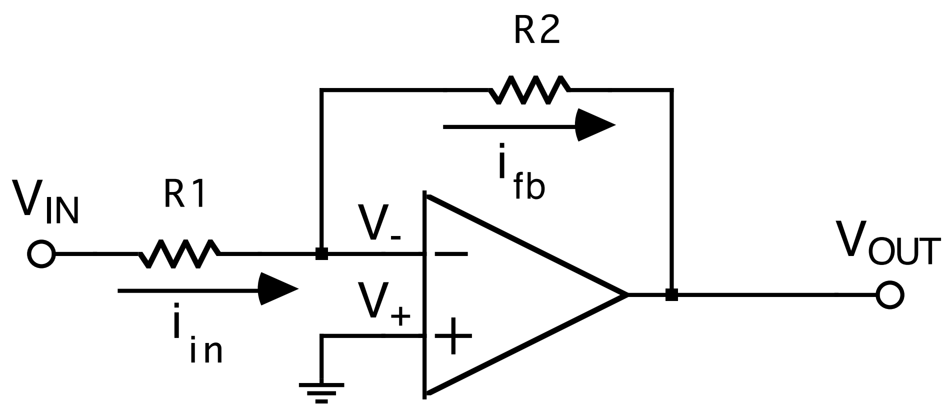
What is it good for?

Buffering a high-impedance signal so you do not load it down when you measure it.

It has the *largest bandwidth* of any op-amp circuit.

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

THE INVERTING AMPLIFIER



The V- terminal is a "virtual ground" due to negative feedback.

$$V_{OUT} = A\left(0 - V_-\right)$$

thus,

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

THIS IS A KEY POINT!!!

Equating currents,

$$\frac{V_{in} - V_-}{R_1} = \frac{V_- - V_{out}}{R_2}$$

Substituting for virtual ground ($V_- = 0$),

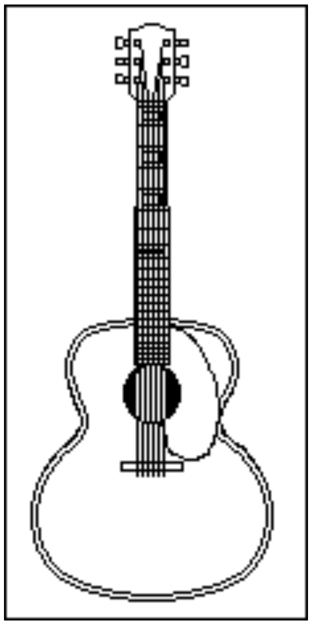
$$\frac{V_{in}}{R_1} = \frac{-V_{out}}{R_2}$$

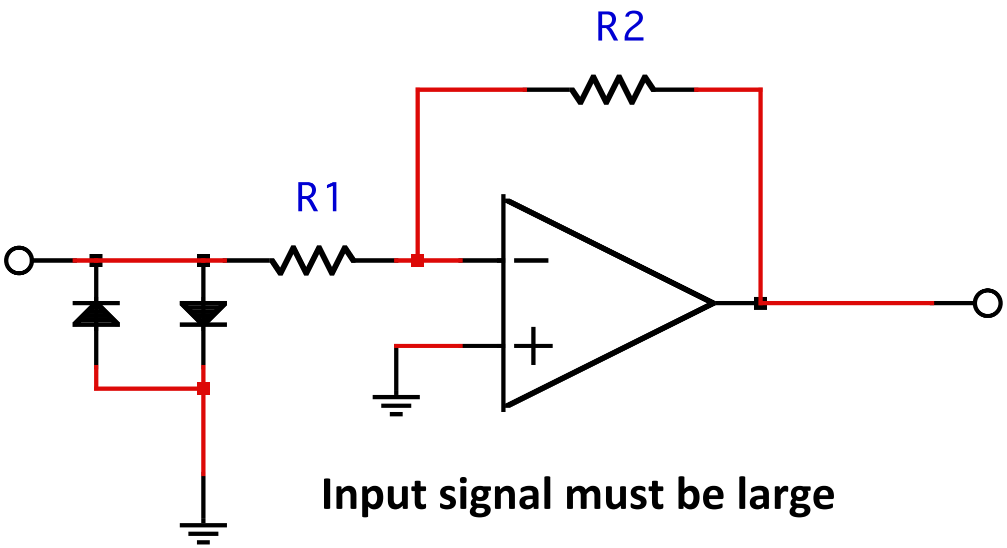
$$Av = \frac{Vout}{Vin} = -\frac{R_2}{R_1}$$

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

Mellow Tunes

IN





Heavy Metal

OUT

Input signal must be large enough to turn on diodes.

Clipping a sinewave, for example, produces harmonics of what is thus closer to a squarewave (recall Fourier series).

GENERAL CASE: V_+ AND V_- ARE EQUAL

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

$$\frac{V_{out}}{A} = V_+ - V_-$$

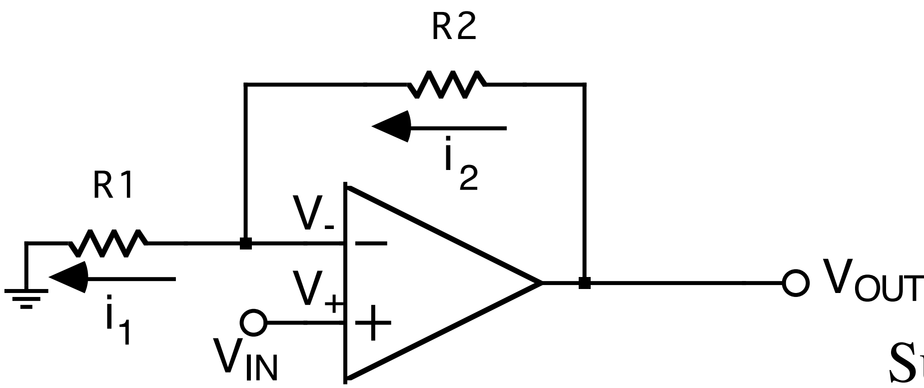
$$\frac{V_{out}}{A} \approx 0 = V_+ - V_-$$

$$0 = V_+ - V_-$$

$$\therefore V_+ = V_-$$

$\therefore$ Kovacs can still teach this when senile.

THE NON-INVERTING AMPLIFIER



Summing currents:

$$\frac{V_-}{R_1} = \frac{V_{out} - V_-}{R_2} \Rightarrow \frac{R_2 V_-}{R_1 R_2} = \frac{R_1 V_{out} - R_1 V_-}{R_1 R_2}$$

$$\frac{R_2 V_-}{R_1 R_2} + \frac{R_1 V_-}{R_1 R_2} = \frac{R_1 V_{out}}{R_1 R_2}$$

Due to negative feedback: $V_- = V_+ = V_{in}$

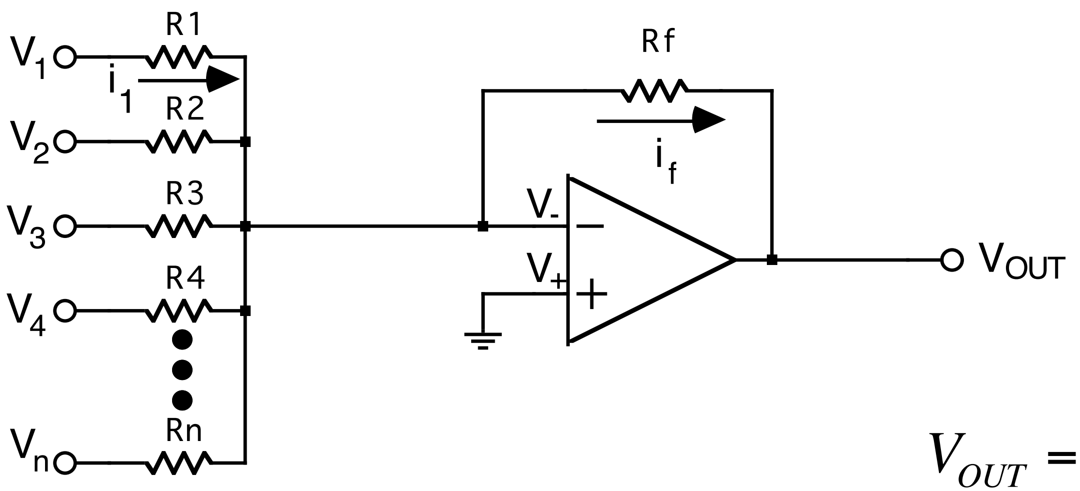
$$\frac{(R_2 + R_1) V_{in}}{R_1 R_2} = \frac{R_1 V_{out}}{R_1 R_2} \Rightarrow (R_2 + R_1) = \frac{R_1 V_{out}}{V_{in}}$$

$$A_V = \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_2}{R_1}\right)$$

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, $V_- \approx V_{IN}$.

THE SUMMING AMPLIFIER



$$V_{OUT} = -V_1 \frac{R_f}{R_1} - V_2 \frac{R_f}{R_2} - \cdots - V_N \frac{R_f}{R_N}$$

or,

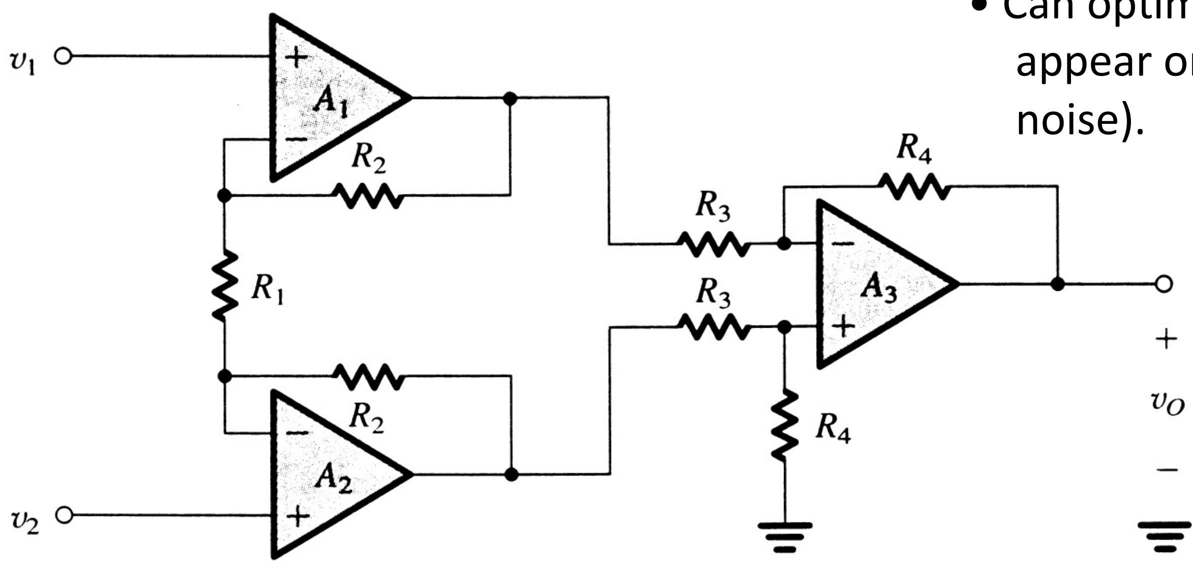
$$V_{OUT} = -R_f \sum_{i=1}^{N} \left(\frac{V_i}{R_i} \right)$$

This circuit can be used for summing multiple input signals in any proportion desired (determined by the relative values of the input resistors.

Averaging of signals can be accomplished by equally scaling the inputs and dividing proportional to N, the number of inputs.

This is the superposition of several inverting amplifiers.

Instrumentation Amplifier



- Very high input impedance.
- Gain can be set with only one resistor.
- Can optimize rejection of signals that appear on both inputs (common mode noise).

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

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

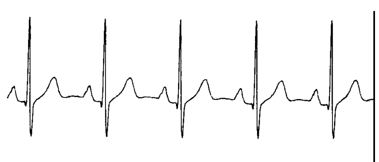
For one-resistor gain adjust, set $R_4 = R_3$ and fix R_2.

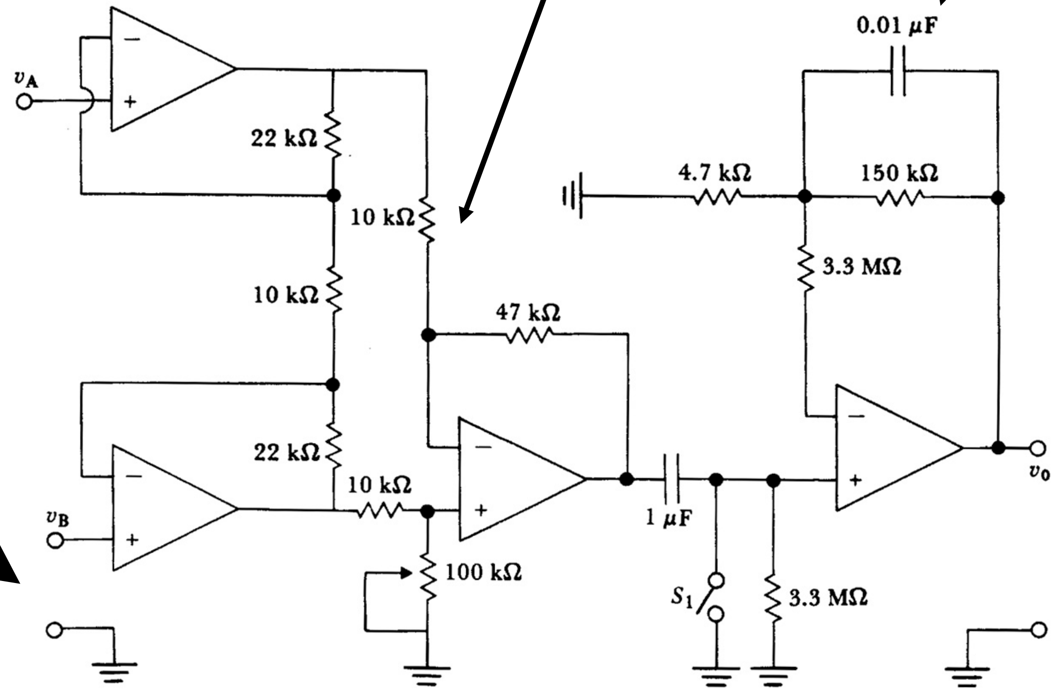
Op-Amp Application: EKG

Filter (0.04 - 150 Hz)

Instrumentation Amplifier

Approximately 1mV P-P





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.

THE INTEGRATOR

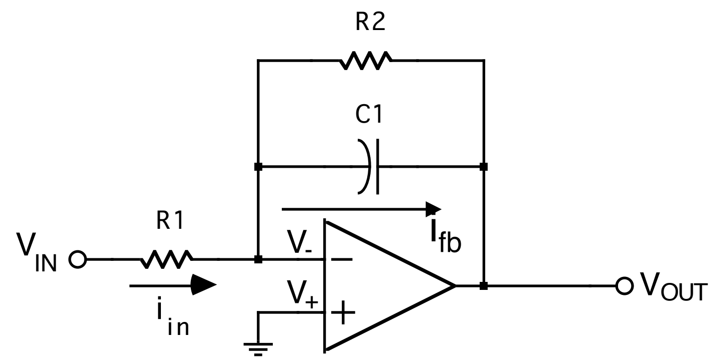
What is it good for?

Triangle wave generation.

Ramp generation ('scopes!).

Math (yuk) as it used to be done!

Need R_2 to gradually leak accumulated charge off C_1, or small DC errors (offsets) would cause it to charge continuously.



What kind of filter is this?

