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The Sight & Sound of Information

Chopper Amplifiers

Achieving Precision

Chopper Amplifiers

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Chopper Amplifiers

- A chopper amplifier is a type of amplifier that exhibits precise outputs and low noise.
- Also called Auto-Zero, Auto-Null, Ping-Pong, Stabilized and Commutated Amplifier.
- A chopper amplifier is often a compound amplifier.

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What is a Chopper good For?

- **What is a precision amplifier?**
- **Why does offset matter?**
- **Terms: Bias, common mode, gain, modulation, servo, AC coupling,**

What's the big deal with offset voltage?

- **What is a precision amplifier?**
- **Why does offset matter?**
- **Terms: Bias, common mode, gain,chopper amplifier, servo, inverting**

Precision Defined:

- **A precision amplifier is an amplifier that outputs and accurate representation of the input signal. This output will be accurate from part to part, over time and over temperature, barometric pressure, sunspots and any other external factors.**

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Precision Defined:

$$e_{id} = \frac{e_o}{A_{VOL}} + V_{OS} + (I_{B+})(R_{S+}) + (I_{B-})(R_{S-}) + \frac{e_{CM}}{CMRR}$$

Amplifier Input Error = (Output Voltage / Open-loop Gain) + Offset Error + (Plus pin Input Bias Current) X (Plus pin Source Resistance)

+ (Minus pin Input Bias Current) X (Minus pin Source Resistance) + (Common Mode Voltage / CMRR (Common-Mode Rejection Ratio))

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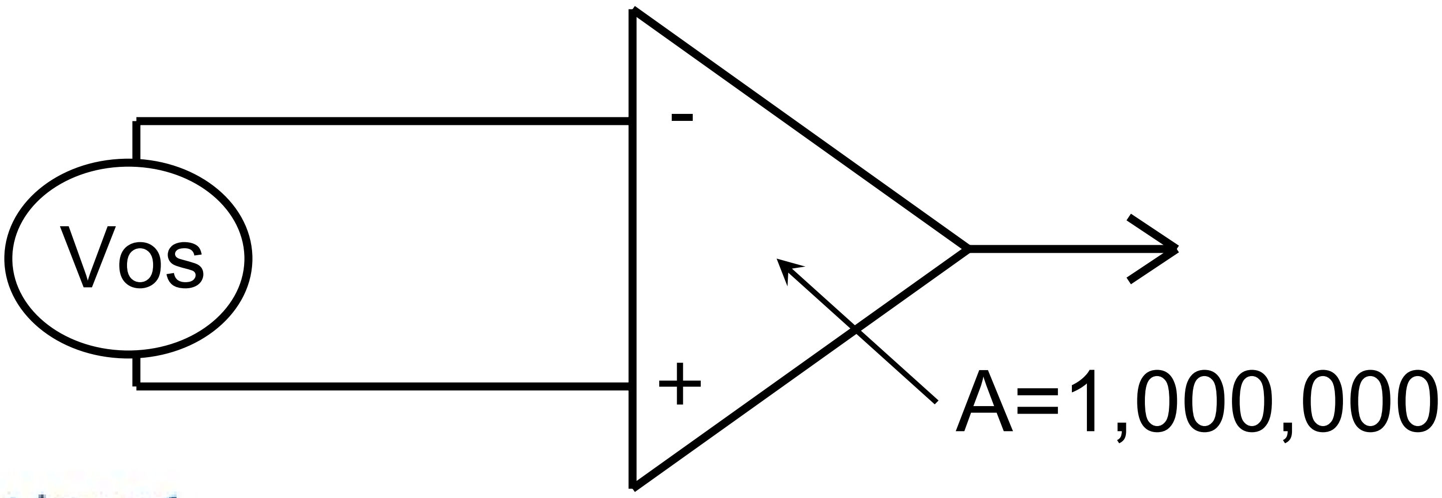
Offset Voltage

- **Offset voltage is the voltage difference on the minus input pin of an amplifier that causes the output to be the same as the plus input pin (with Vcm=0).**



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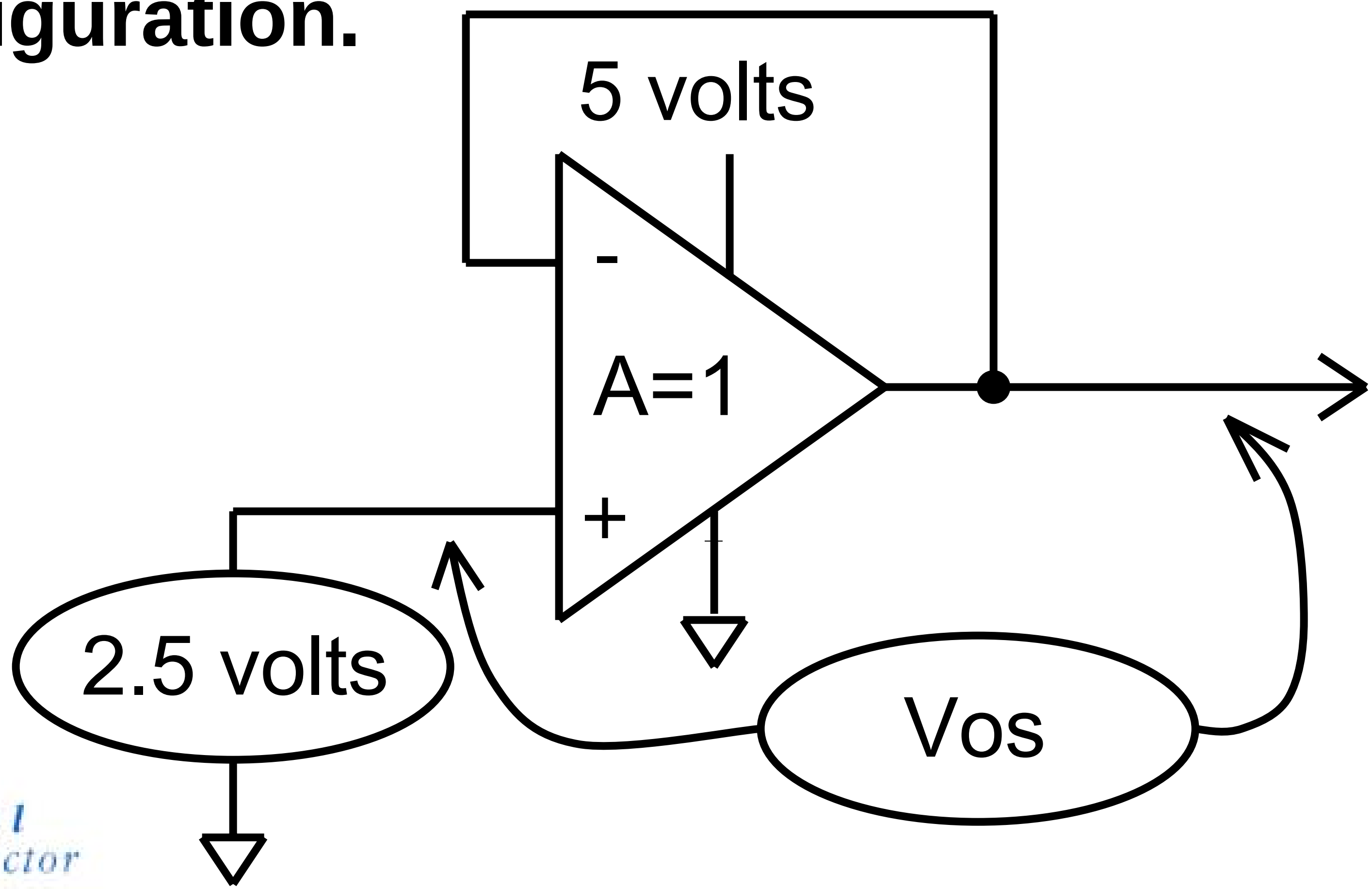
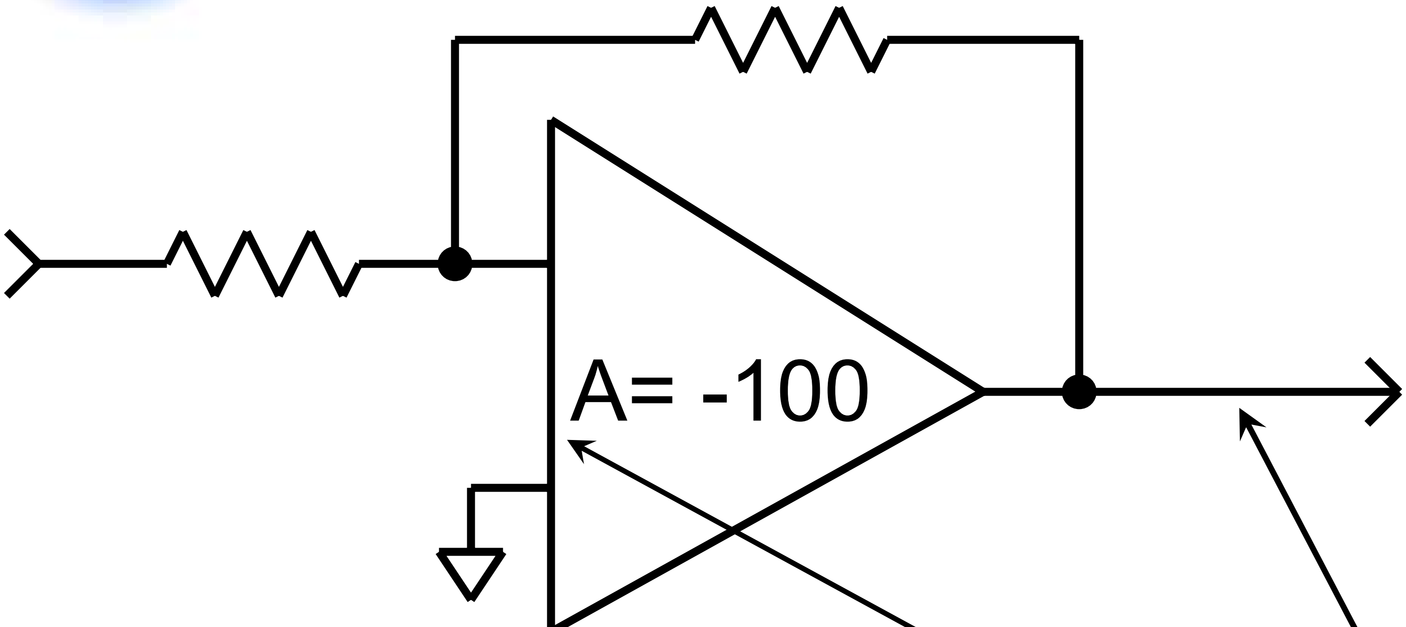
Offset Voltage measurement

- **Here is a way to measure it in closed-loop configuration.**



How does offset hurt precision?

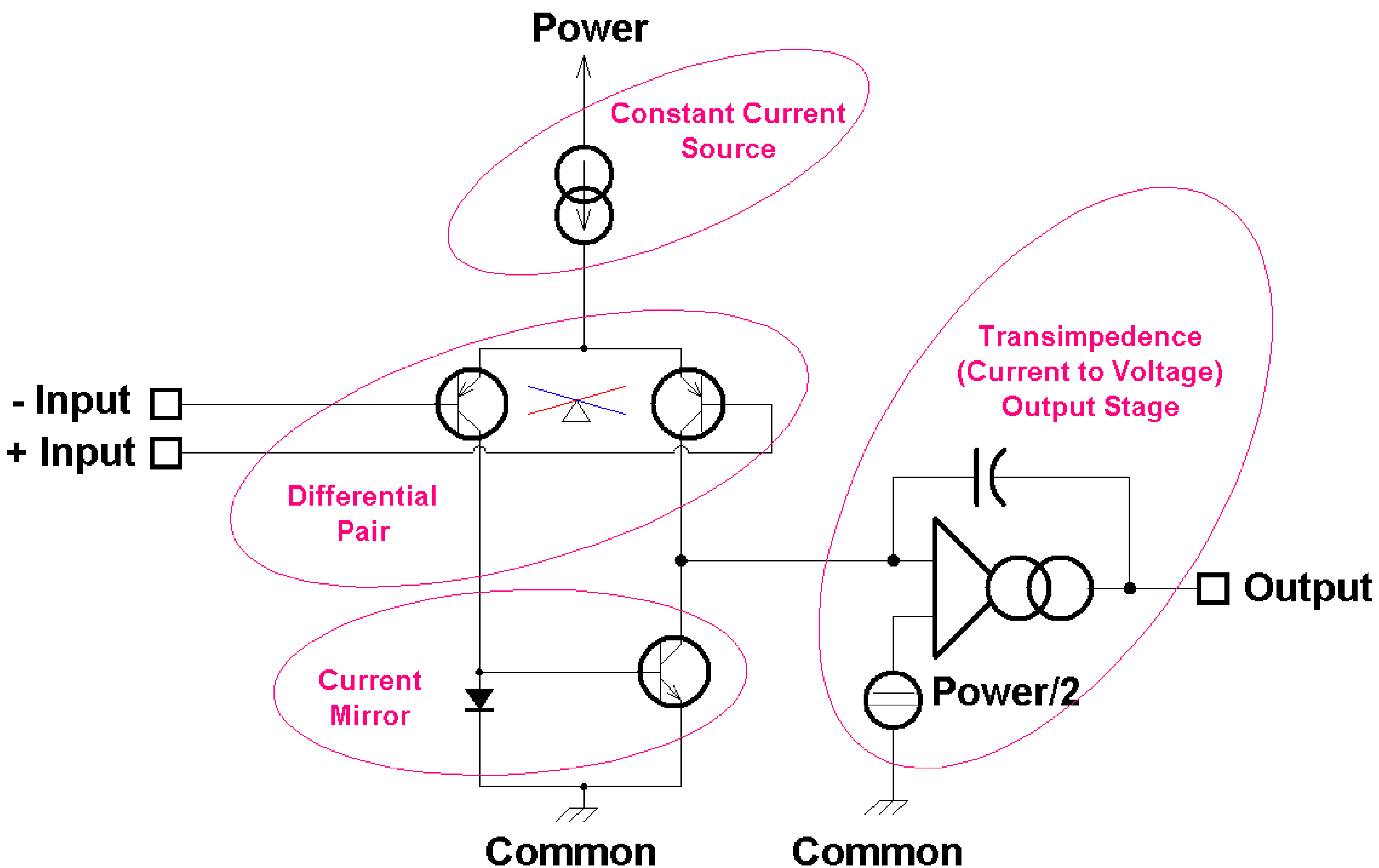


- A one millivolt offset here makes a tenth of a volt error here.
  - If the gain was 1000 the error would be a full volt.

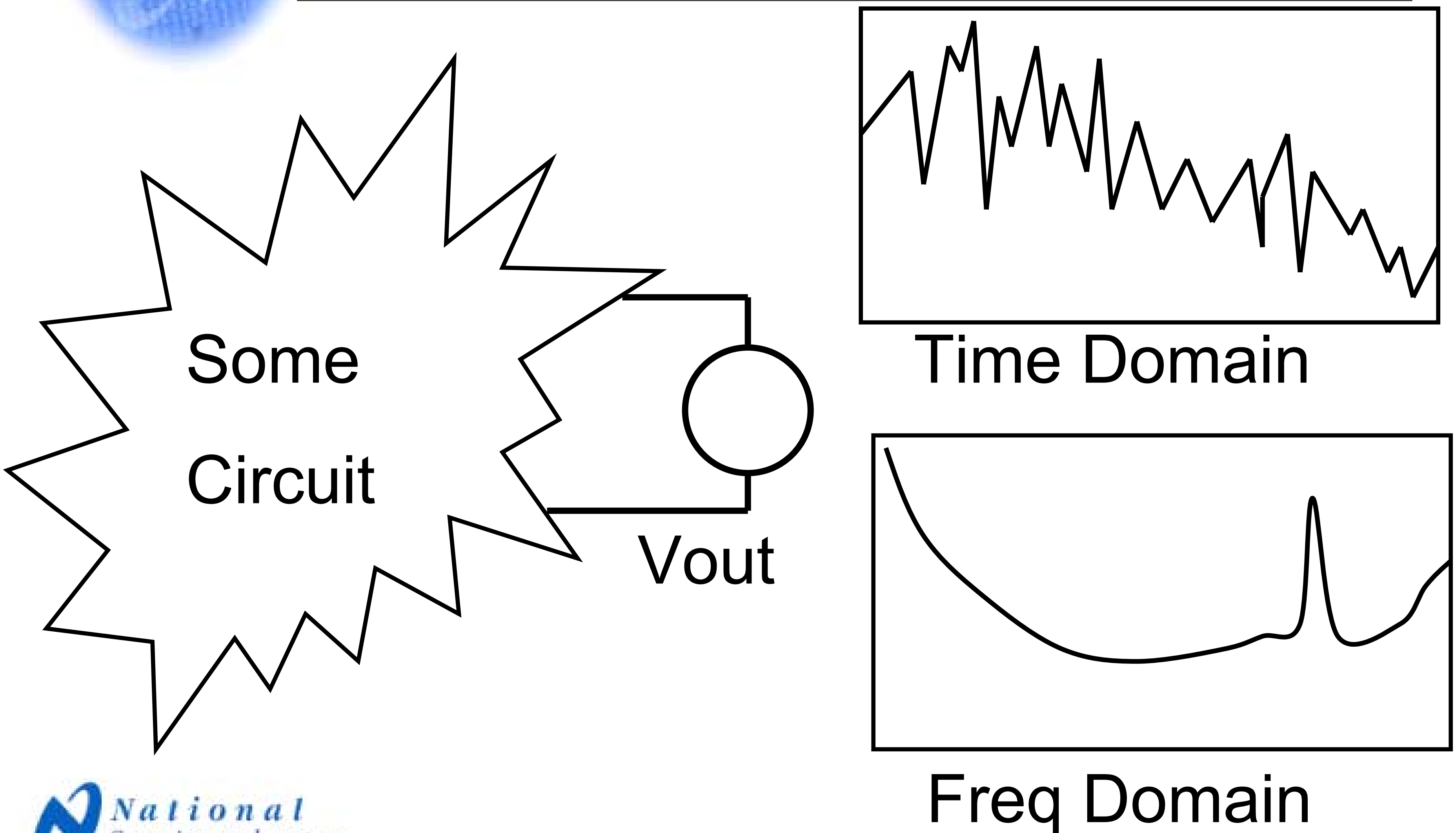
Offset voltage causes

- Small differences in the size of the input stage transistors.
- Differences in the doping of the input stage transistors.
- Differences in the thickness of the base diffusion of the input stage transistors.
- Current mirror inaccuracies.
- Resistor mismatch.
- Packaging/mounting stress.
- Dynamic considerations: Thermal and light and radiation.
- Circuits aren't perfect (despite those IC designer's egos).