For DC inputs:

$$\frac{V_{out}}{V_{in}} = -\frac{R_1}{R_2}$$

$$(\text{for DC}, Z_{C1} = \infty)$$

For AC inputs:

Summing currents:

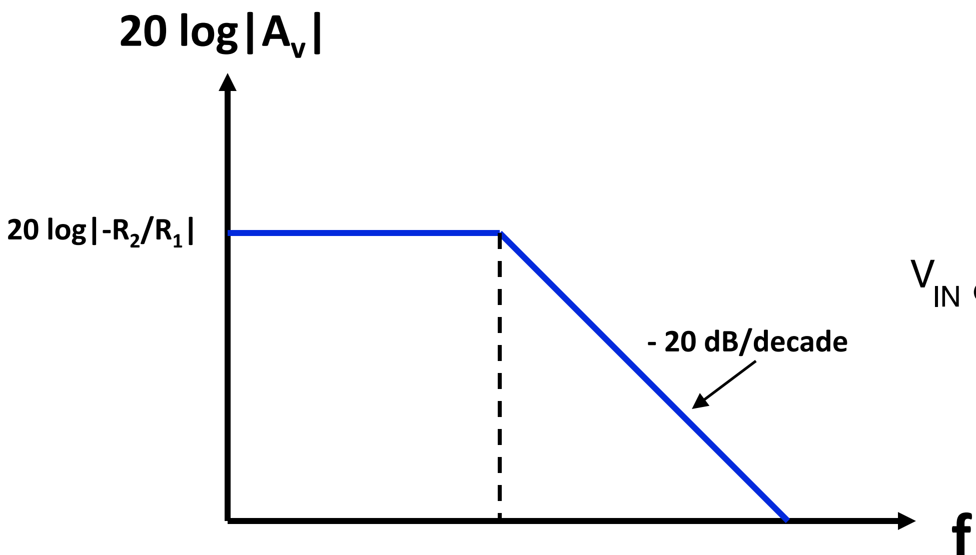
$$i_{in} = i_{fb}$$

$$\frac{v_{in}}{R_1} = -C_1 \frac{dv_{out}}{dt}$$

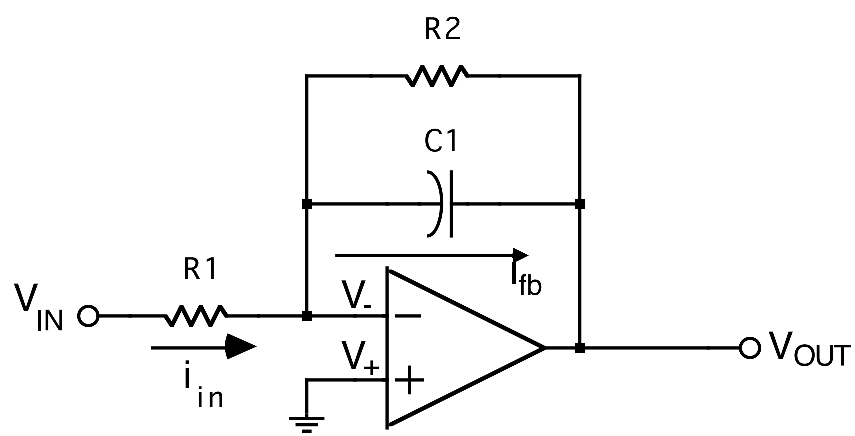
$$v_{out} = -\frac{1}{R_1 C_1} \int v_{in}\, dt$$

INTEGRATOR FREQUENCY RESPONSE

The time constant for the integrator is R_2C_1 and the cutoff frequency is as shown below.

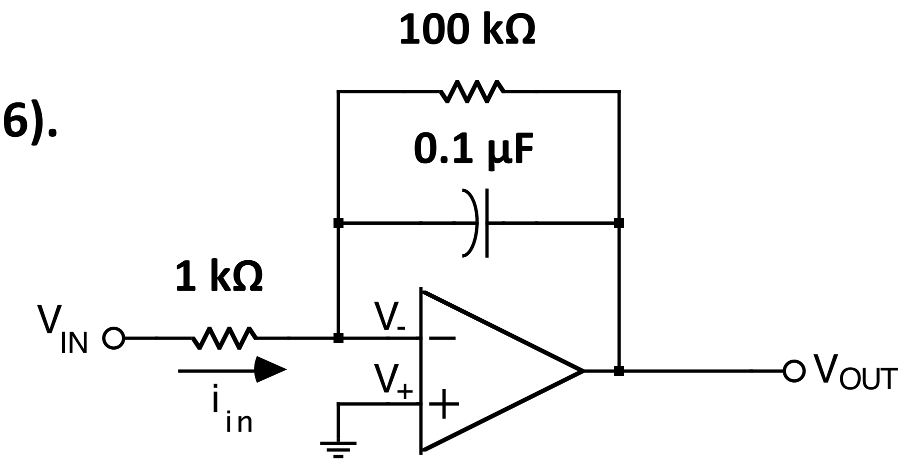


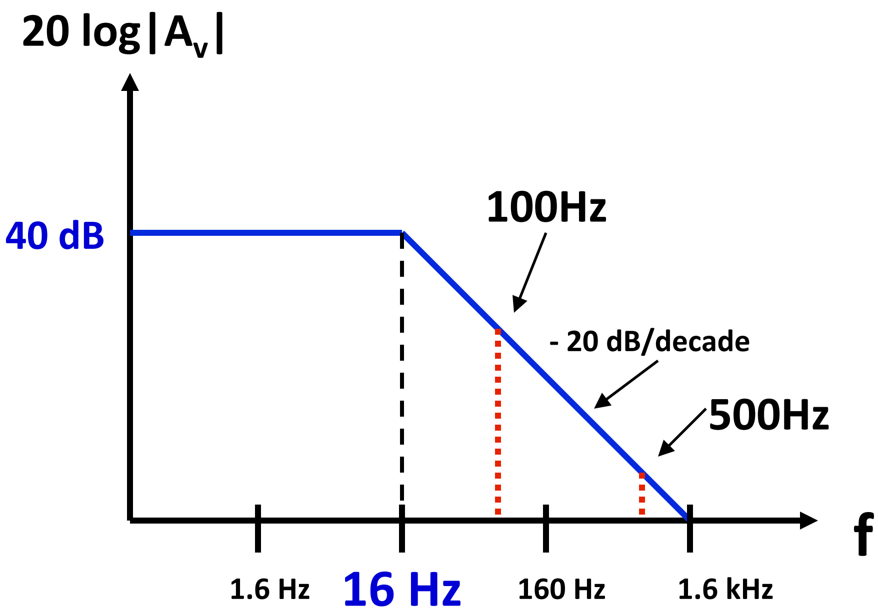
$$fc = \frac{1}{2\pi R_2 C_1}$$

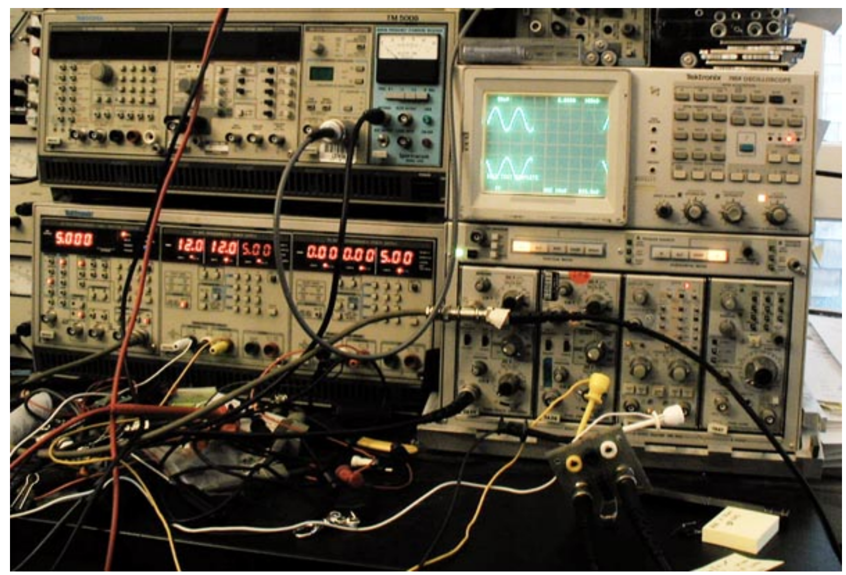


INTEGRATOR EXAMPLE

- τ = 10 ms, f_c = 16 Hz
- Physical experiment with op-amp (LF356).

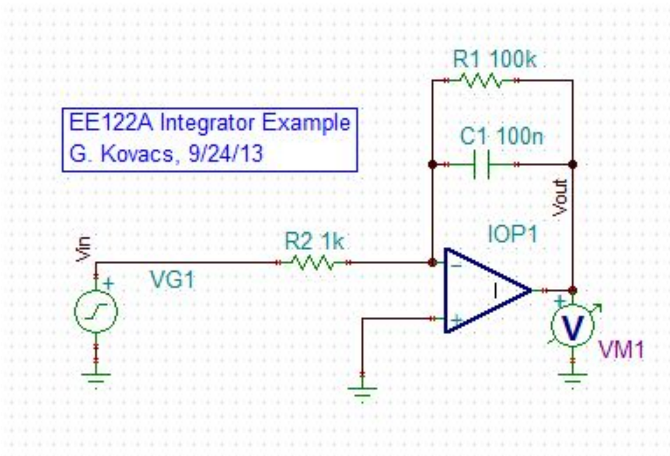


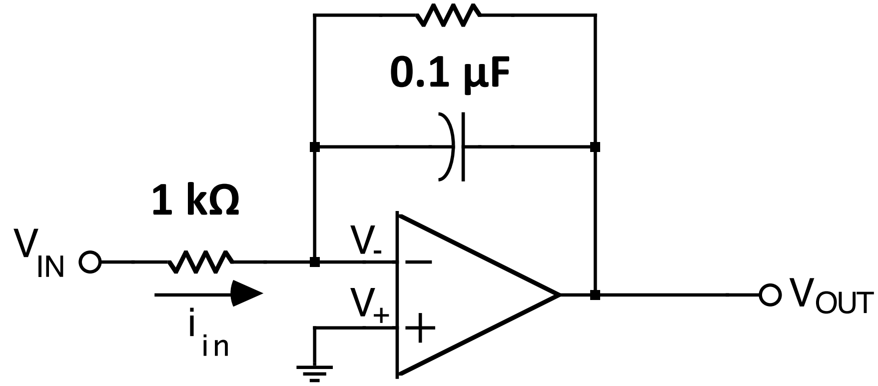


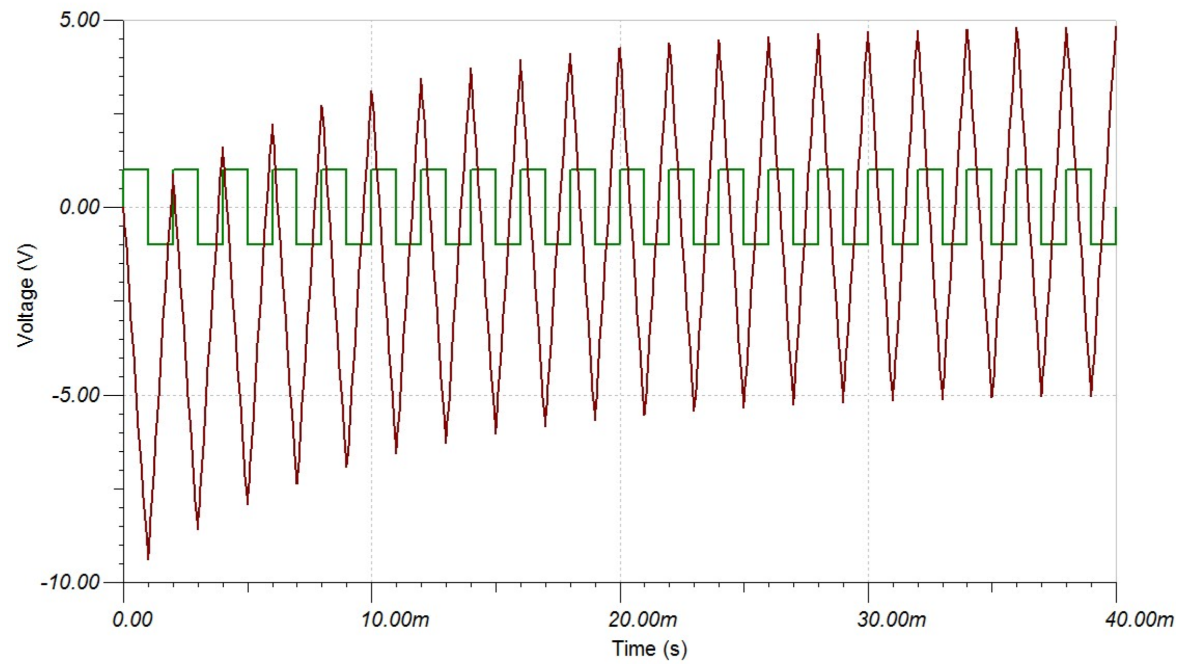


INTEGRATOR EXAMPLE: SIMULATION

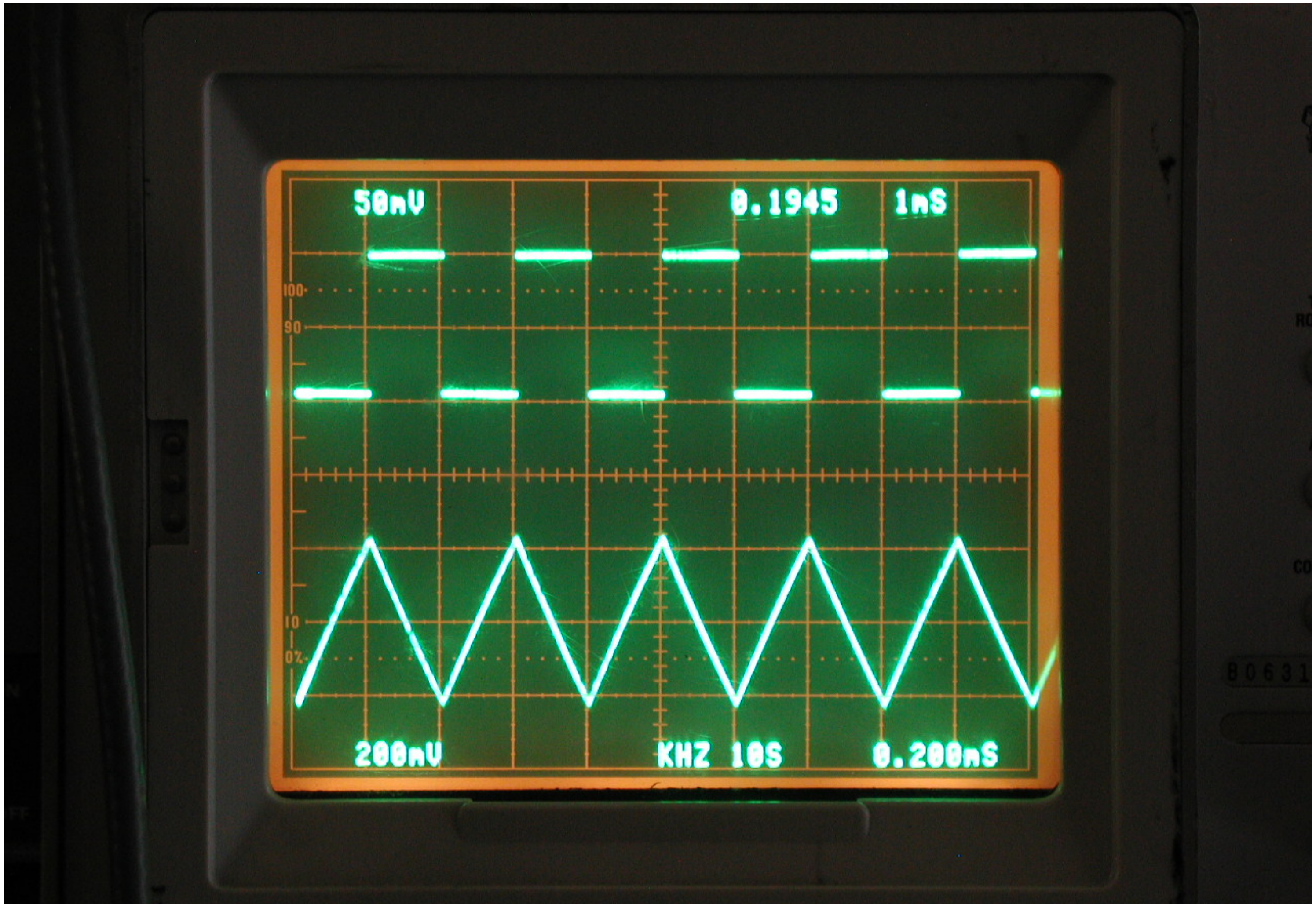
- τ = 10 ms, f_c = 16 Hz
- Simulation with "TINA" software.