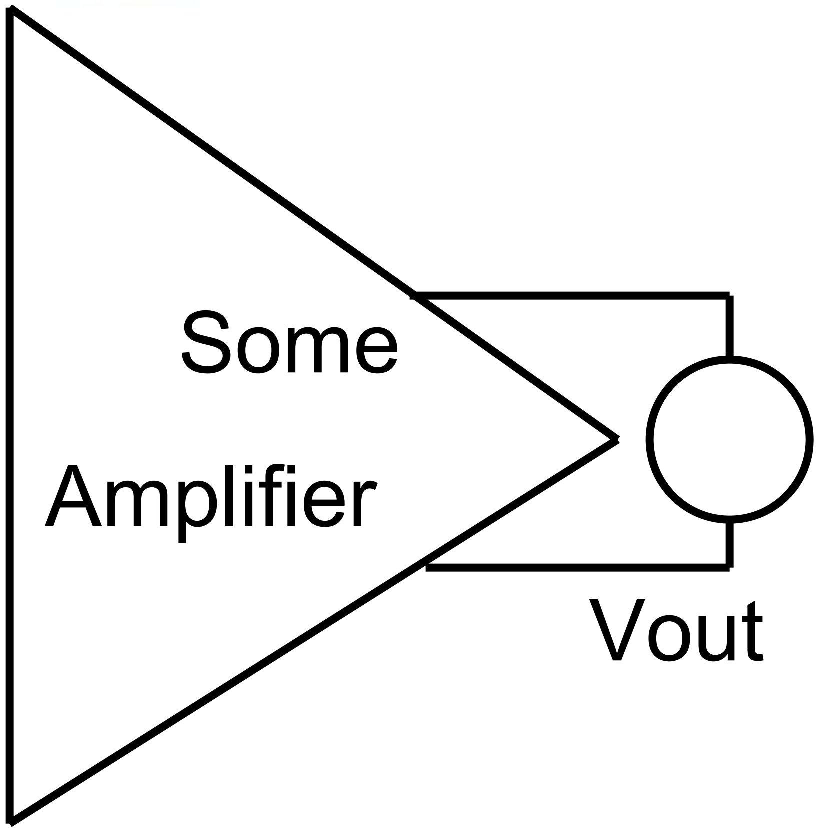
Amplifier Input Stage

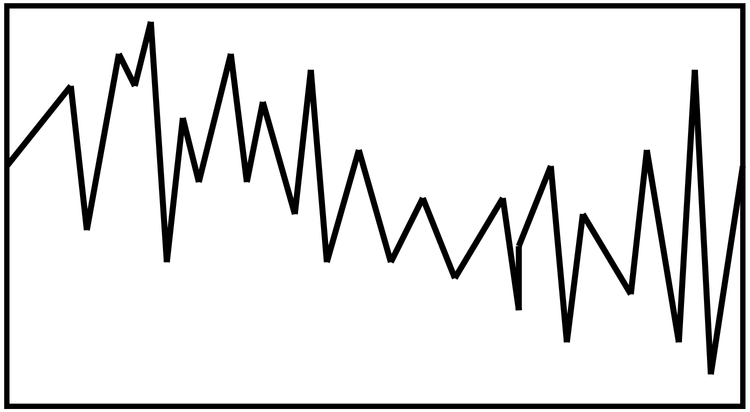


Noise

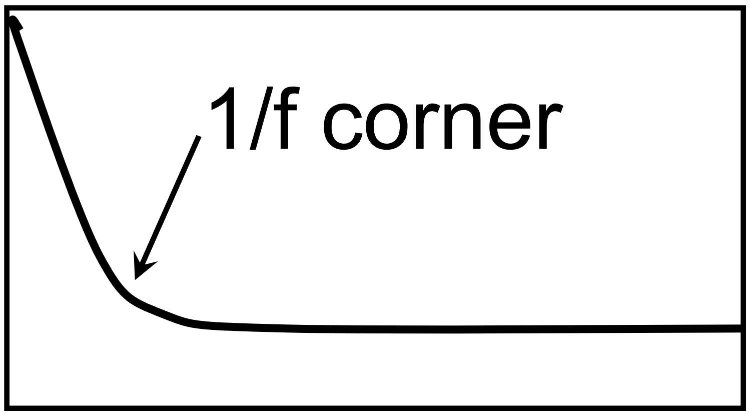


Amplifier Noise



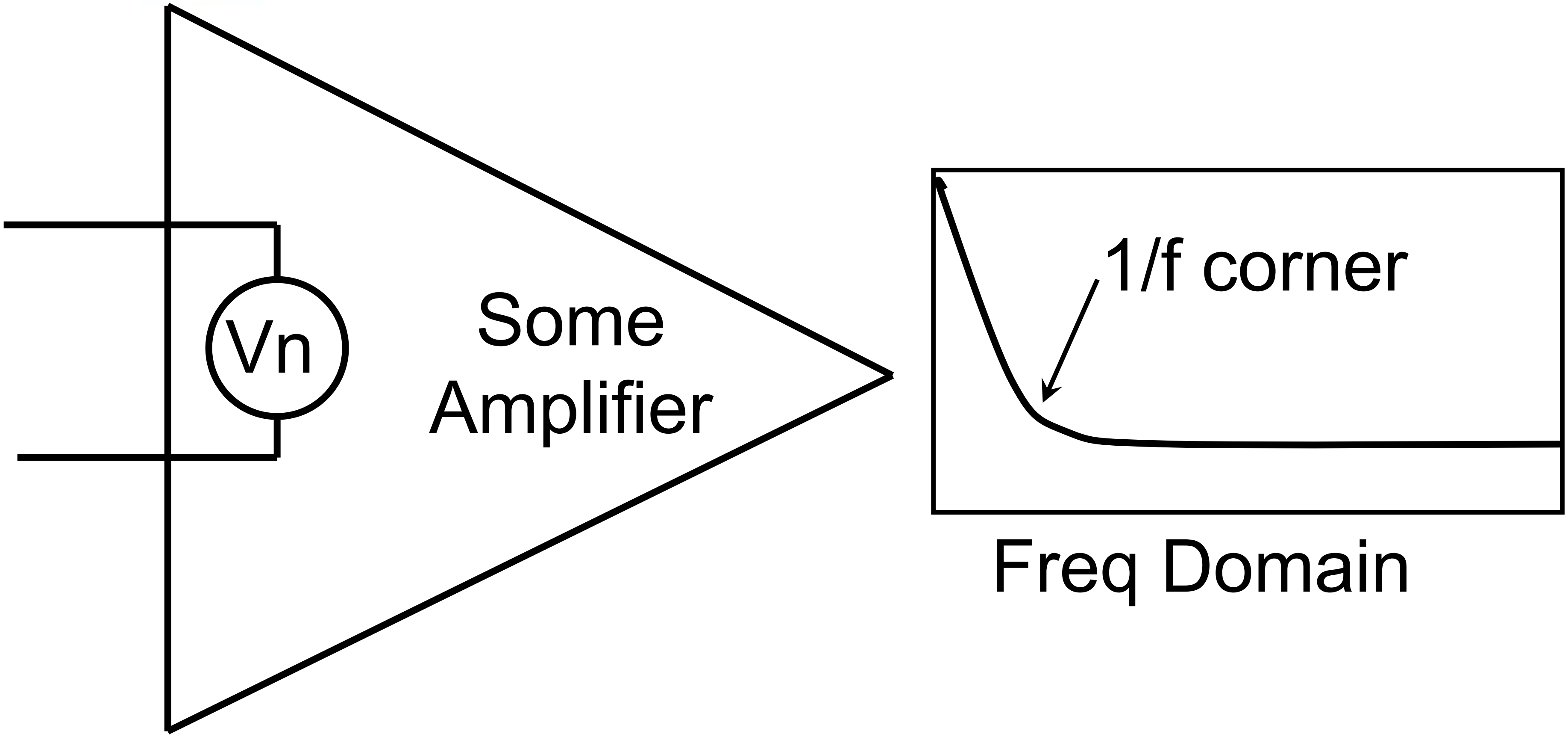


Time Domain

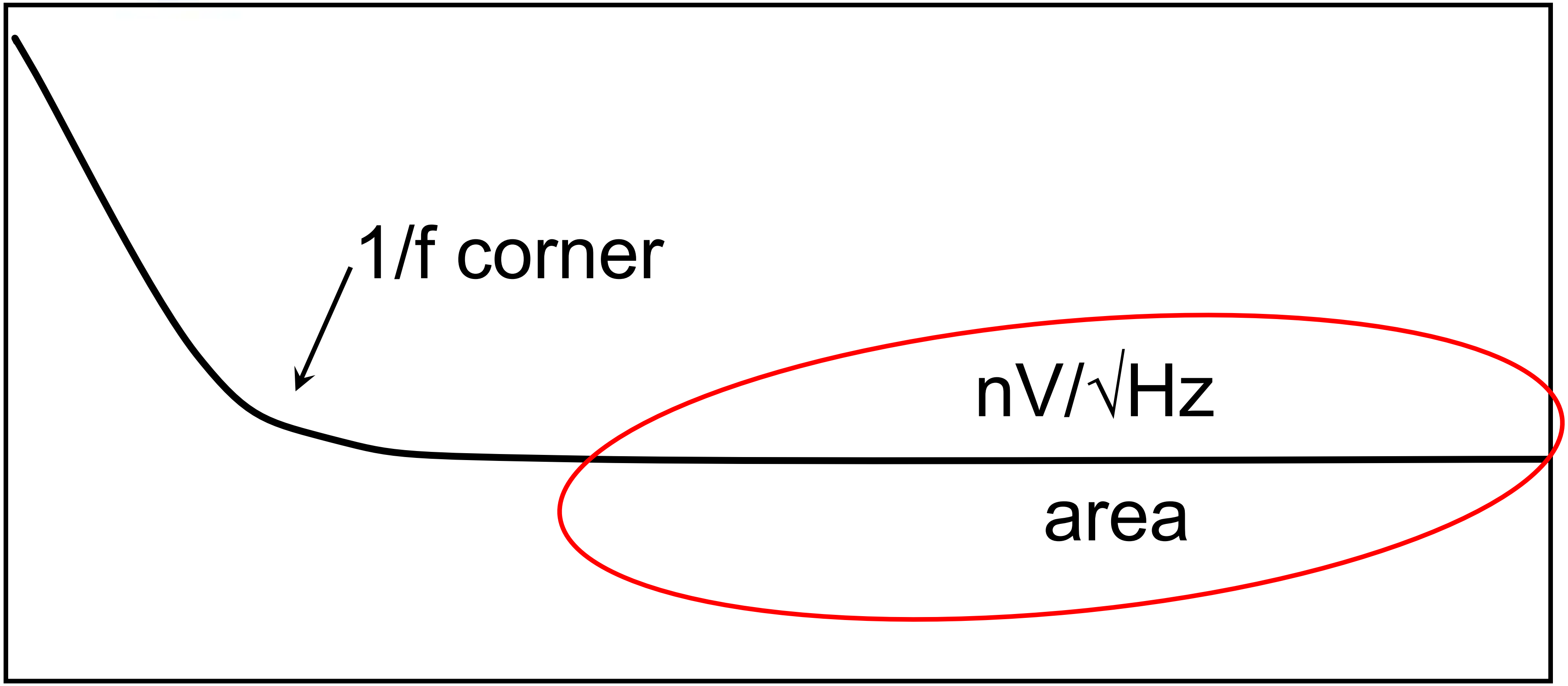


Freq Domain

Amplifier Input Noise

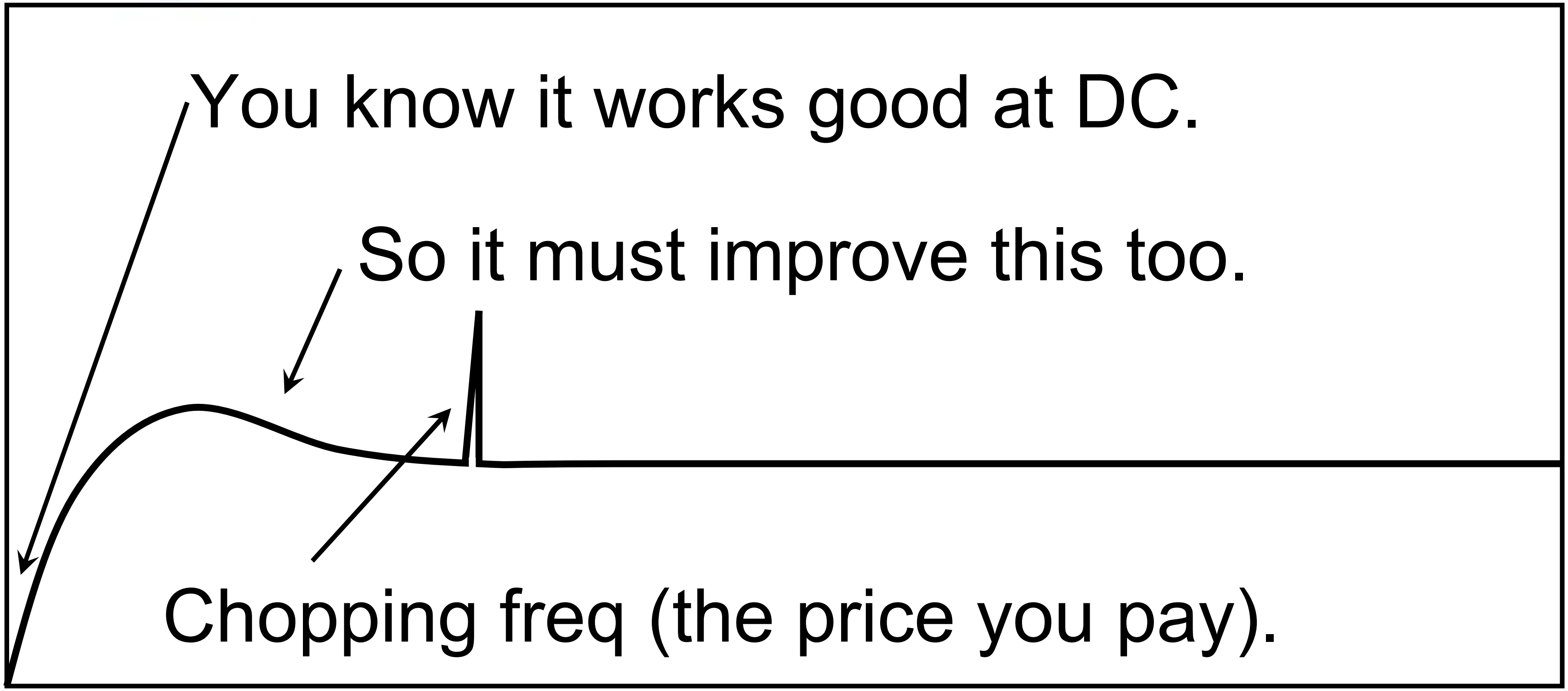


Amplifier Input Noise Plot



Freq Domain
(i.e.– a spectrum analyzer)

Chopper Amplifier Noise



Frequency Domain
(i.e.– a spectrum analyzer)

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How does it work? Simple:

How does it work? Simple:

$$v_m(t) = \frac{1}{2} v_i(t) + v_i(t) \sum_{n=1,3,5\cdots}^{\infty} \left(\frac{2}{n\pi}\right) \sin(n\omega_{ch} t)$$

$$v_d(t) = A v_i(t) \sum_{n=1,3,5\cdots}^{\infty} \left(\frac{2}{n\pi}\right) \sin(n\omega_{ch} t) \sum_{m=1,3,5\cdots}^{\infty} \left(\frac{2}{m\pi}\right) \sin(m\omega_{ch} t)$$

$$V_{o,rip} = V_{os} \frac{g_m}{2\pi f_{chop} C_m}$$

$$S(t) = 2 \sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi}{2}\right)}{\left(\frac{n\pi}{2}\right)} \cos(n\omega_c t)$$

$$v_m(t) = 2v(t) \sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi}{2}\right)}{\left(\frac{n\pi}{2}\right)} \cos(n\omega_c t)$$

$$v_d(t) = 4Av(t) \sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi}{2}\right)}{\left(\frac{n\pi}{2}\right)} \cos(n\omega_c t) \sum_{m=1}^{\infty} \frac{\sin\left(\frac{m\pi}{2}\right)}{\left(\frac{m\pi}{2}\right)} \cos(m\omega_c t)$$

$$m(t) = 2 \sum_{k=1}^{\infty} \frac{\sin\left(\frac{k\pi}{2}\right)}{\left(\frac{k\pi}{2}\right)} \cos(2\pi f_{chop} k t)$$

$$V_d(t) = 4AV_{in}(t) \sum_{k=1}^{\infty} \frac{\sin\left(\frac{k\pi}{2}\right)}{\left(\frac{k\pi}{2}\right)} \cos\left(2\pi f_{chop} k t\right) \sum_{l=1}^{\infty} \frac{\sin\left(\frac{l\pi}{2}\right)}{\left(\frac{l\pi}{2}\right)} \cos(2\pi f_{chop} l t)$$

$$S_{CS}(f) = \sum_{k=-\infty}^{\infty} \left|M_{2k+1}\right|^2 S_N\left(f - \frac{2k+1}{T}\right) = \left(\frac{2}{\pi}\right)^2 \sum_{k=-\infty}^{\infty} \frac{1}{(2k+1)^2} S_N\left(f - \frac{2k+1}{T}\right)$$

$$S_{CS-white}(f) = S_{CS-white}(f=0) = S_0 \left[1 - \frac{\tanh\left(\frac{\pi}{2} f_c T\right)}{\frac{\pi}{2} f_c T}\right]$$

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How to reduce offset

- **Tweak and adjust the input stage**
- **Tweak and adjust later stages**
- **Tweak and adjust the output (yuk)**

Or :

- **Measure it and “servo” it out.**
- **Use AC amplification.**

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Chopper benefits:

- Reduces the offset from part to part.
- Reduces the offset over time
- Reduces the offset over temperature.
- Reduces offset over common mode voltage.

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Chopper architectures

- Auto-nulling (auto-zero)
- Synchronous switching (True chopper)
- Single vs. compound

The Quandary:

- **How to measure the offset of an amplifier in order to “servo” it out when whatever you measure it with will also have a unique (and different) offset?**

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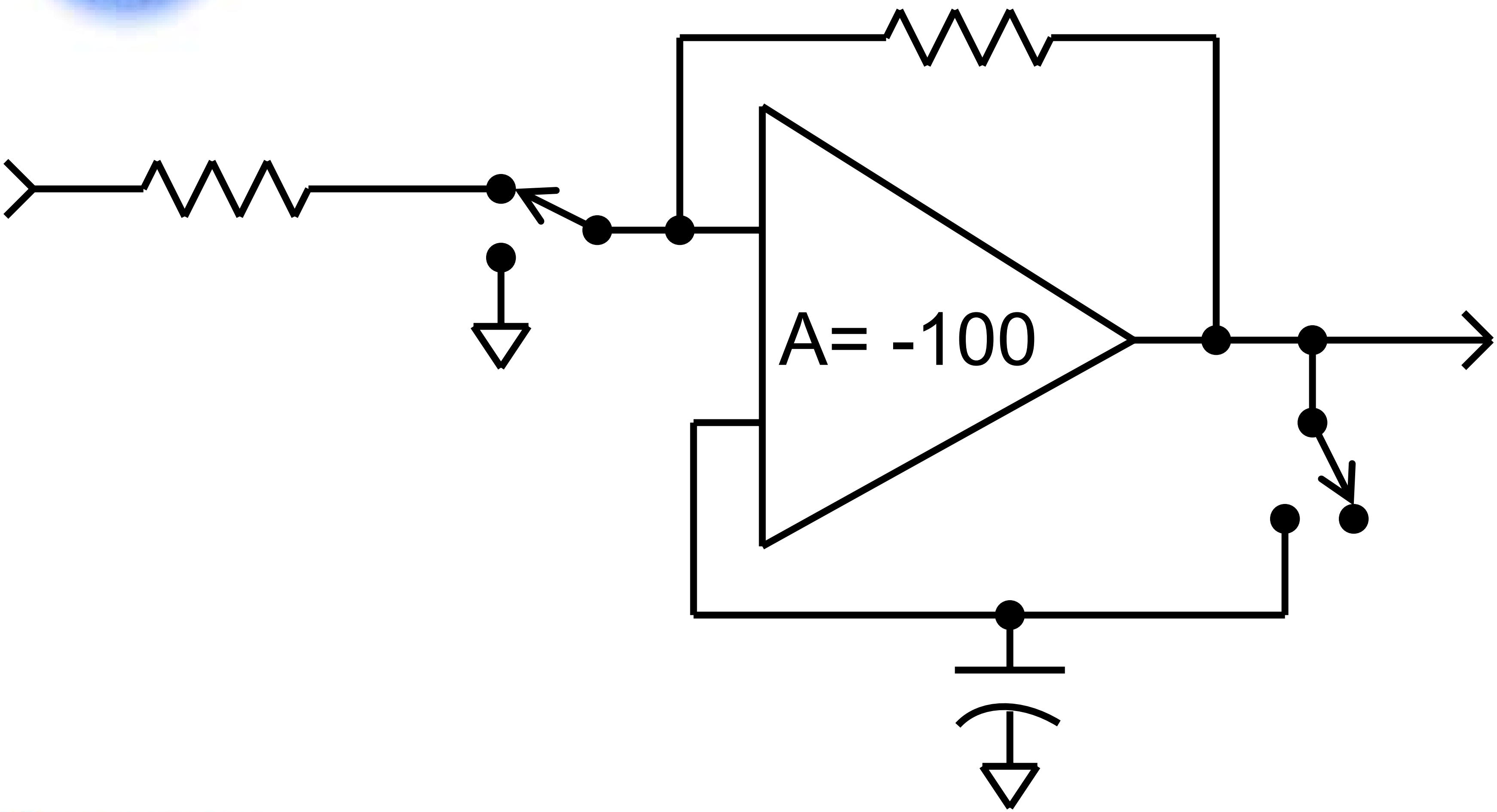
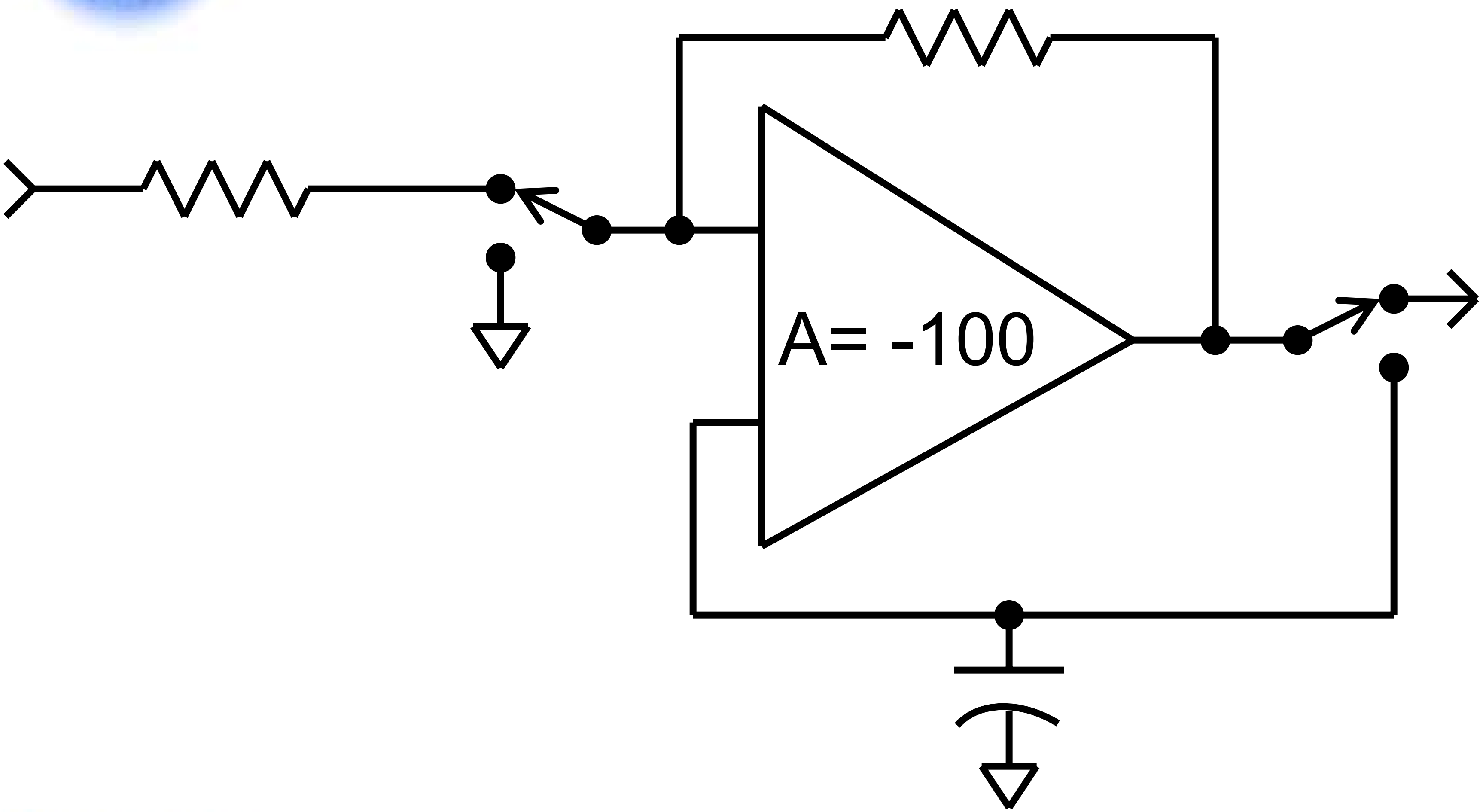
Auto Nulling amp



Auto Nulling amp (mo' betta)



Auto Nulling Defined

- **A Nulling (or auto zero) amp works as an amp for a little while, then corrects its offset voltage, then it goes back to working as an amplifier again.**
  How often? 100 Hz – 1000 kHz is commonly seen.