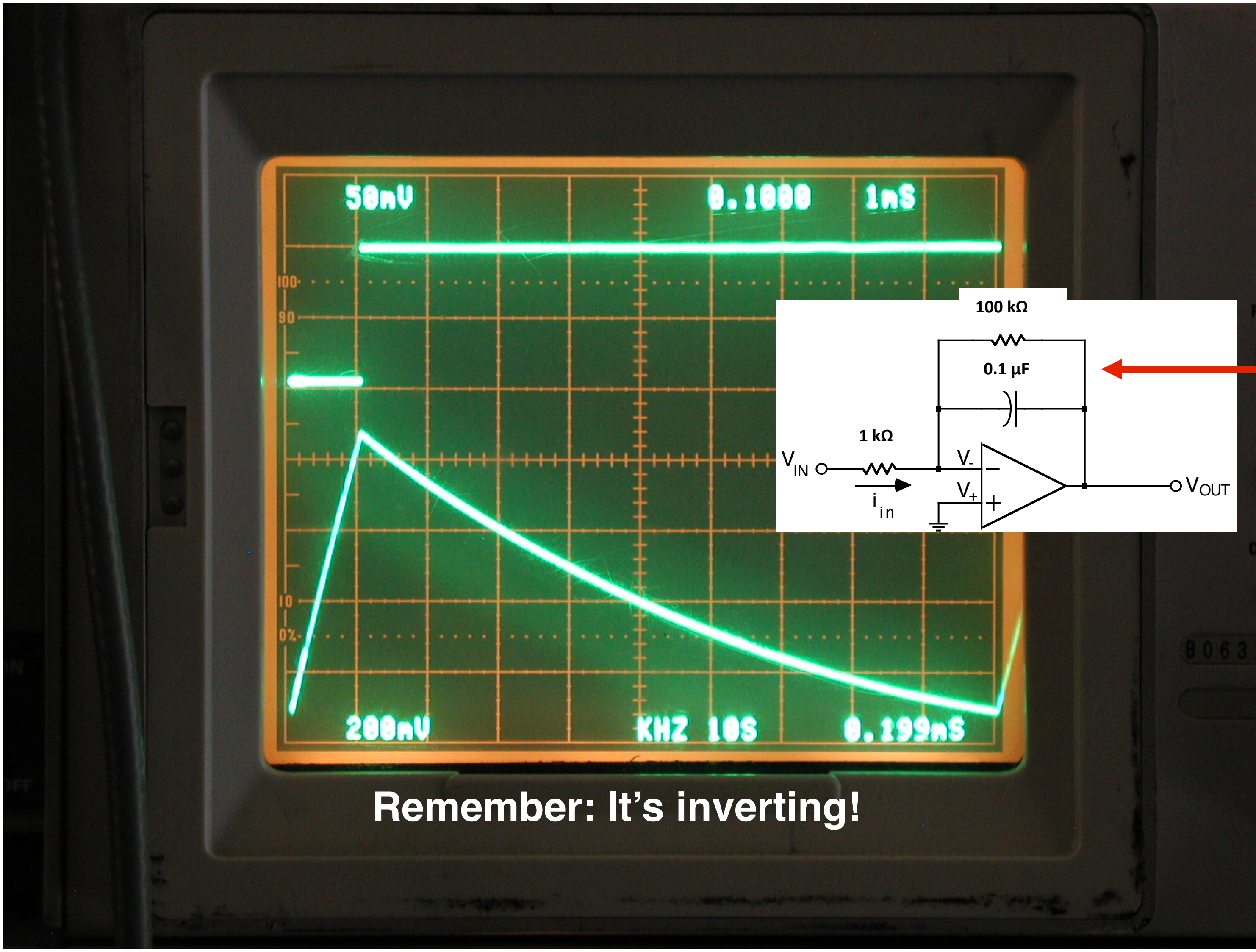


500 Hz Squarewave T = 0.2τ - Integration



Note voltage scales. Triangle wave ≈4X input squarewave.

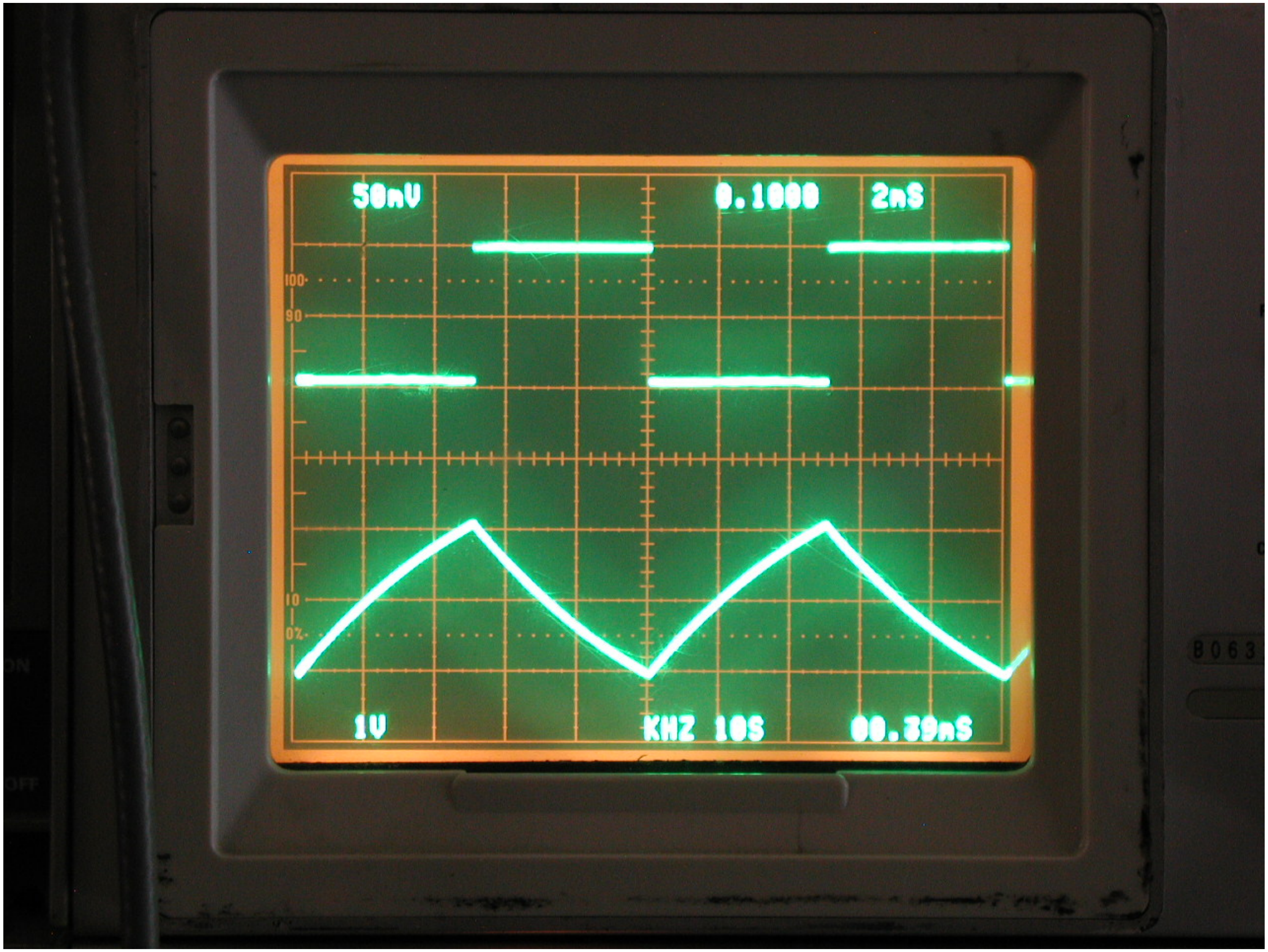
Step-And-Hold: Exponential Decay



Time constant
Due to R2 and C1.

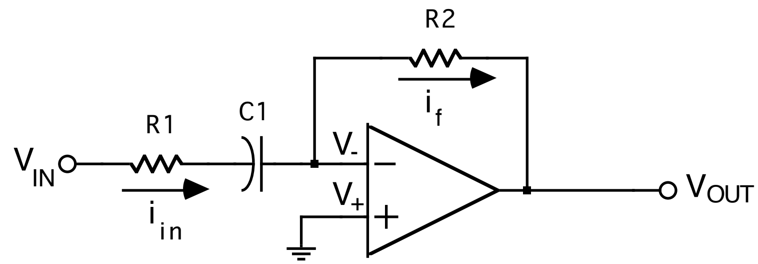
What if you remove
R2?

100 Hz Squarewave Input T = τ
Exponential Shape



THE DIFFERENTIATOR

R_1 is needed to limit the high-frequency gain (noise may be small, but it can have a very large derivative).



$$v_{out} = -R_2 C_1 \frac{dv_{in}}{dt}$$

Design for use below this frequency:

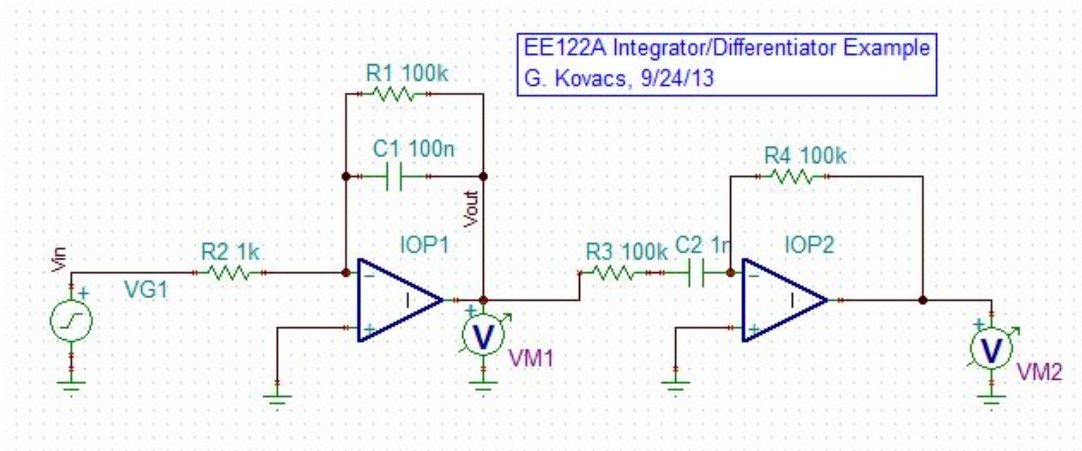
$$f_{max} = \frac{1}{2\pi R_1 C_1}$$

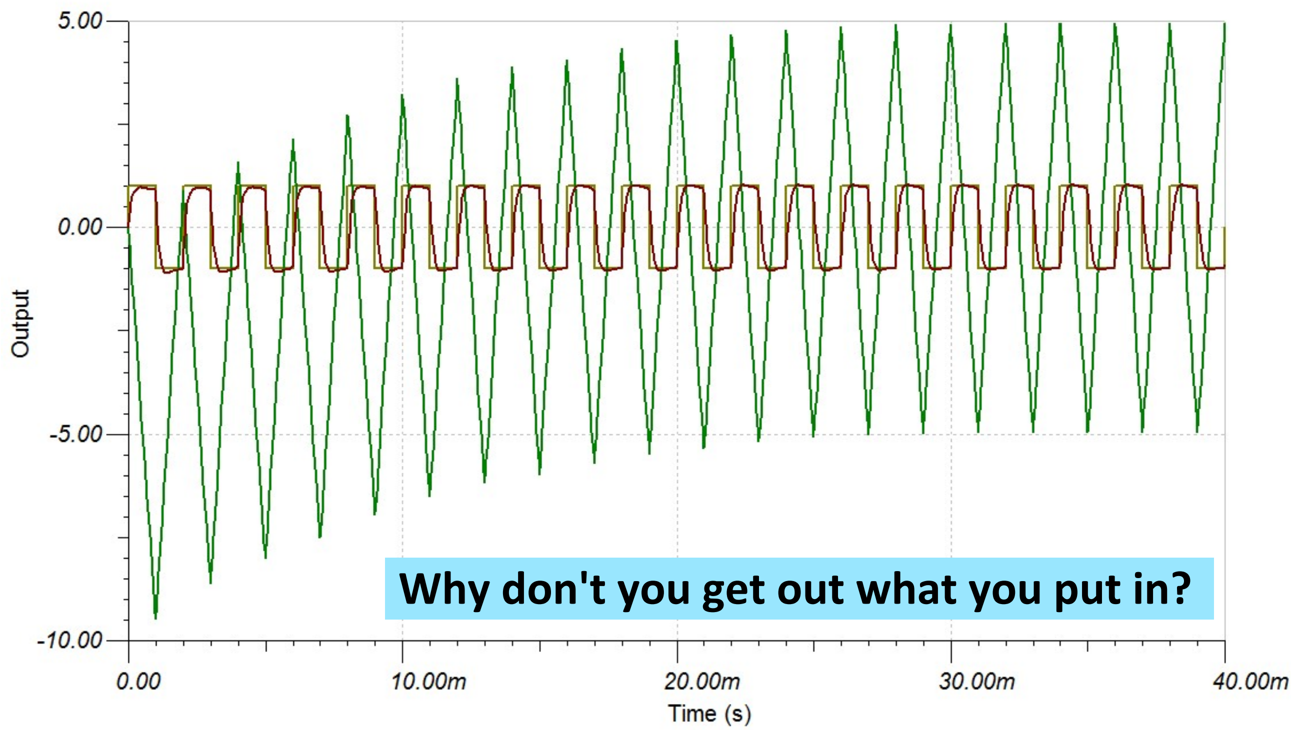
What kind of filter is this?

High-frequency gain is:

$$A_v = -\frac{R_2}{R_1}$$

INTEGRATOR/DIFFERENTIATOR SIMULATION





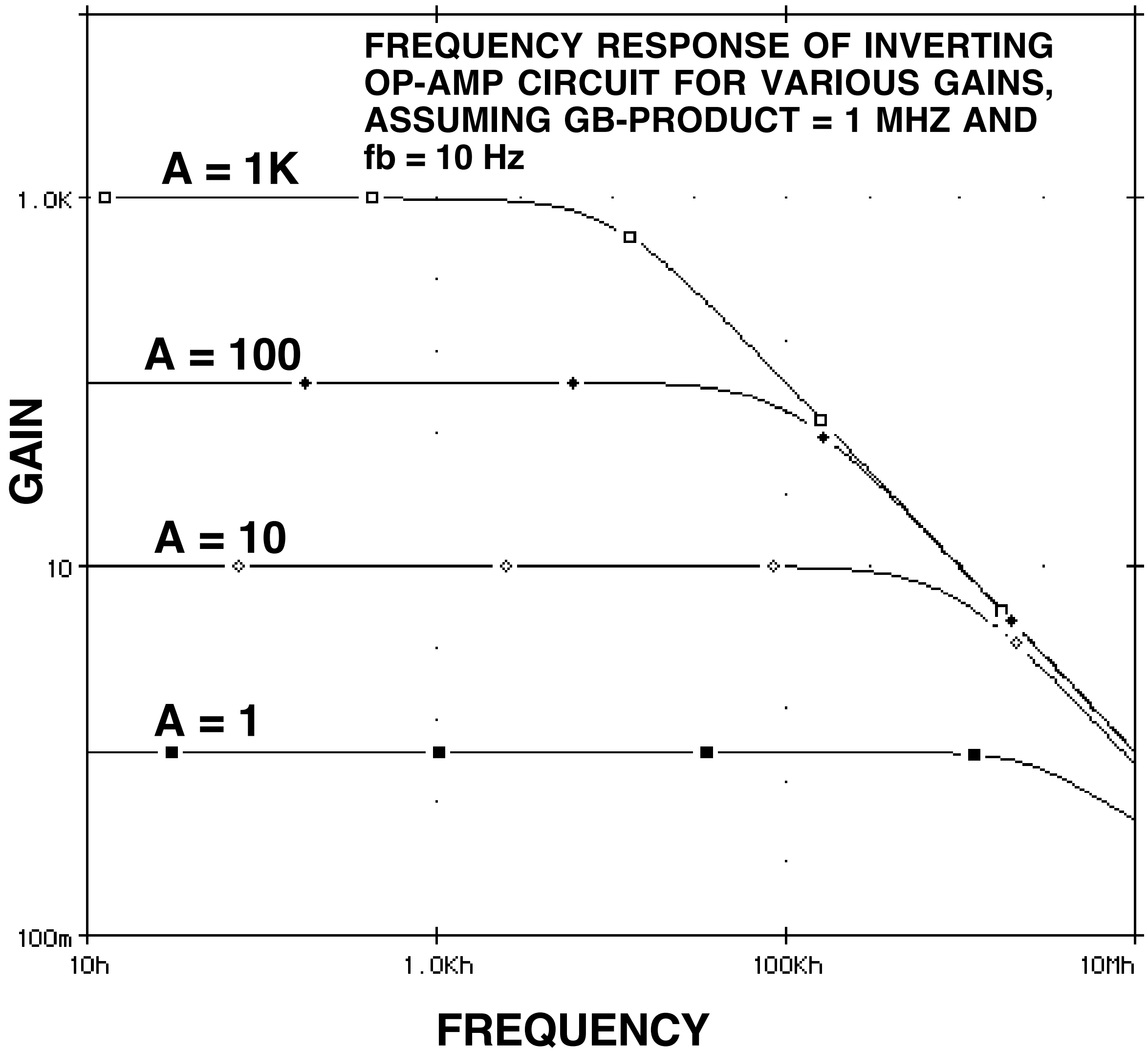
"REAL" OP-AMPS ARE NOT PERFECT

What You WANT	What You GET
1) The input impedance is infinite - i.e. no current ever flows into either input of the op-amp.	NO, but it is often GIGA or TERA Ω!
2) The output impedance is zero - i.e. the op-amp can drive any load impedance to any voltage.	NO, but is can be a few ohms in many cases!
3) The open-loop gain (A) is infinte.	NO, but it is usually several million!
4) The bandwidth is infinite.	NO, usually several MHz.
5) The output voltage is zero when the input voltage difference is zero.	NO, offset voltages exist, but can be trimmed.

Gain-Bandwidth Product is Constant

- For small-signal operation (see below for discussion of large-signal and potentially slew-rate-limited operation), gain and bandwidth can be considered to form a "product," the "gain-bandwidth product."
- This is a function of the common "internally compensated" op-amps being designed to have a first-order roll-off in response (an internal, deliberate pole that rolls the gain off in a controlled fashion at 20 dB per decade of frequency).
- The point here is that there is a clear trade-off between gain and bandwidth, and for small-amplitude signals, things work pretty much like that.
- More bandwidth comes only for smaller gains, with the maximum "spec sheet" bandwidth of an op-amp being specified for a gain of one.
- In general, smaller or more advanced technologies yield faster transistors, that in turn translate into higher achievable gain-bandwidth products, which presently (2020) can be as high as low GHz.

Gain-Bandwidth Product Curves



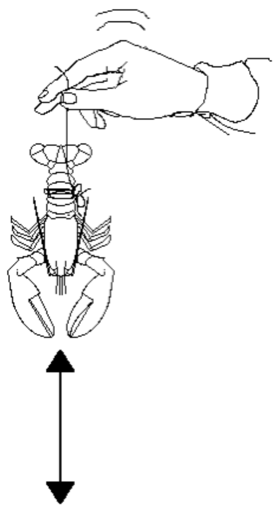
SLEW RATE

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

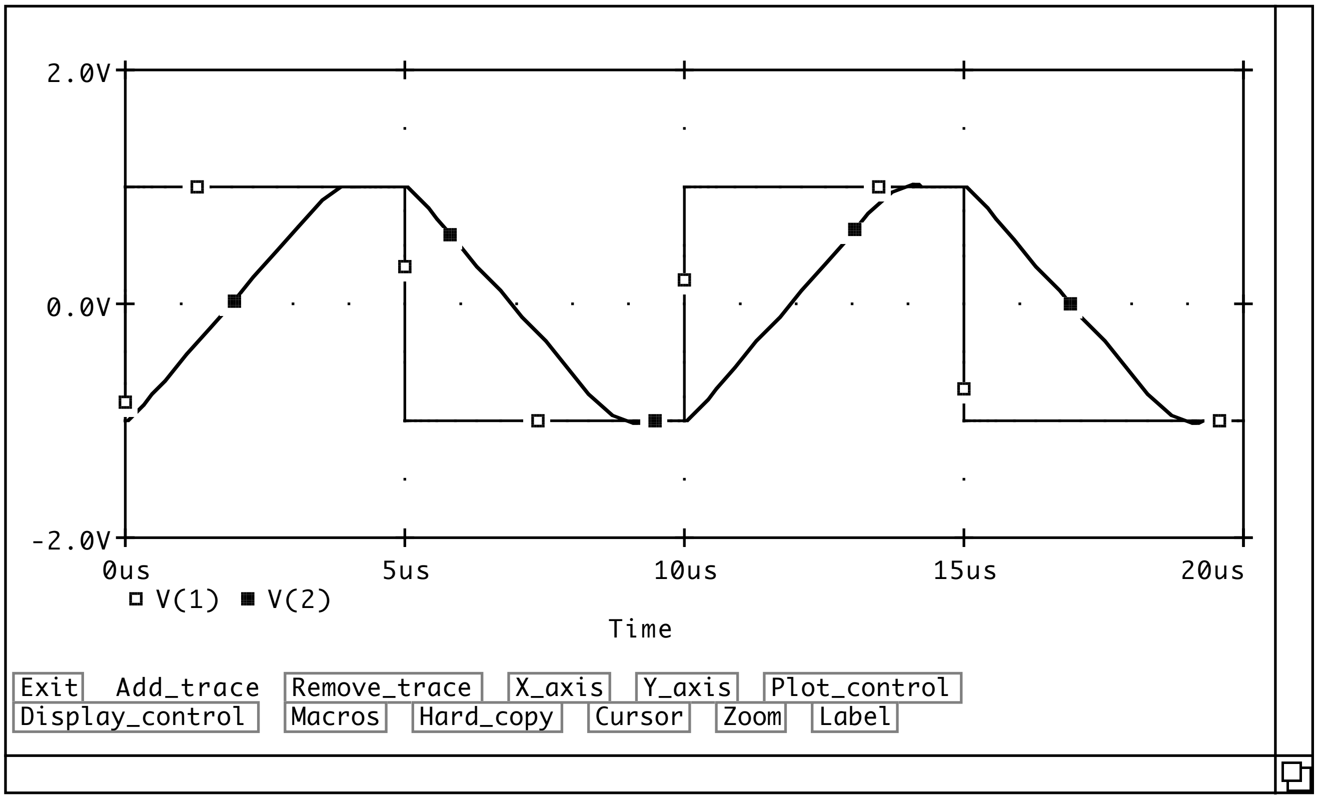
If you try an make them go faster, they try, but you get a limiting rate of change, the SLEW RATE!

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

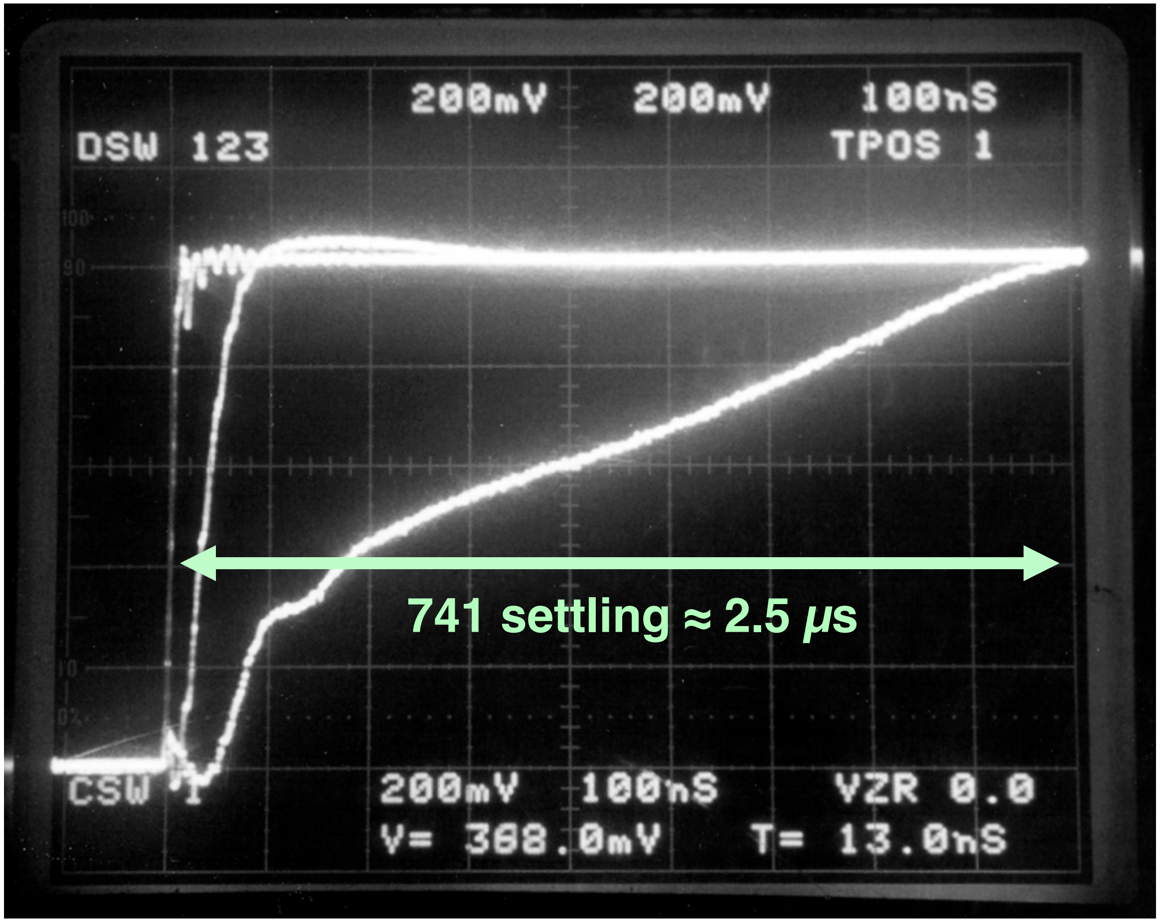
≈ 3.9 µS to swing 2 V gives a slew rate of ≈ 0.5 V/µS