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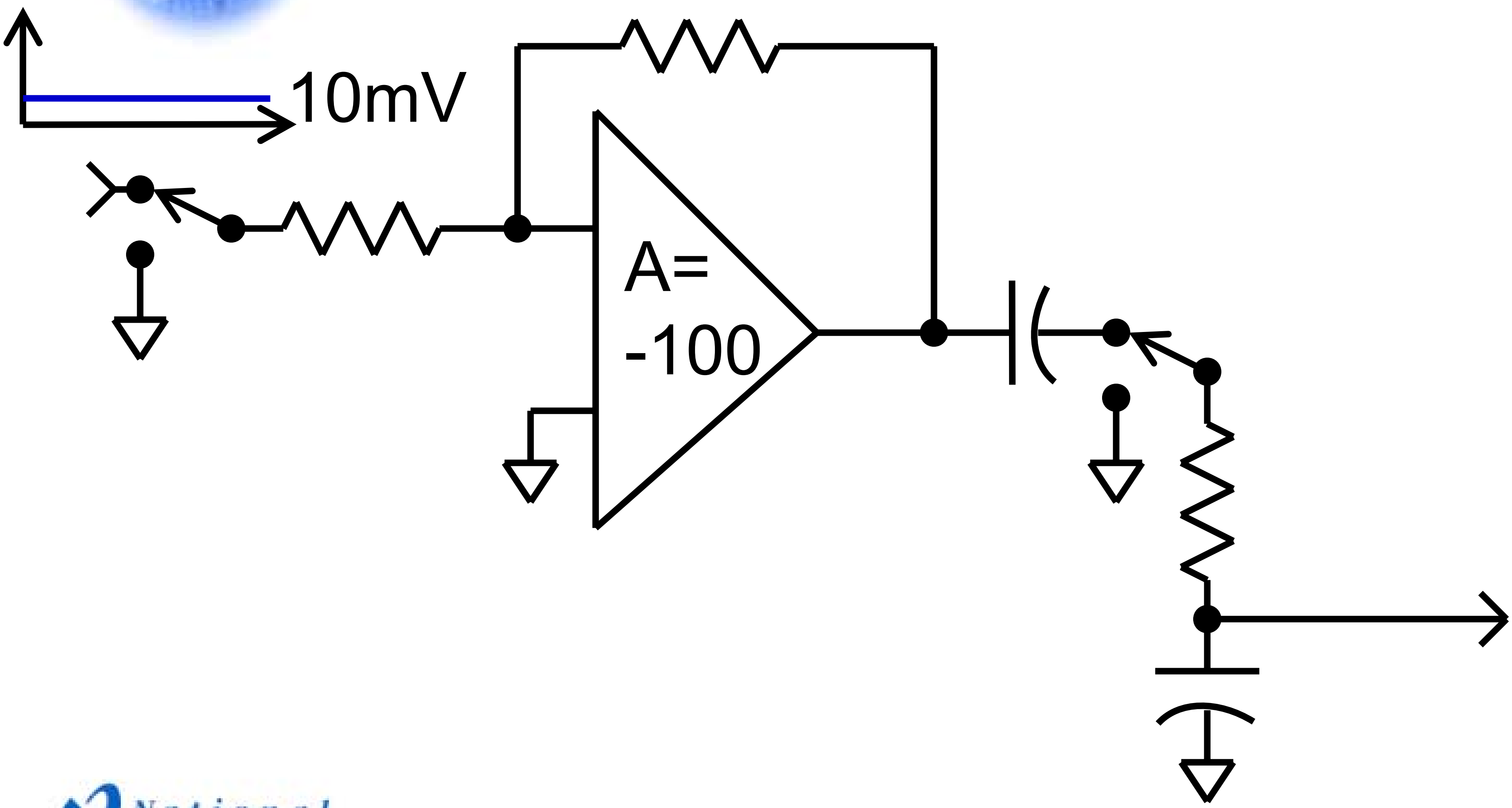
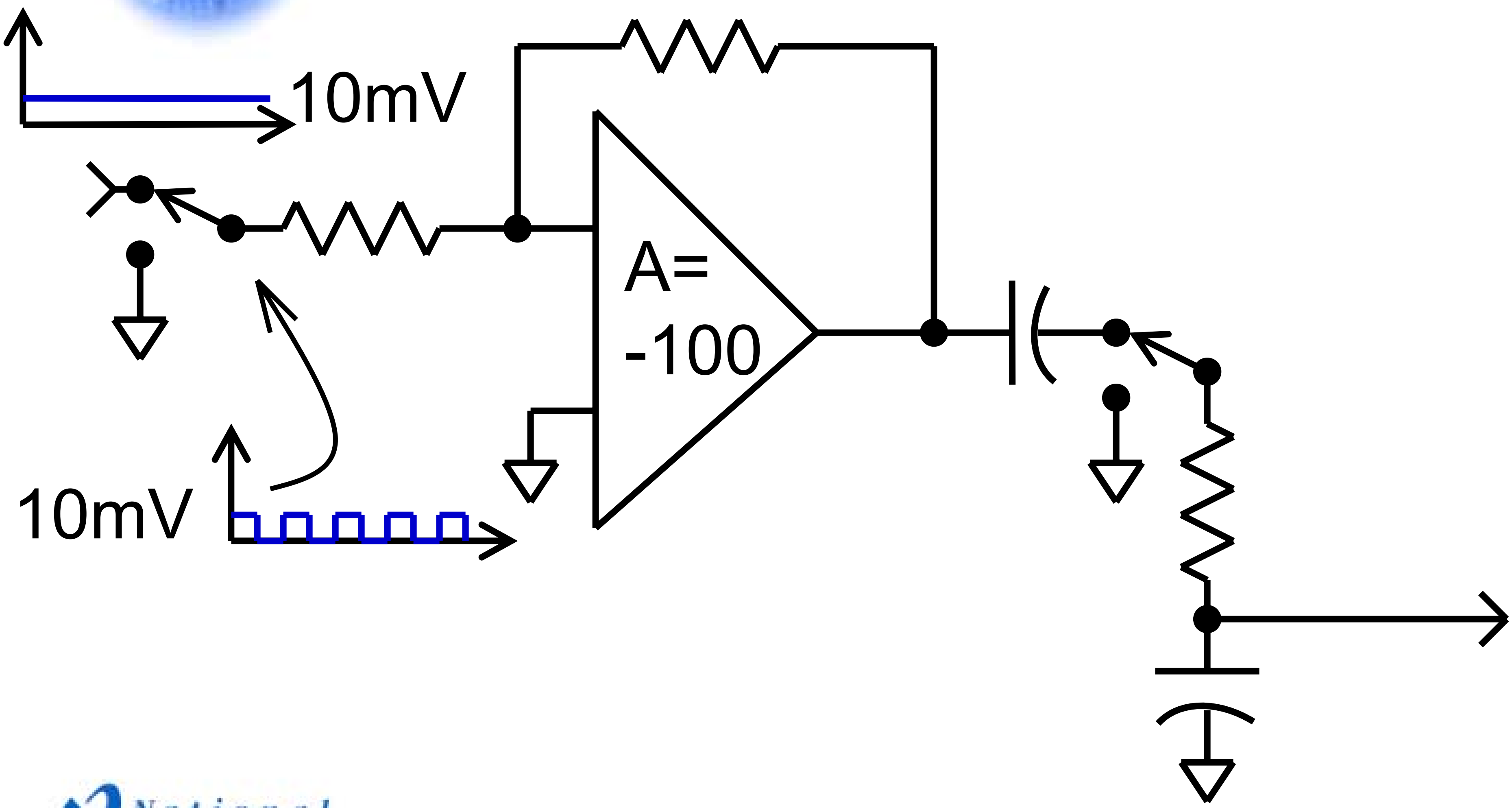
Simple Chopper amp



Simple Chopper amp



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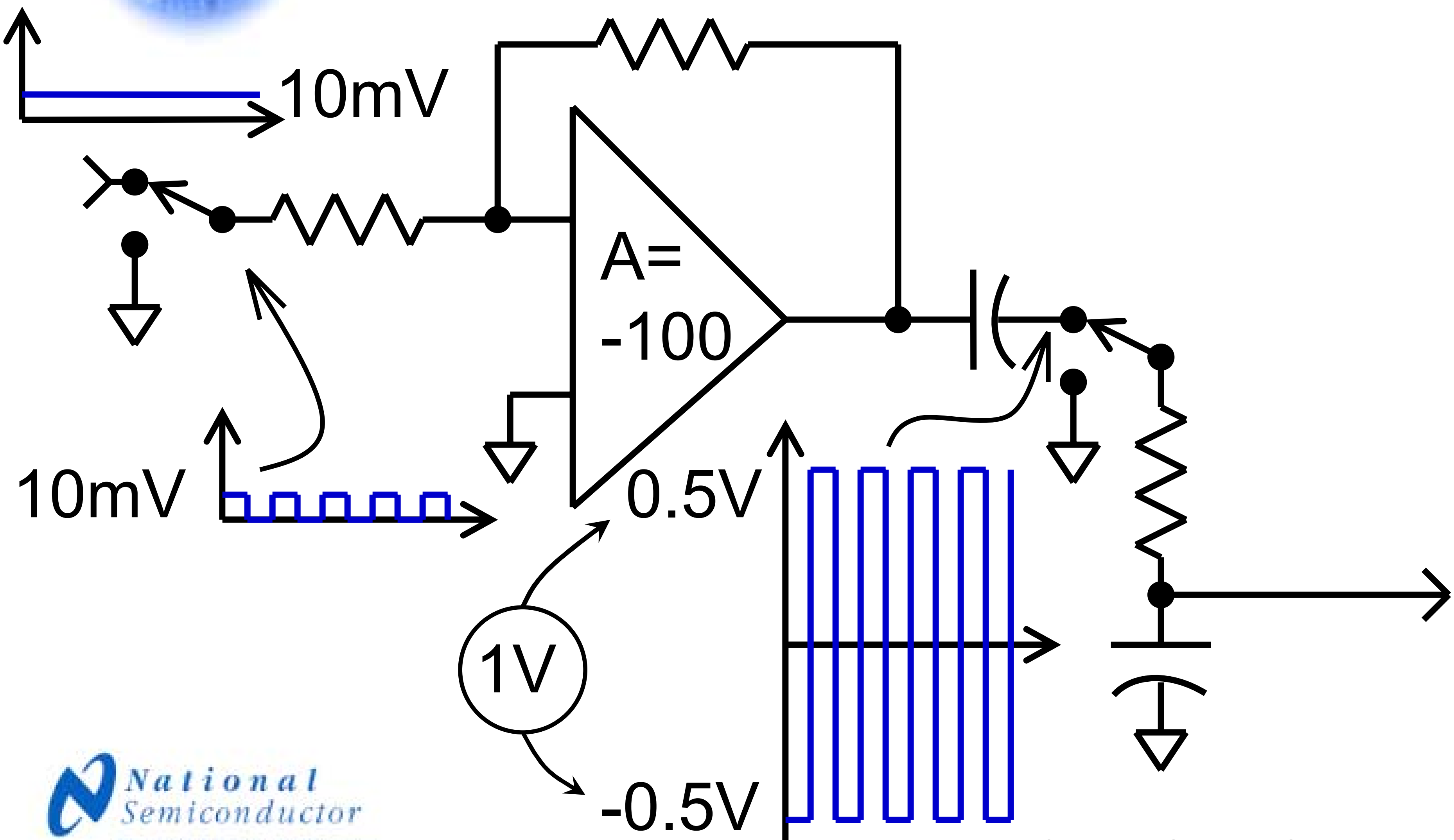
Simple Chopper amp



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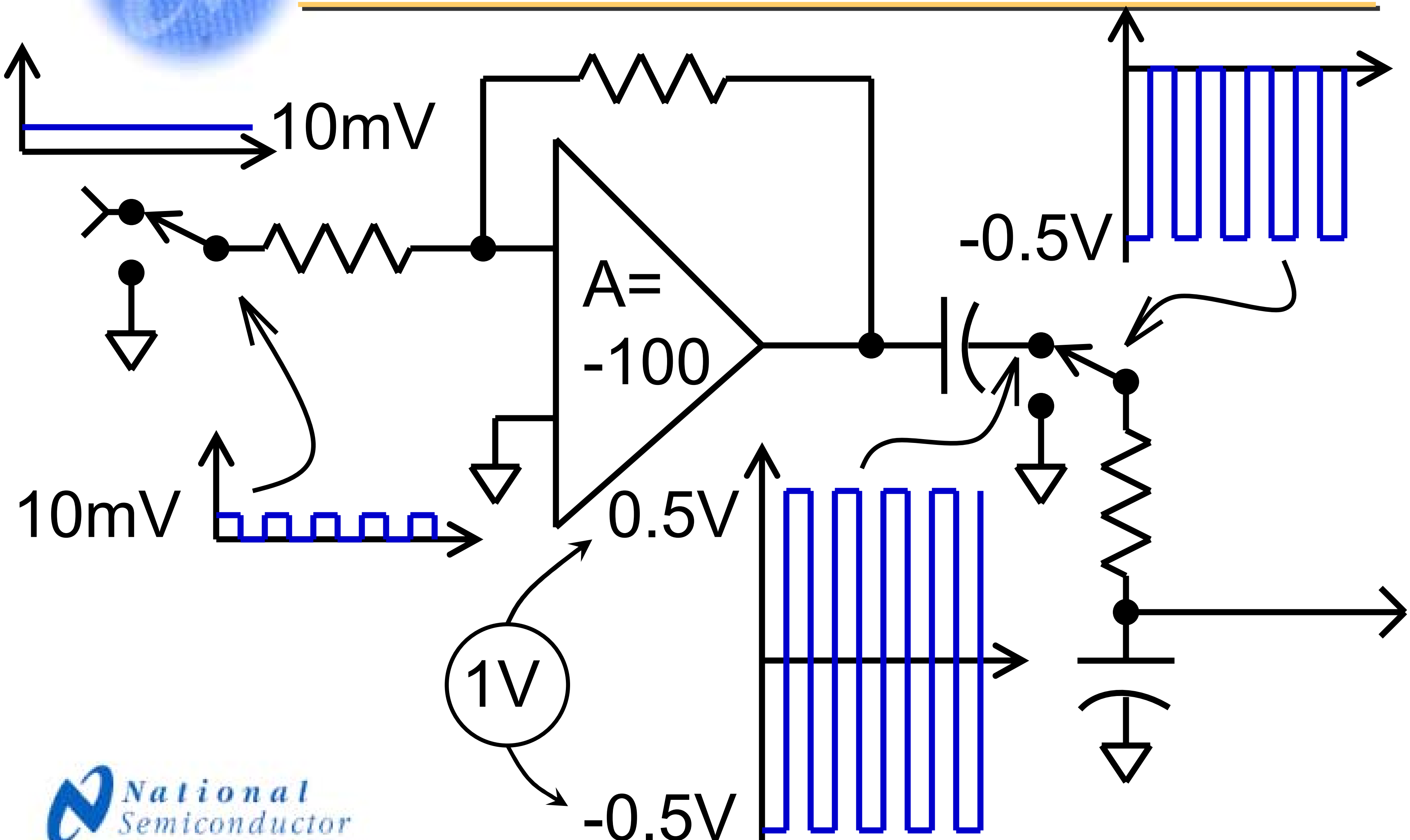
Simple Chopper amp