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

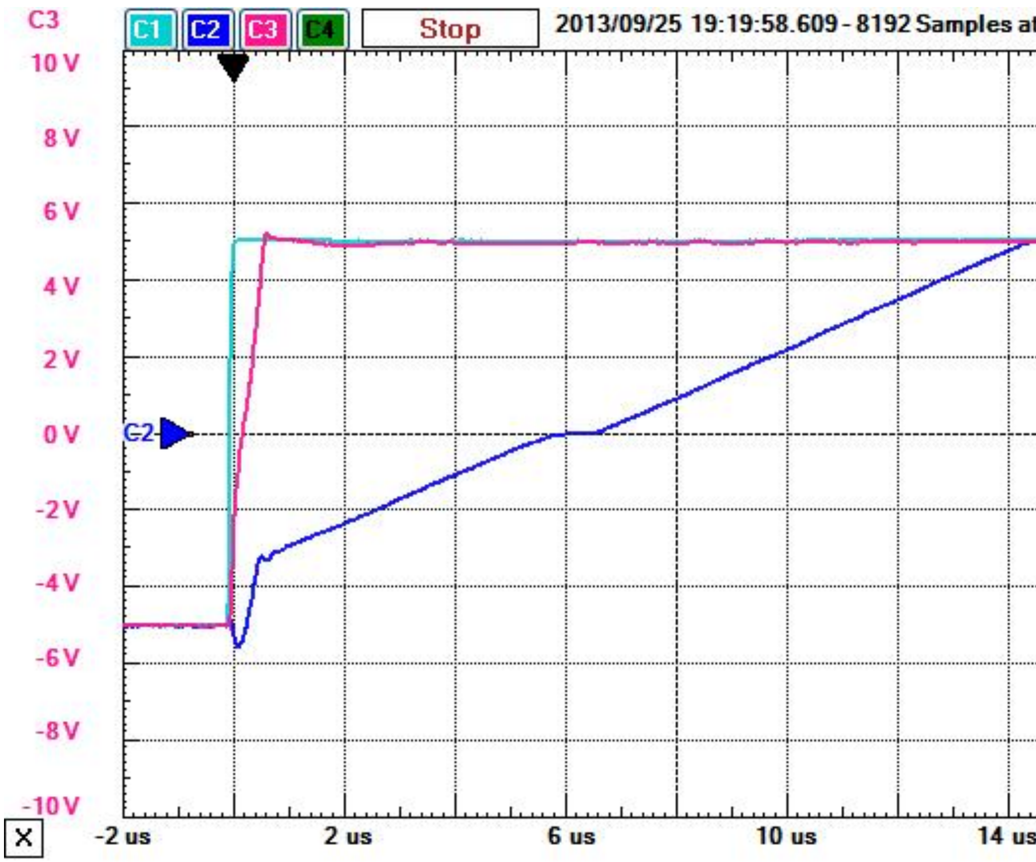


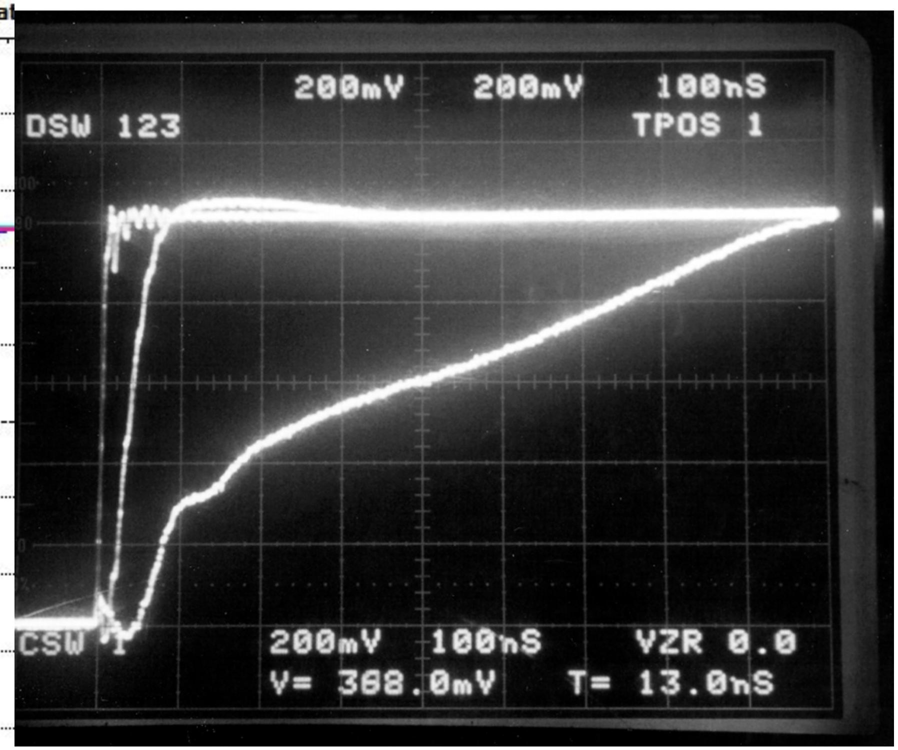
Slew Rate Example - Rising



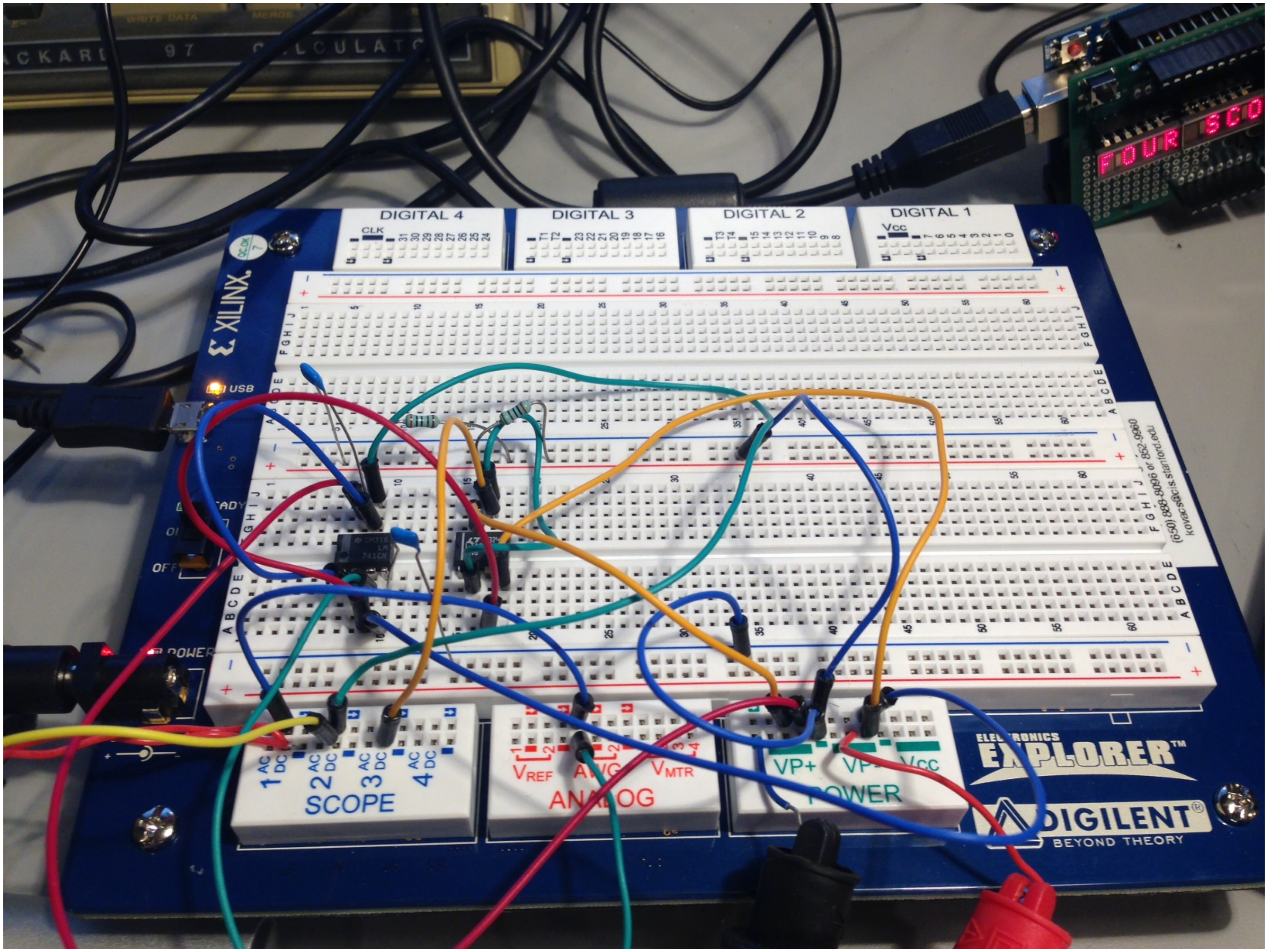
LM741 (slow) and LT1056, ±15V Supplies, 2kΩ Load, 1 VPP Squarewave Input (locally terminated into 50Ω).

Slew Rate – Rising – Electronics Explorer

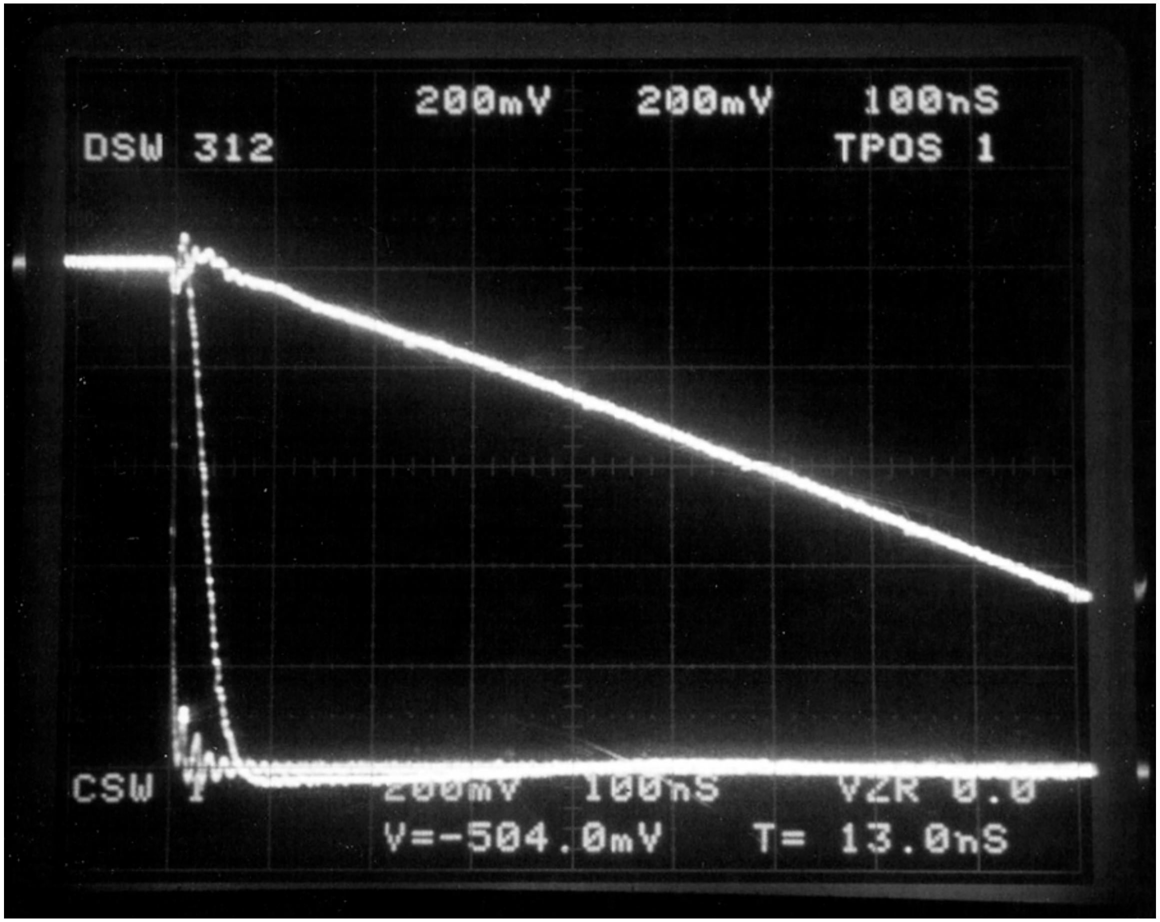




Slew Rate Setup (Crude)

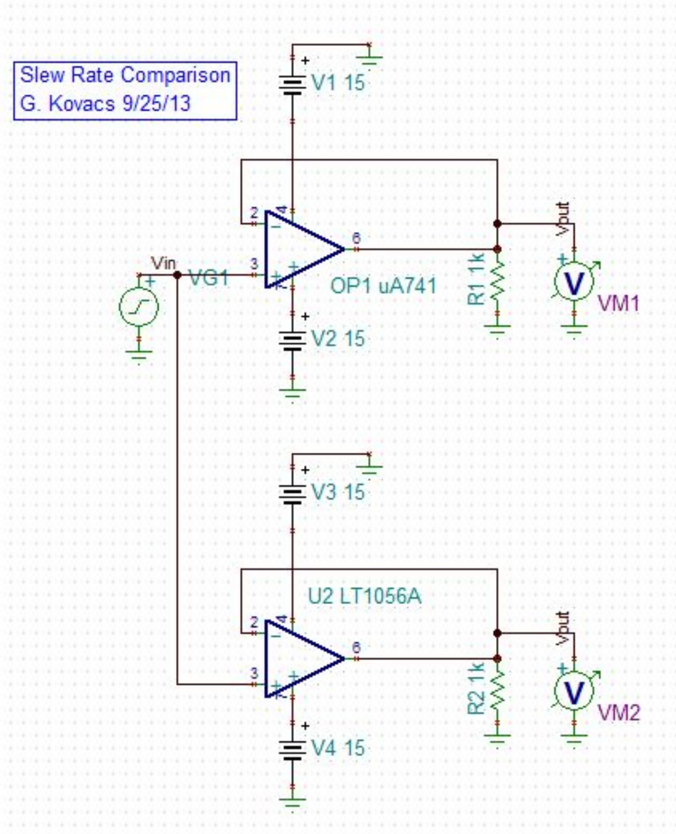


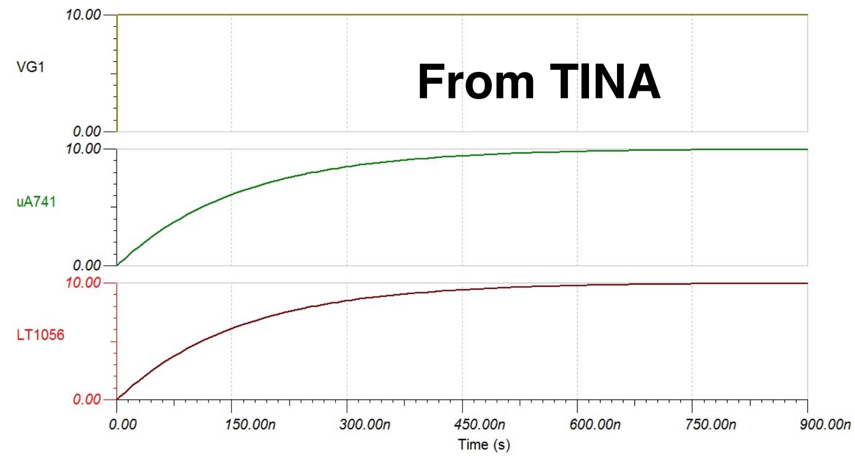
Slew Rate Example - Falling

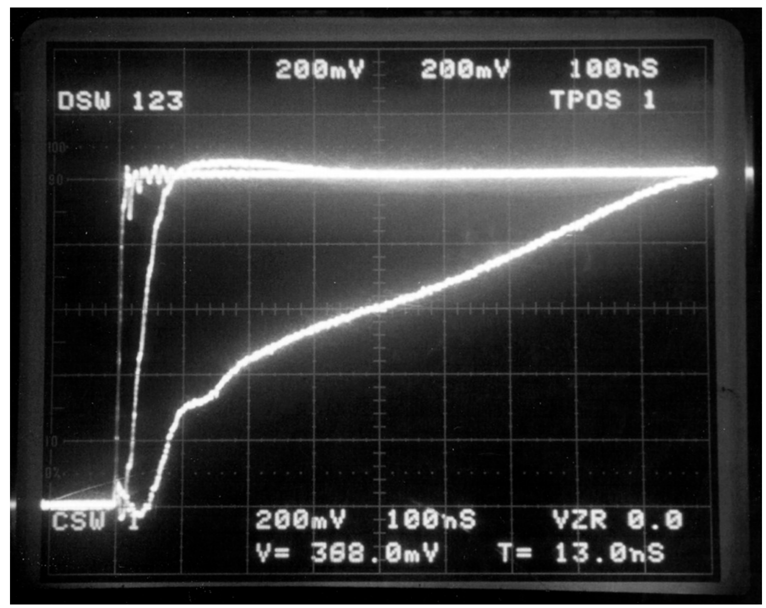


LM741 (slow) and LT1056, ±15V Supplies, 2kΩ Load, 1 VPP Squarewave Input (locally terminated into 50Ω).

Simulation? Not Always Useful!







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

SLEW RATE AND ACTUAL BANDWIDTH

- **For small amplitude signals, op-amps generally do quite well because they do not have to slew very far in terms of voltage.**
- **"Slew-rate limiting" is a term used to define the transition from small-signal to large-signal, where one begins to see significant degradation in performance. For a given peak output voltage swing, v_p, one obtains:**

$$v_o = v_p \sin(2\pi ft)$$

$$\frac{dv_o}{dt} = 2\pi v_p \cos(2\pi ft)$$

The maximum slope occurs at the zero crossing, so, the slew rate limit is:

$$S_r = \left.\frac{dv_o}{dt}\right|_{t=0} = 2\pi f v_p$$

Thus, the maximum frequency without slew-rate distortion is:

$$\mathrm{f}_{\mathrm{max}} = \frac{\mathrm{S_r}}{2\pi v_p}$$

See: "Predicting Op Amp Slew Rate Limited Response, National Semiconductor Linear Brief 19, TI SNOA852)

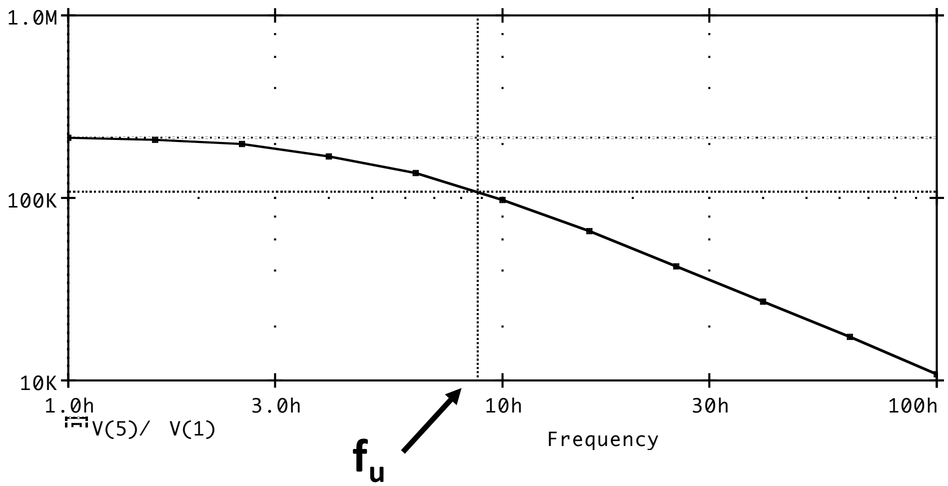
SLEW RATE BOTTOM LINES

- **The impressive bandwidths on op-amp spec sheets are for small-signal operation, which is ok for some cases.**
- **However, as discussed above, when signals get larger in amplitude, slew-rate limiting can introduce serious distortion unless the more limited large-signal (or "full power") bandwidth of the op-amp is considered.**
- **If this effect is not taken into account, serious distortion of waveforms can occur, with a forest of harmonics. This is not good in precision applications such as instrumentation and audio.**
- **The bottom line here is that it is more work to swing more widely in amplitude, so amplifiers of any kind will show their weaknesses more in large-signal operation.**
- **Combined with higher frequency operation, large signals can be quite challenging to create (consider the output of a 20MHz sinewave generator that has to swing 10 VPP − that's really a non-trivial output amplifier).**

Thought Problem

- **Series of non-inverting amps at gains stepped up by factors of ten, driven by voltage dividers to cancel their gains.**
- **Look at bandwidth and noise.**

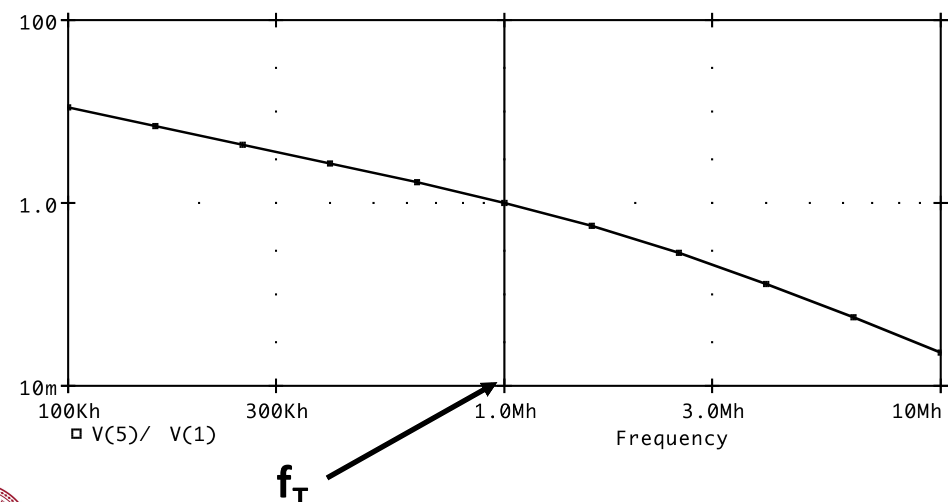
OPEN-LOOP CHARACTERISTICS OF "REAL" OP-AMPS



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

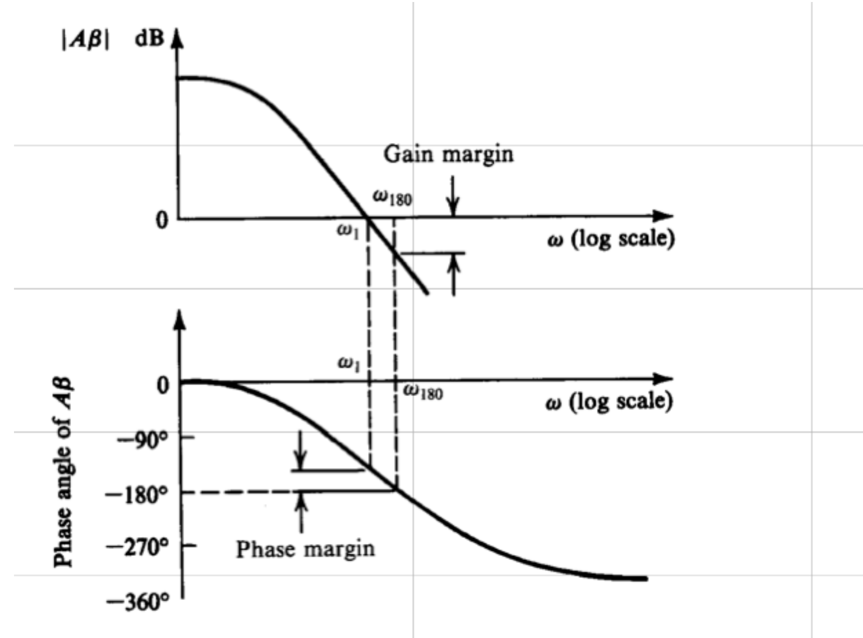
$$f_U = \frac{f_T}{Closed - Loop\_Gain}$$

STABILITY AND COMPENSATION

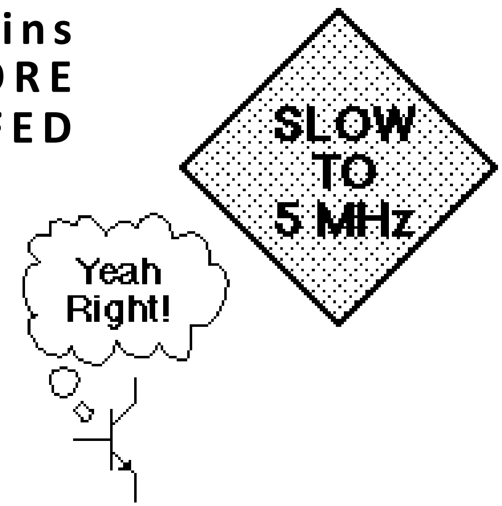
With negative feedback, if the input of the amplifier receives a -180° out-of-phase replica of the output signal (via the feedback circuit) you end up with OSCILLATIONS!!!!

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!



POWER SUPPLY REJECTION

- Op-amps are not perfect at rejecting noise coming in on the power supply inputs (AKA "power supply rejection") − ***this gets worse as the frequency of the noise increases.***
- The specification that describes how good an op-amp is at rejecting such noise is the power supply rejection ratio (PSRR).
- Unfortunately, definitions are not consistent. One is input referred and one is output referred.
- Input-referred PSRR is defined as the ratio of the change in supply voltage (noise) to the equivalent signal it would take at the input of the op-amp to get the same output signal (i.e., the resulting output perturbation is divided by the gain of the circuit to make it seem as an input signal).
- Output-referred PSRR is defined as the ratio of the change in supply voltage (noise) to the signal it produces at the output of the op-amp.
- The ratio is given in dB:

$$PSRR_{RTI} = 20\log\frac{\Delta V_s}{\Delta V_{ineq}} \qquad PSRR_{RTO} = 20\log\frac{\Delta V_s}{\Delta V_{out}}$$

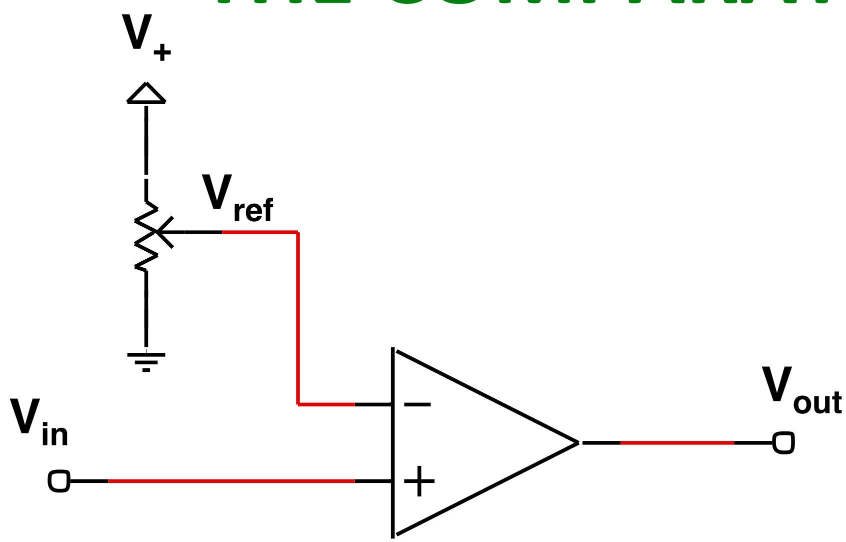
$$\Delta V_{ineq} = \text{input equivalent voltage to cause output response}$$

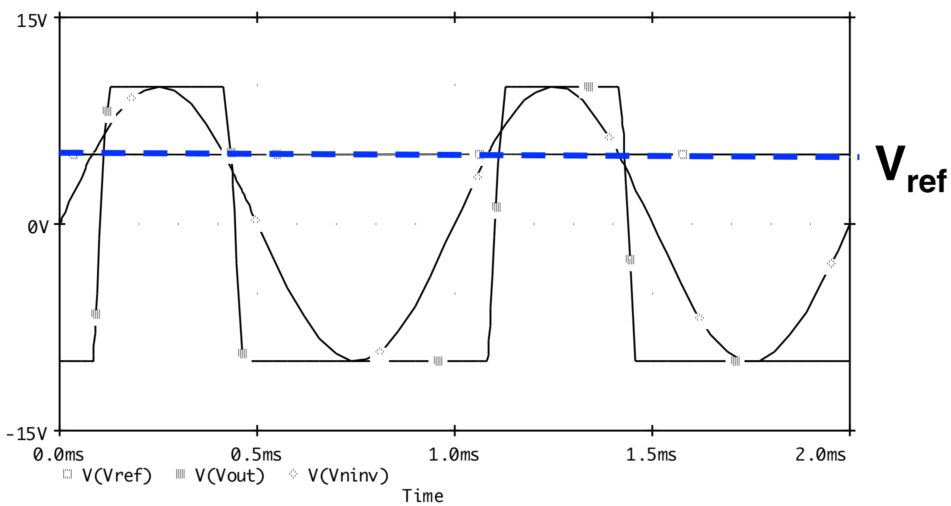
$$= \frac{\Delta V_{out}}{A_V}$$

DECOUPLING CAPACITORS

- Since PSRR is not infinite, we use local capacitors to try to "absorb" noise on power supplies that could otherwise get into the op-amp.
- Typically, 0.1 μF is used from each power supply rail to ground.
- 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.

THE COMPARATOR: ONE-BIT A/D





This is basically a one-bit A/D converter, which compares in the input signal to a reference and decides if it is smaller or larger than a reference voltage.

Open loop, HUGE gain, like the clipper or "fuzz" box but without diodes – even the smallest signals get "clipped," causing the output of the op-amp to swing between the extremes.

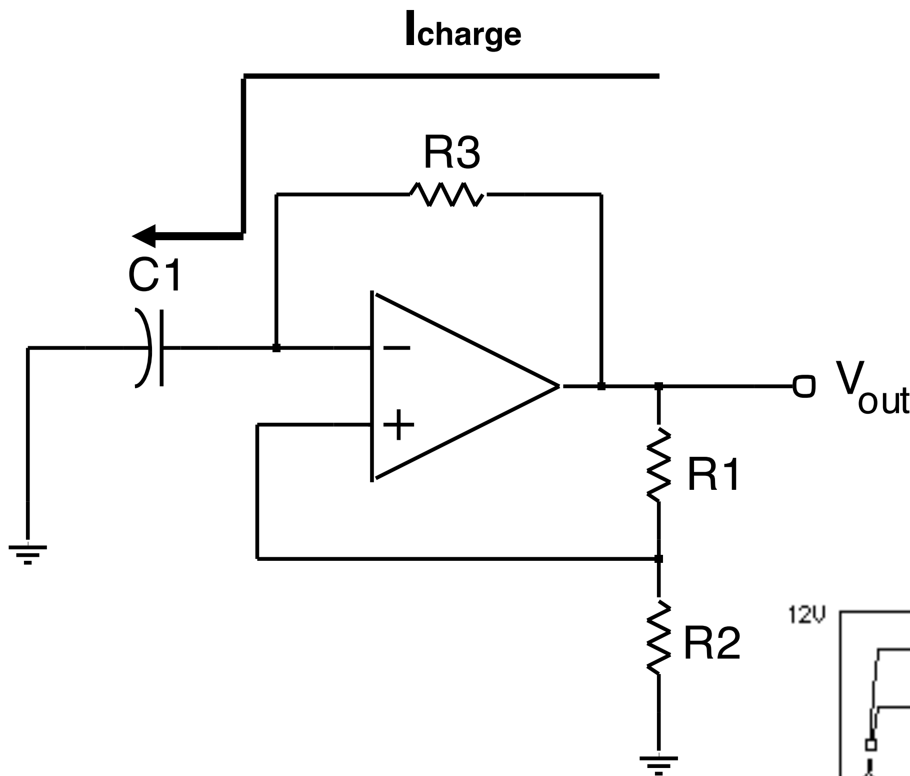
This circuit only has two output states:

$$+V_{sat} \text{ IF } V_{in} > V_{ref}$$

$$-V_{sat} \text{ IF } V_{in} < V_{ref}$$

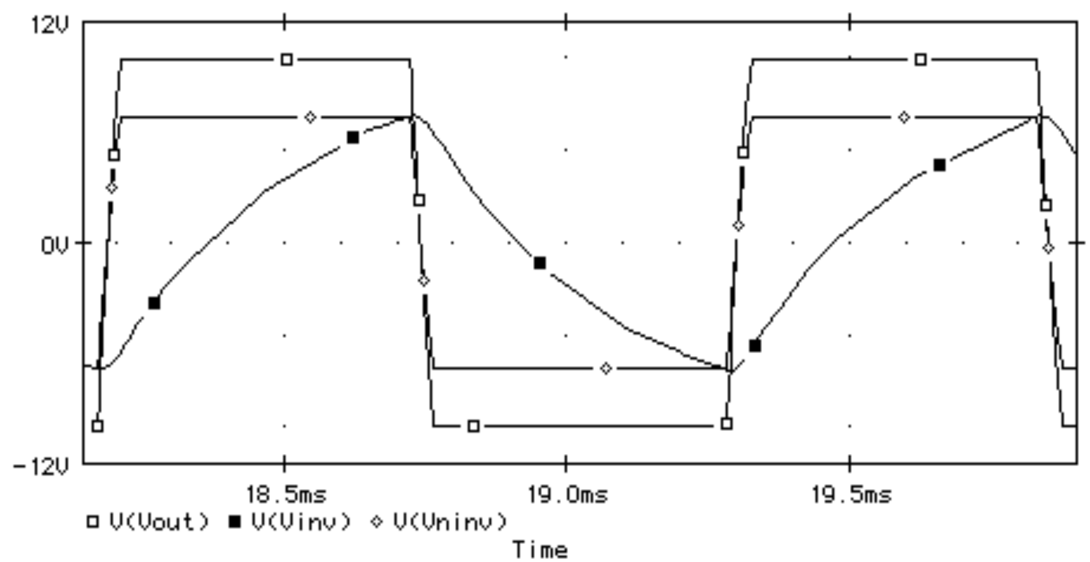
Can have problems with small noise voltages being hugely amplified!