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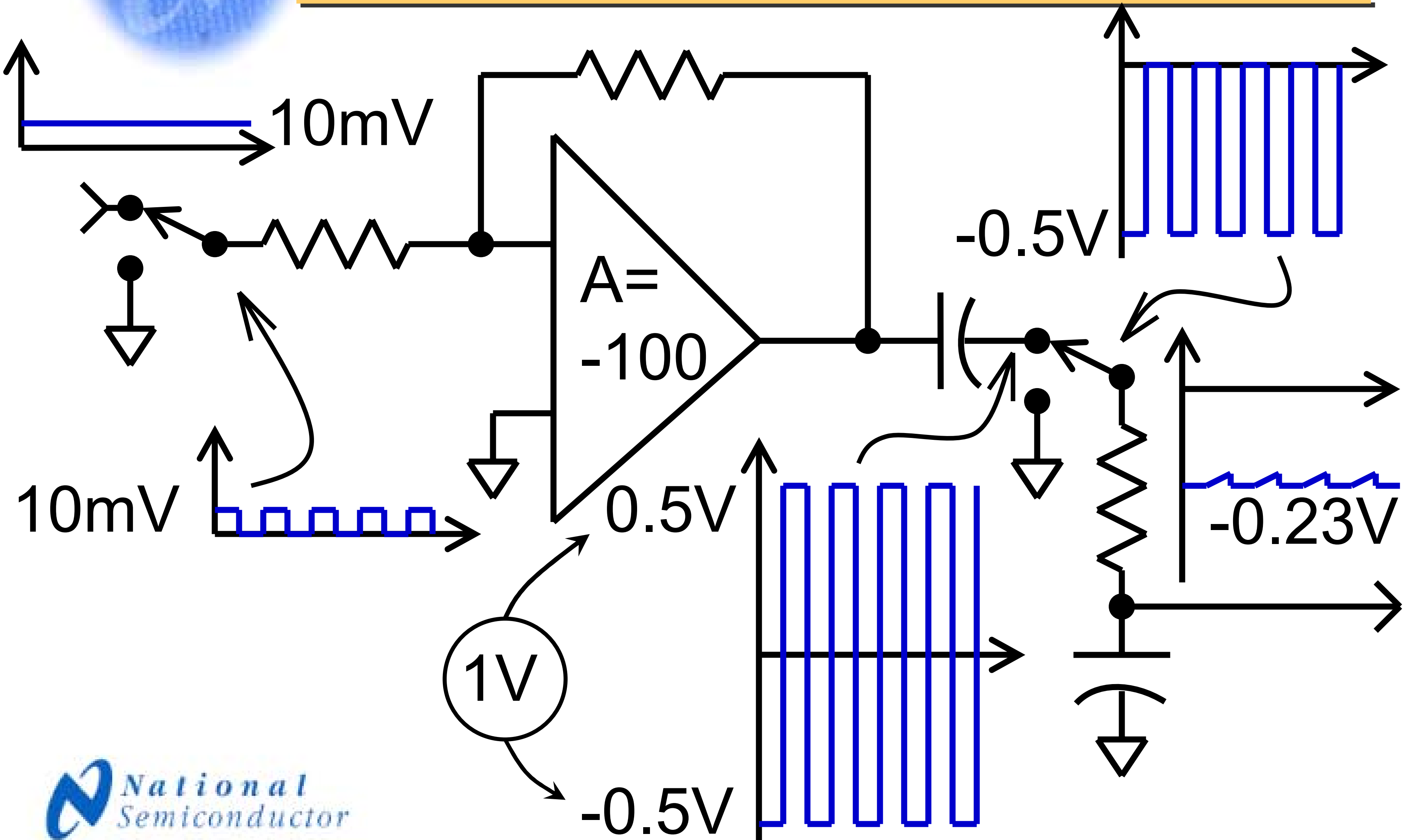
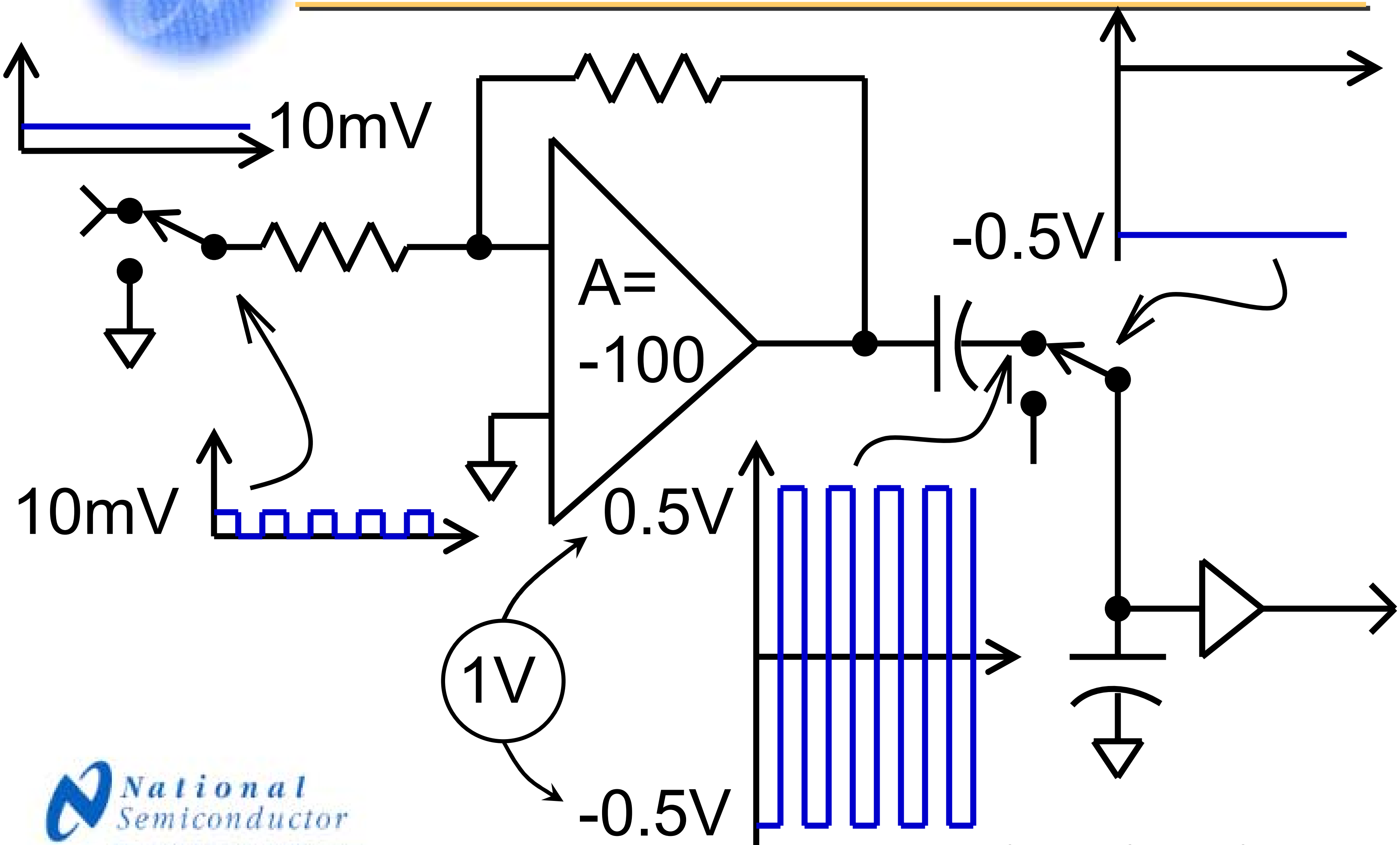
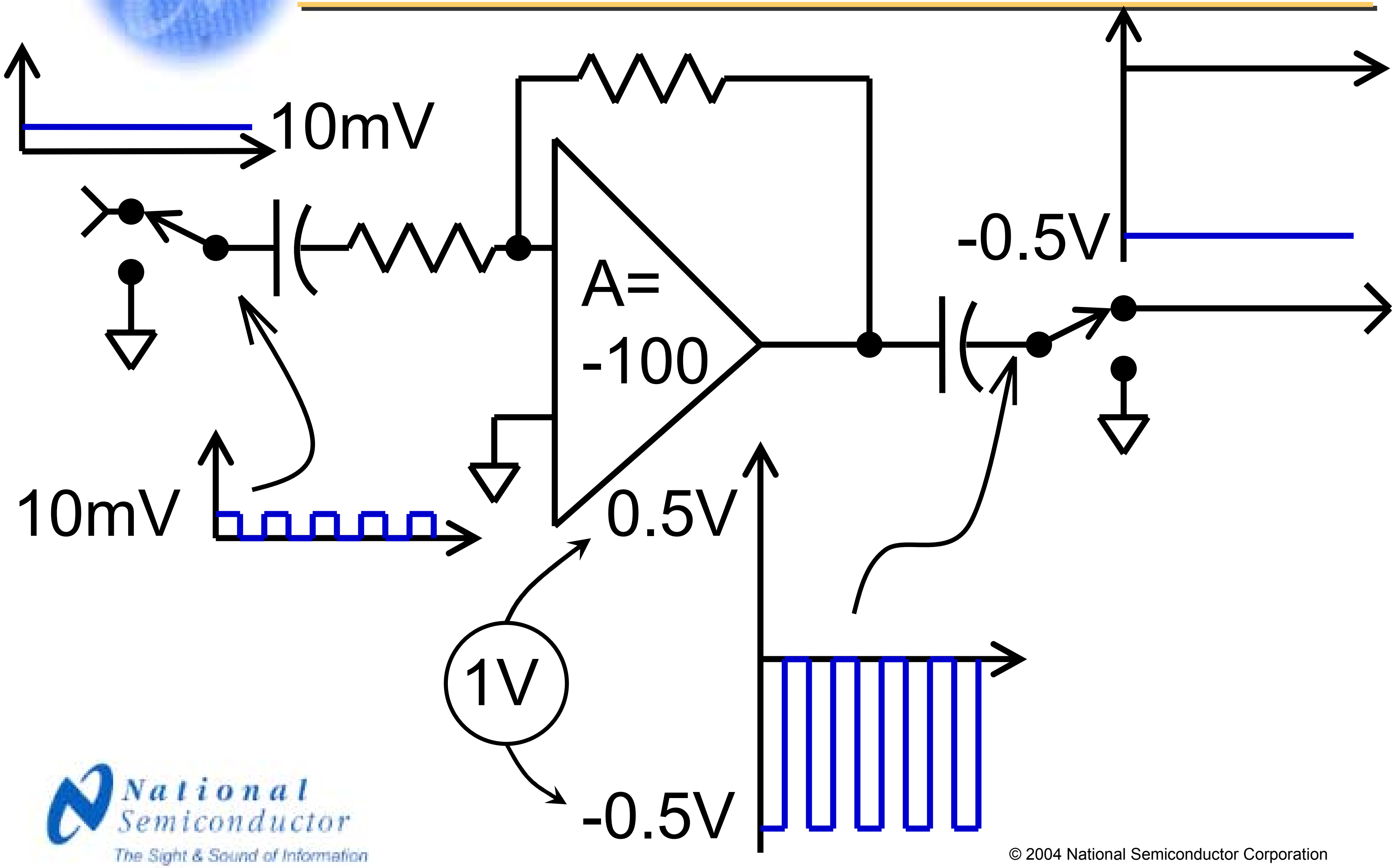
Simple Chopper amp



Simple Chopper amp (mo' betta)



"Classic" Chopper amp



Chopping Defined

- A Chopper (or commutating) amp modulates the input to create an AC signal that can be amplified with and AC amp, then it demodulates the AC back to DC. How often? 100 Hz – 25,000 KHz is commonly seen.

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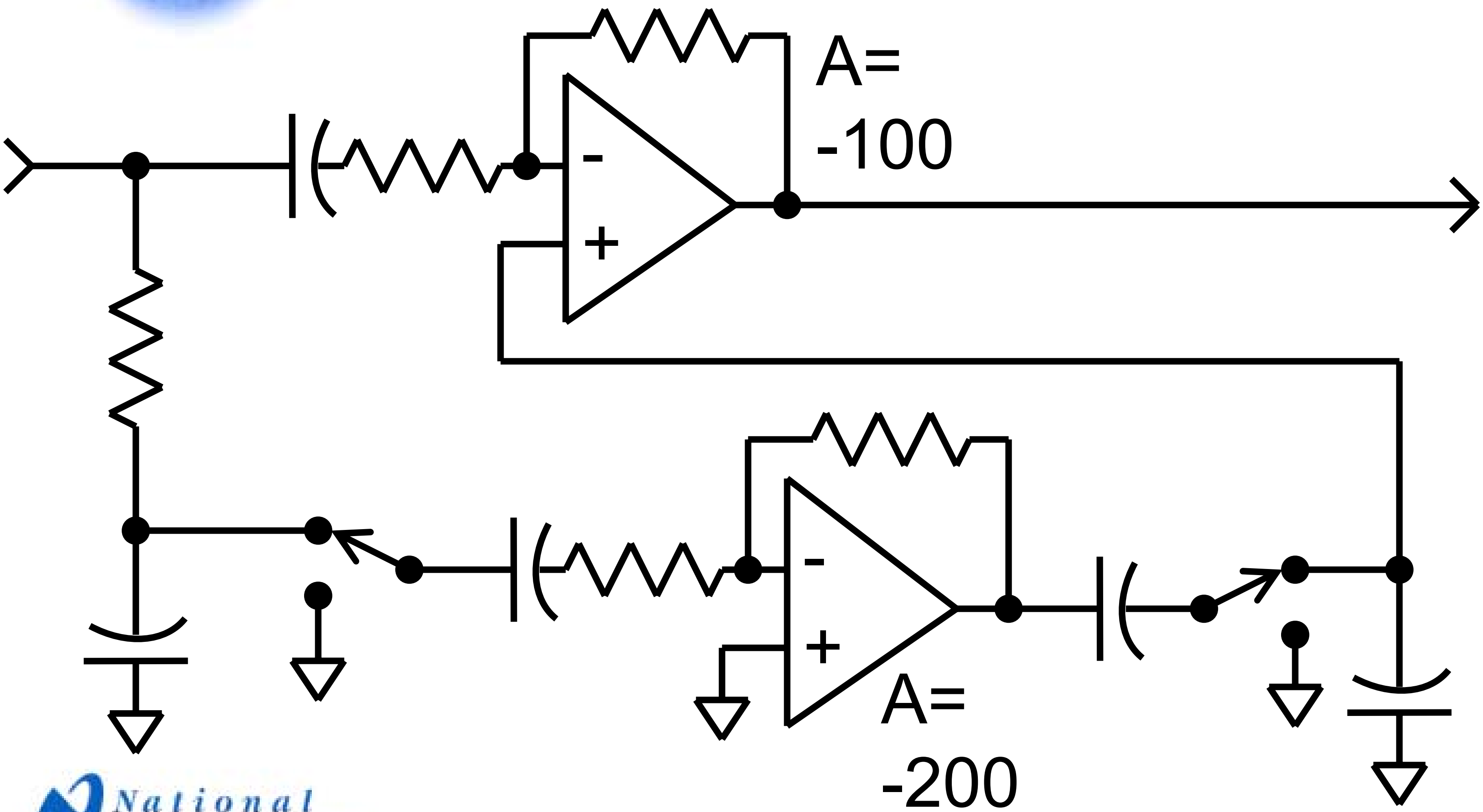
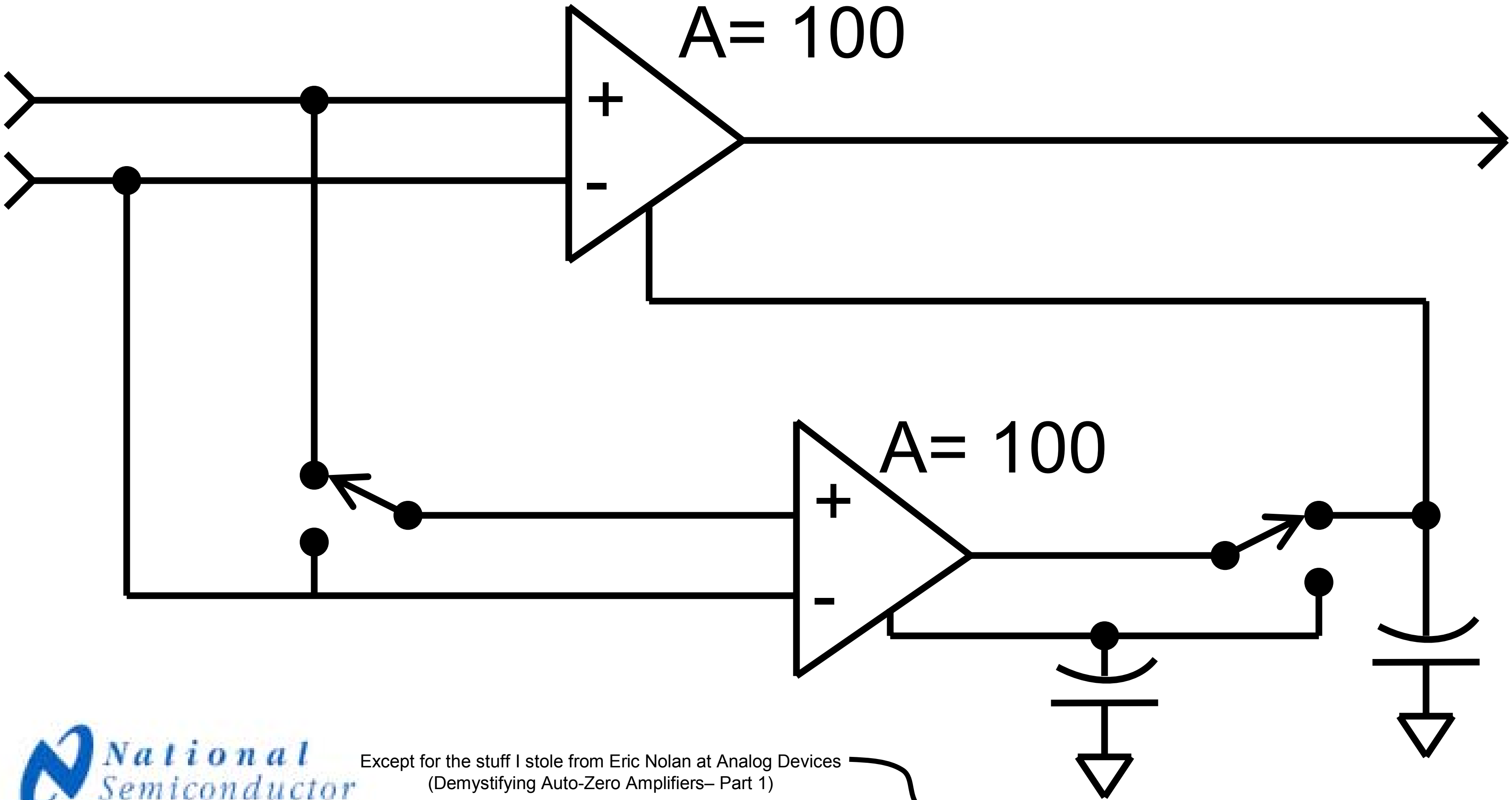
Compound Amp (Bias adjust)