SQUAREWAVE OSCILLATOR



$$f_o \approx \frac{1}{2R_3C_1 \ln\left(\frac{2R_1}{R_2}+1\right)}$$

The output swings between the maximums V_{sat+} and V_{sat-}.



Think About Your Projects Please!

Talk to your partner about areas of common interest.

Brainstorm.

Talk to your TA and instructors about pre-defined project concepts.

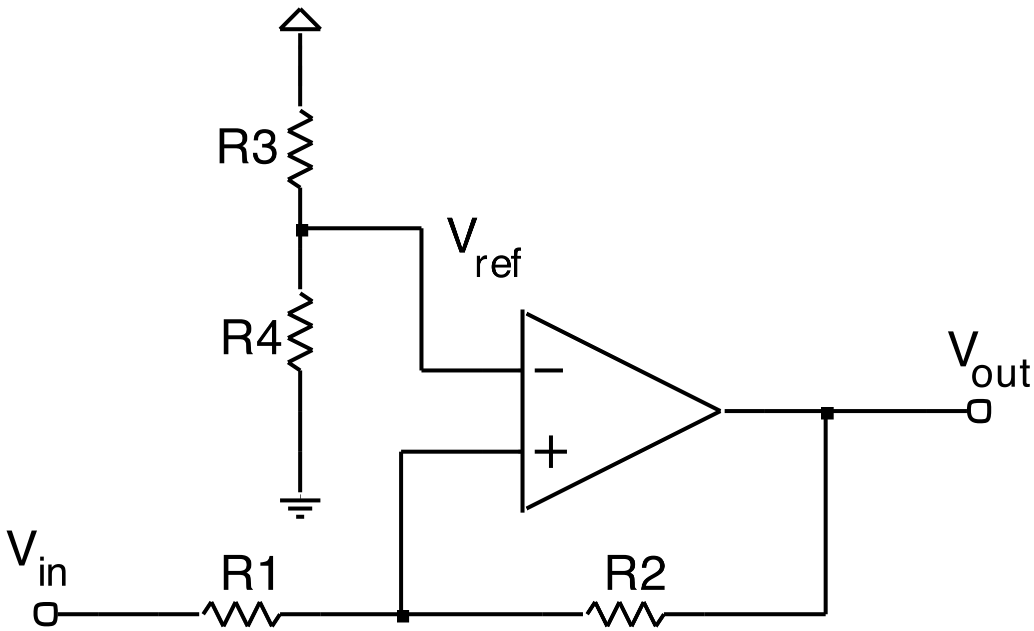
Please do not put this off!

CONCLUSIONS

- Op-amps are useful for lots of things.
- Op-amps deliver a lot of performance for very low cost, but it is important to understand their imperfections and limitations.
- Op-amp circuits are generally fairly intuitive if you remember the basic "rules" of op-amp operation.

Appendix 1: Schmitt Trigger Circuits

THE SCHMITT TRIGGER

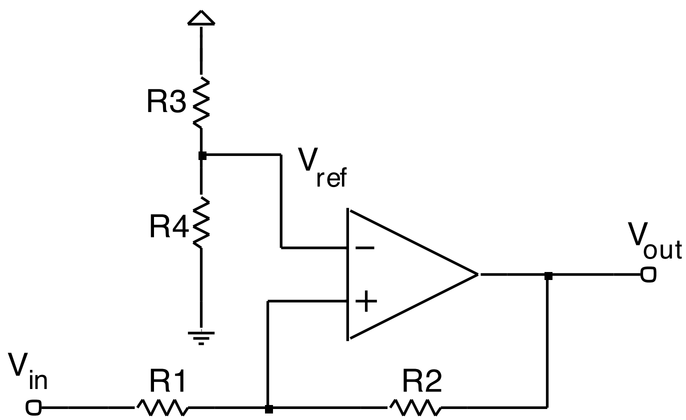


- POSITIVE FEEDBACK (NOT OPEN LOOP)...
- HYSTERESIS.... THERE ARE NOW TWO DISTINCT THRESHOLD VOLTAGES THAT DETERMINE THE STATE OF THE OUTPUT...

  ONE THRESHOLD TO GO HIGH IF IT'S LOW

  ANOTHER THRESHOLD TO GO LOW IF ITS HIGH...
- GOOD FOR REJECTING NOISE!!!

SCHMITT TRIGGER DESIGN



VOLTAGE AT NON-INVERTING INPUT BY SUPERPOSITION:

$$V_+ = V_{out}\frac{R1}{R1 + R2} + V_{in}\frac{R2}{R1 + R2}$$

TO FIND THE TRIP-POINTS
LET Vin = Vu or V_L AND SOLVE...

$$V_U = V_{ref}\left(\frac{R1 + R2}{R2}\right) - V_{sat-}\frac{R1}{R2}$$

$$V_L = V_{ref}\left(\frac{R1 + R2}{R2}\right) - V_{sat+}\frac{R1}{R2}$$

SUBTRACT THE TRIP-POINTS TO GET THE HYSTERESIS...

$$V_U - V_L = V_{ref}\left(\frac{R1 + R2}{R2}\right) - V_{sat-}\frac{R1}{R2} - V_{ref}\left(\frac{R1 + R2}{R2}\right) + V_{sat+}\frac{R1}{R2}$$

TO DESIGN:

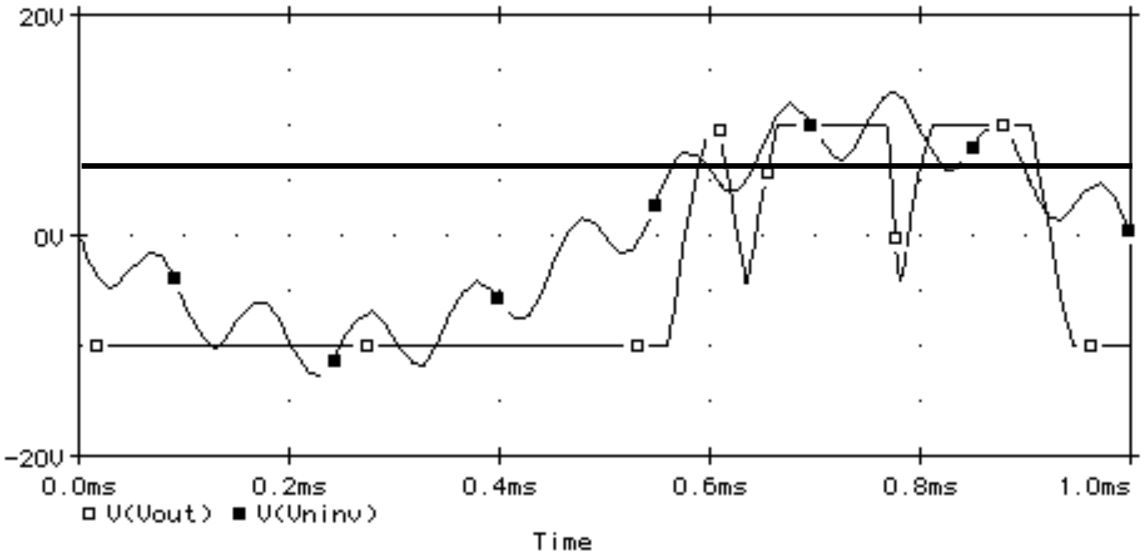
1) **Determine R1 and R2 based on trip-points:**

$$\frac{R1}{R2} = \frac{V_U - V_L}{2V_{sat+}}$$

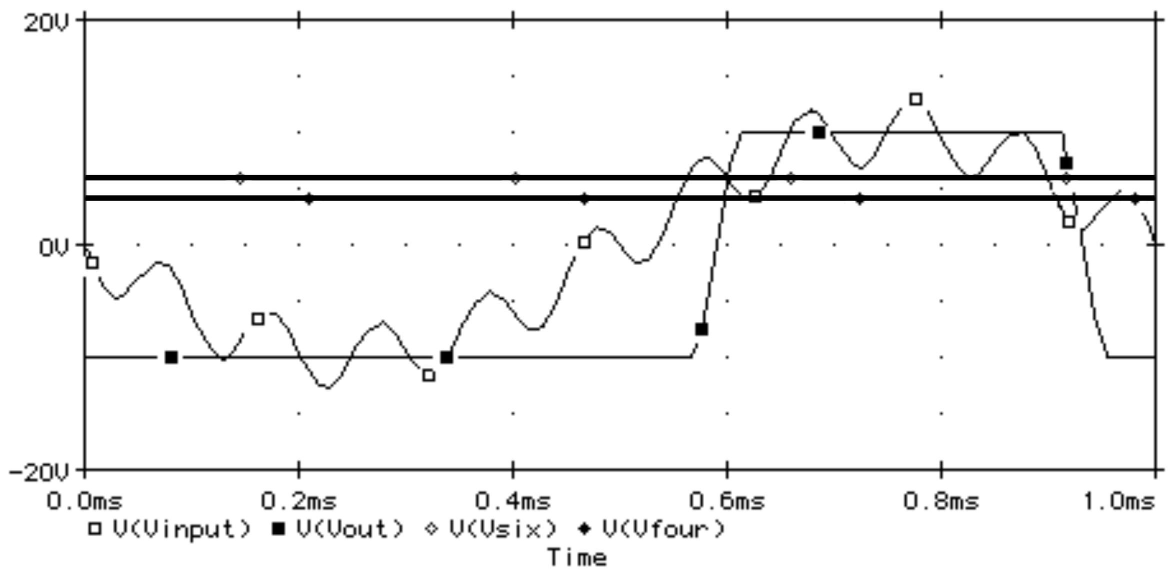
2) **Determine Vref (R3 and R4) from R1 and R2:**

$$V_{ref} = \frac{V_U + V_{sat-}\frac{R1}{R2}}{\left(\frac{R1 + R2}{R2}\right)}$$

SCHMITT TRIGGER VS COMPARATOR NOISE PERFORMANCE...



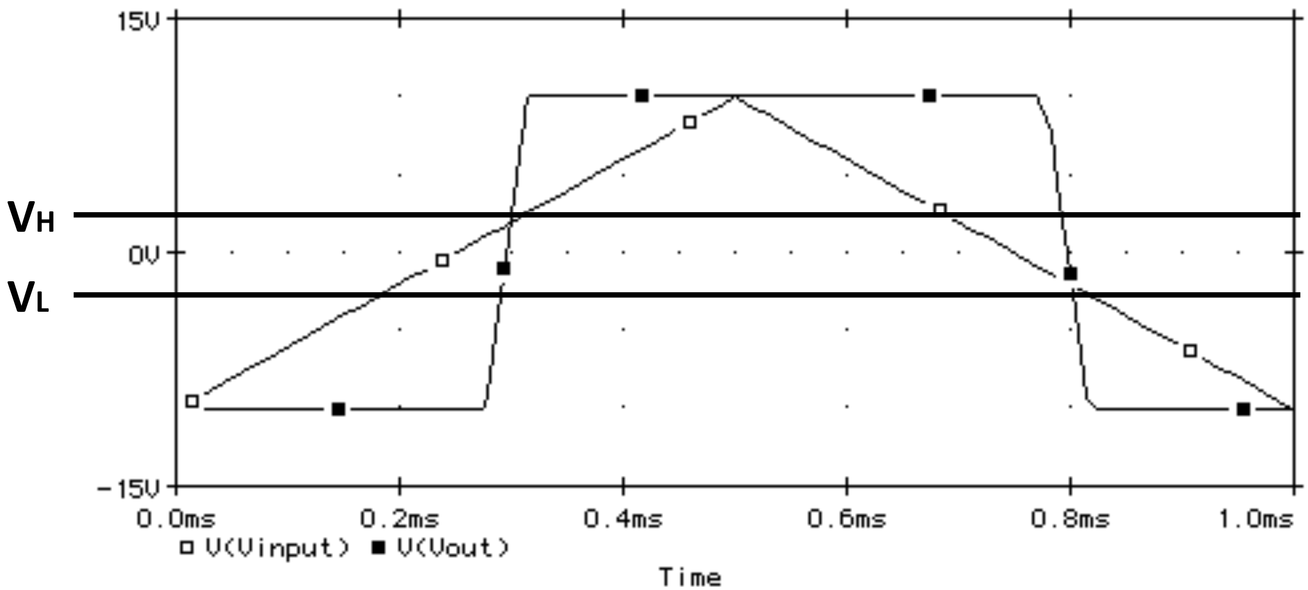
COMPARATOR



SCHMITT TRIGGER

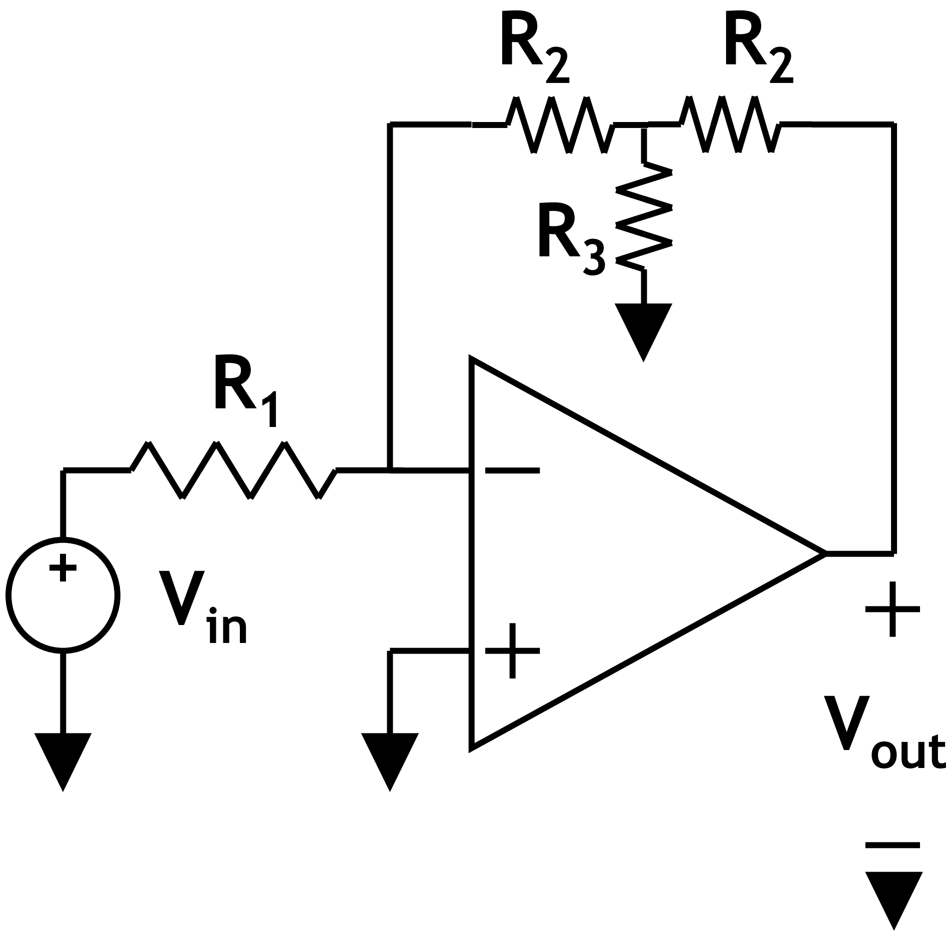
TESTING A SCHMITT TRIGGER

DESIGN FOR SYMMETRICAL +/- 1.1 V TRIP POINTS...



Appendix 2: T-Network Feedback

T-Network Feedback



Write KCL at V- of op-amp:

$$\frac{V_{in}}{R_1} = -V_{out} \cdot \frac{R_2 // R_3}{R_2 + R_2 // R_3} \cdot \frac{1}{R_2}$$

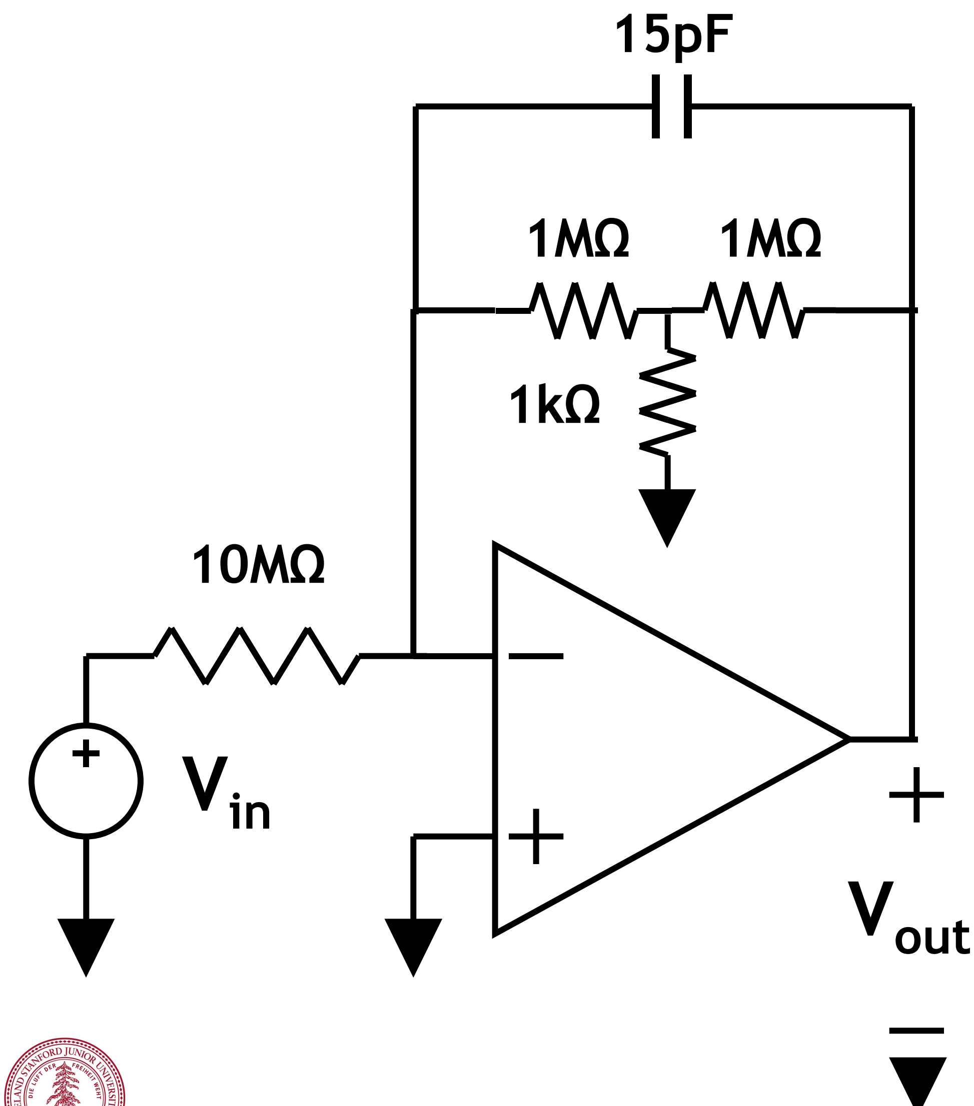
$$\frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \frac{R_2 + R_2 // R_3}{R_2 // R_3}$$

If R2 >> R3:

$$\frac{V_{out}}{V_{in}} \cong -\frac{R_2}{R_1} \cdot \frac{R_2}{R_3} = -\frac{\left(R_2^{\,2} / R_3 \right)}{R_1}$$

This is equivalent to an inverting circuit where the feedback resistor is R2/R3 times bigger than R2. Very useful if large resistors are needed!

T-Network Example

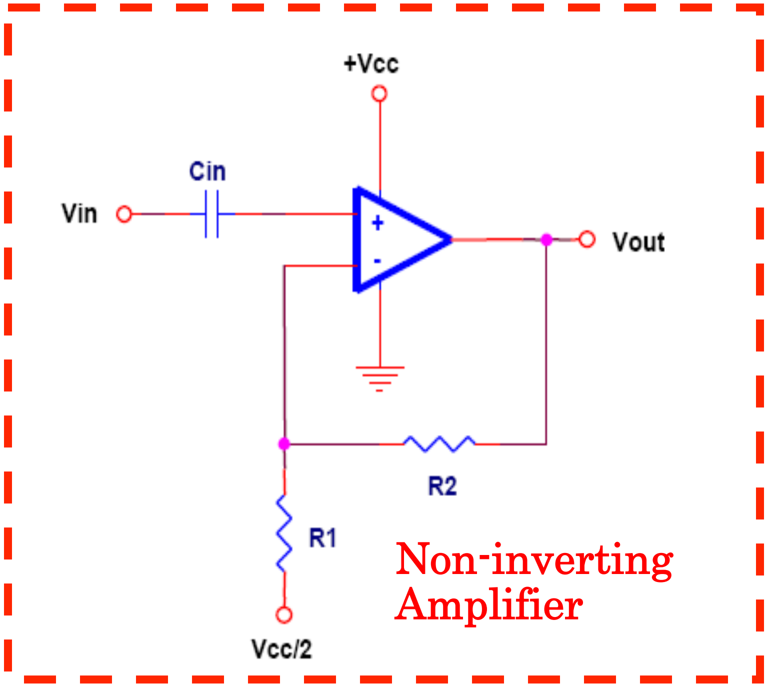


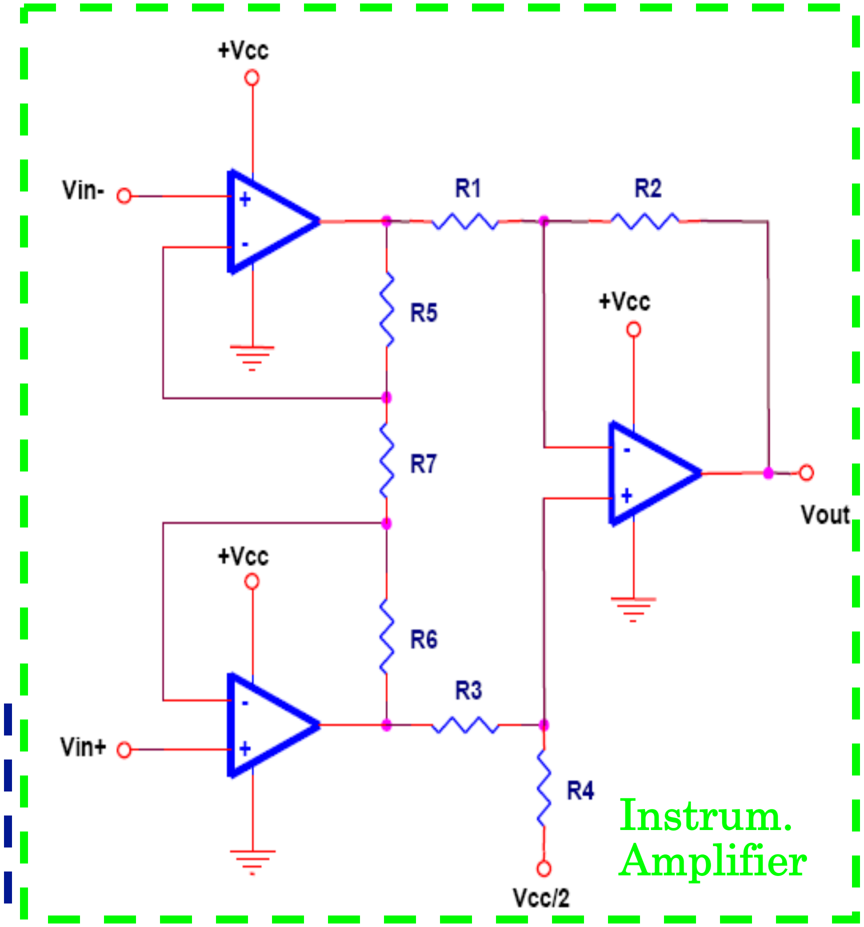
- Create a single-pole op-amp low-pass filter with:
  - 3dB cutoff at 10Hz
  - 40dB attenuation at 1kHz
  - An input impedance of 10MΩ or greater
  - DC gain of 100

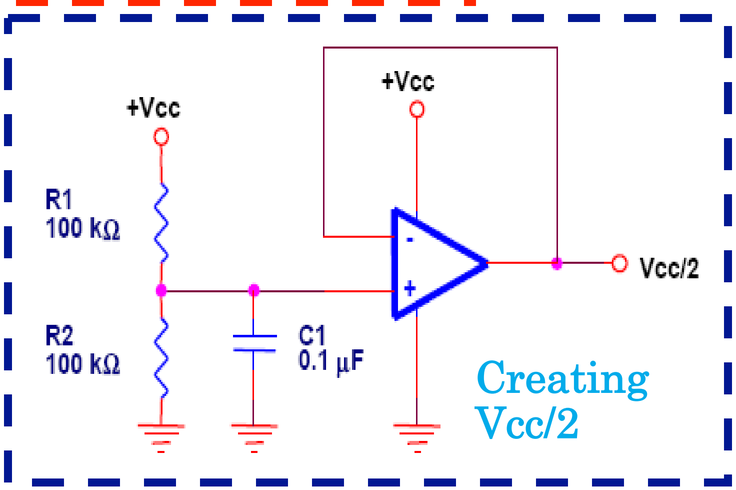
- Question: why might you need 10MΩ input impedance?

Appendix 2: Single-Supply Operation

Single-supply Operation



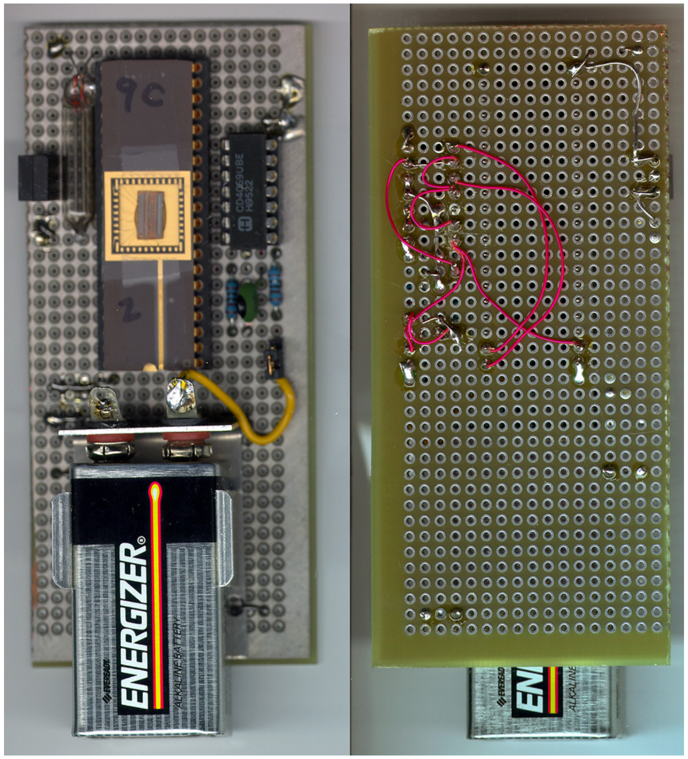


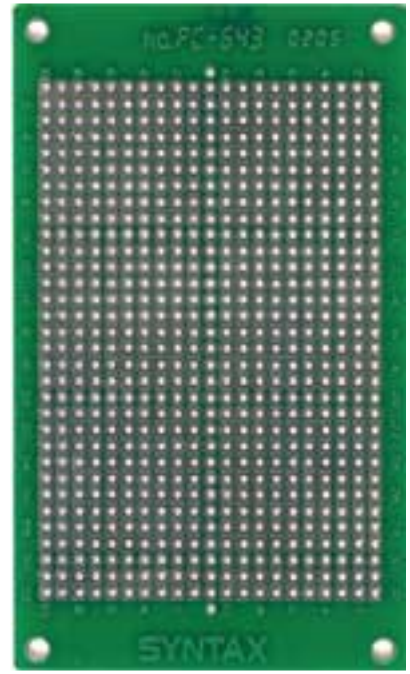


From TI App. Note SLOA058 (see course website).

Appendix 2: Miscellaneous Items

Point-To-Point Soldering On A Prototype Board

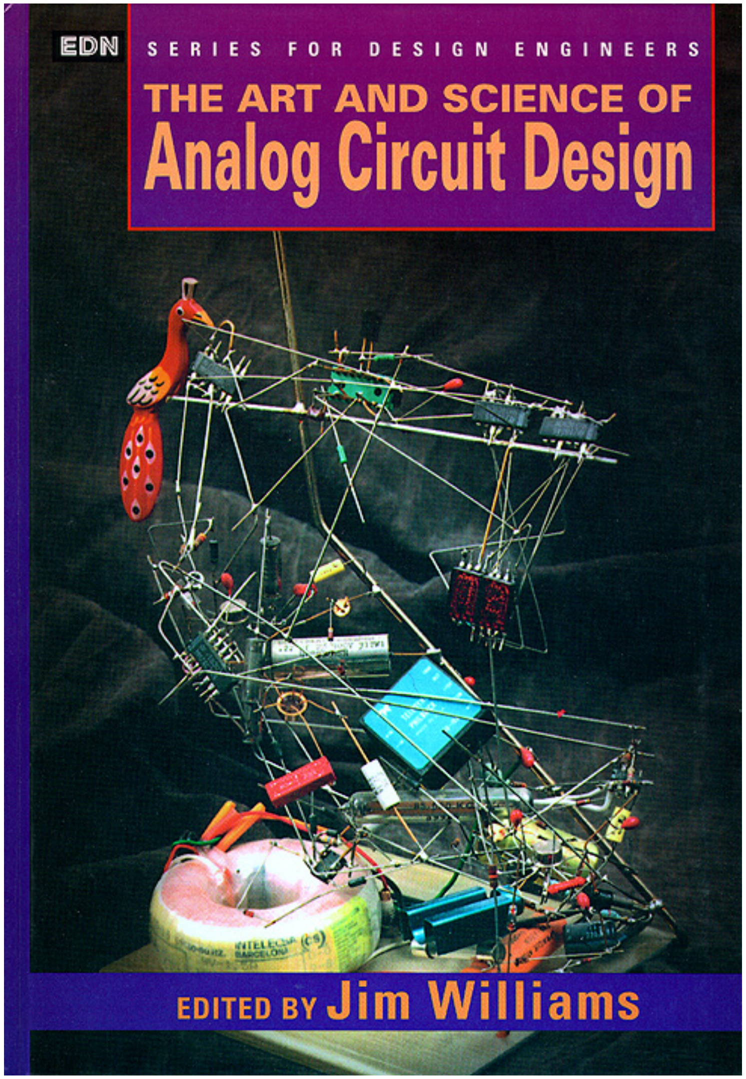




We will use the Syntax PC-643 boards for your projects (104 mm X 60 mm).

Use fine wire. So called "wire-wrap wire" is fine, solid-core wire that is handy for point-to-point but use stranded wire if you need to bring signals on- or off-board and the wires must flex (solid-core will fatigue and break!).

Analog Hacker's Bible Edited by the late Jim Williams



Greg Jim