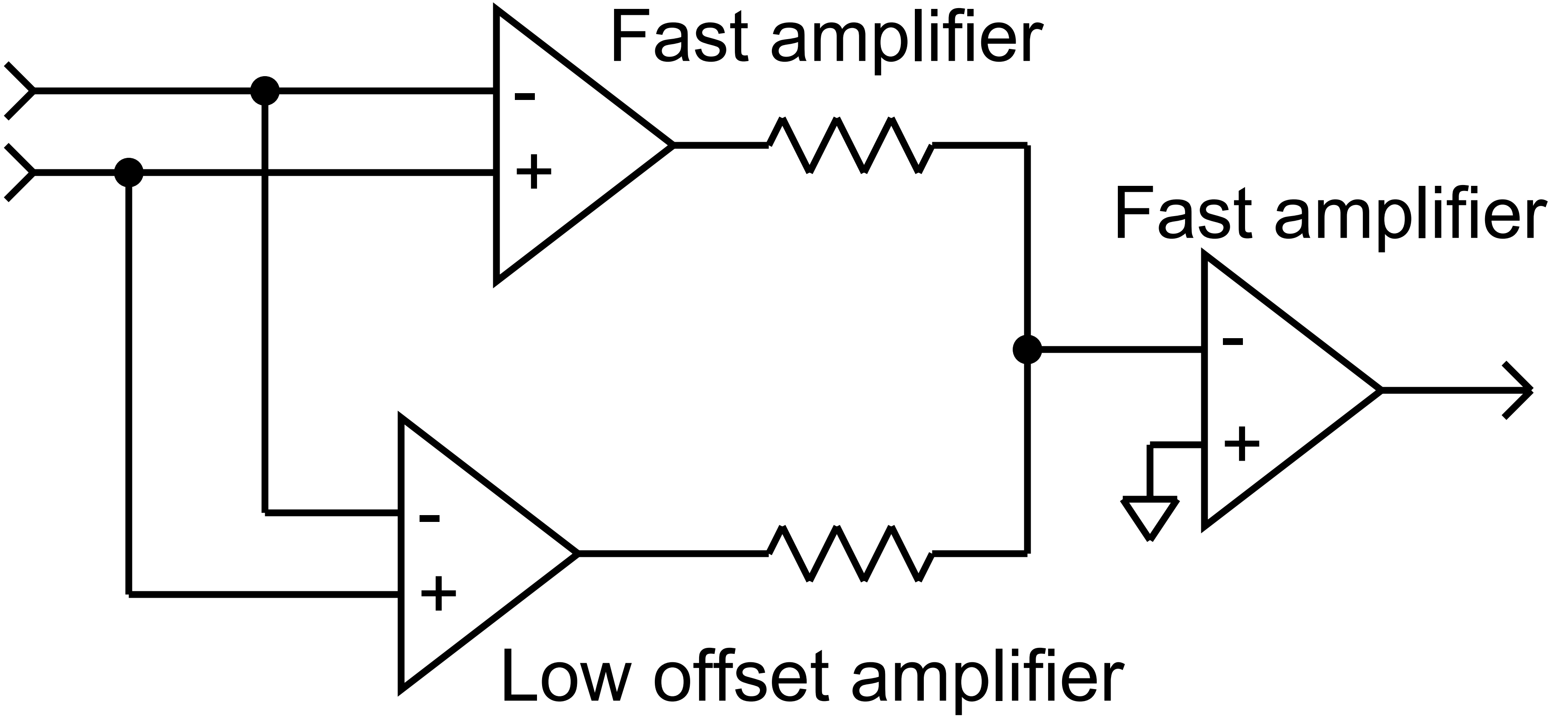


Compound Amp (Offset servo)



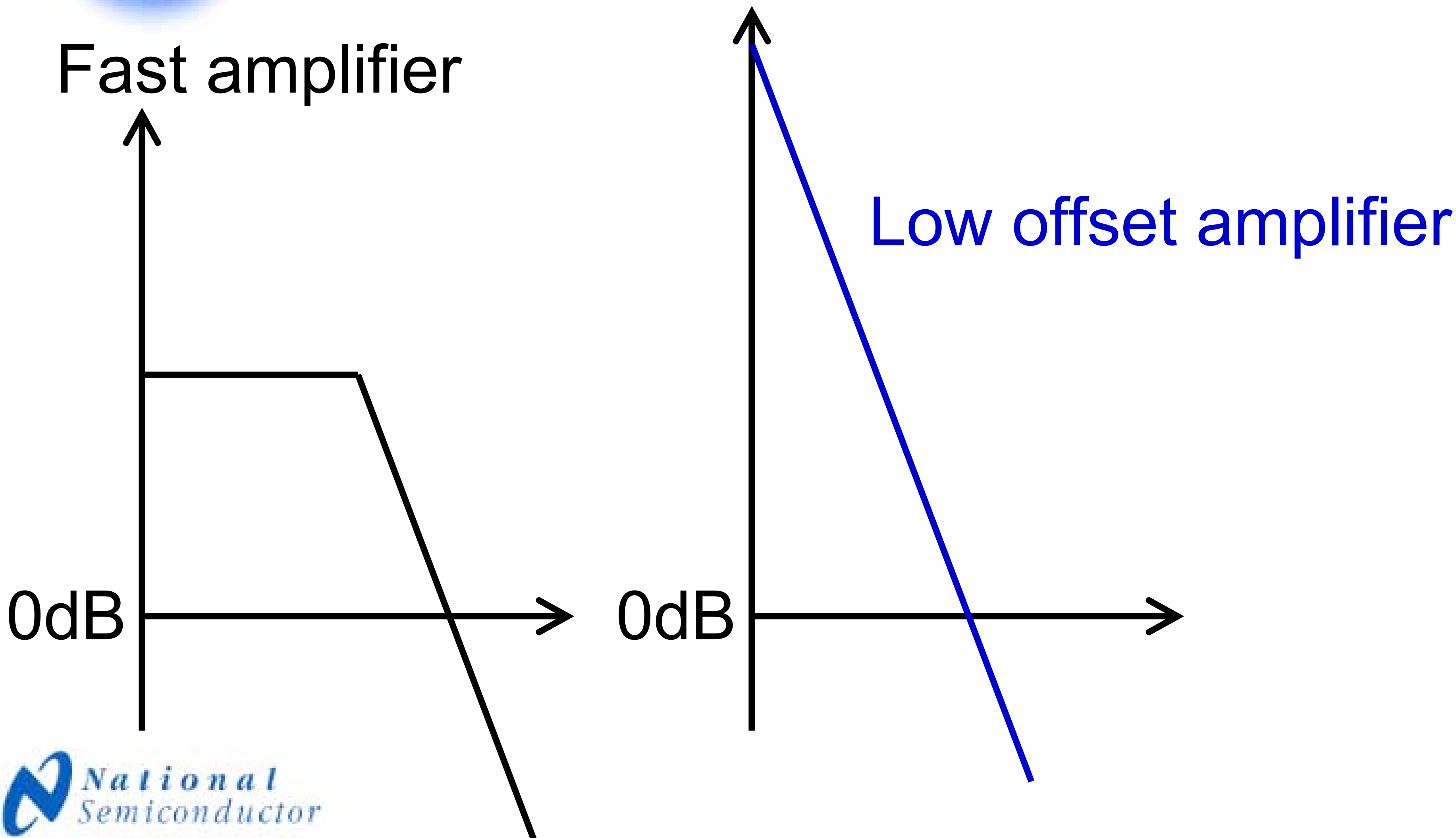
Except for the stuff I stole from Eric Nolan at Analog Devices
(Demystifying Auto-Zero Amplifiers– Part 1)

Compound Amp (Dual input)

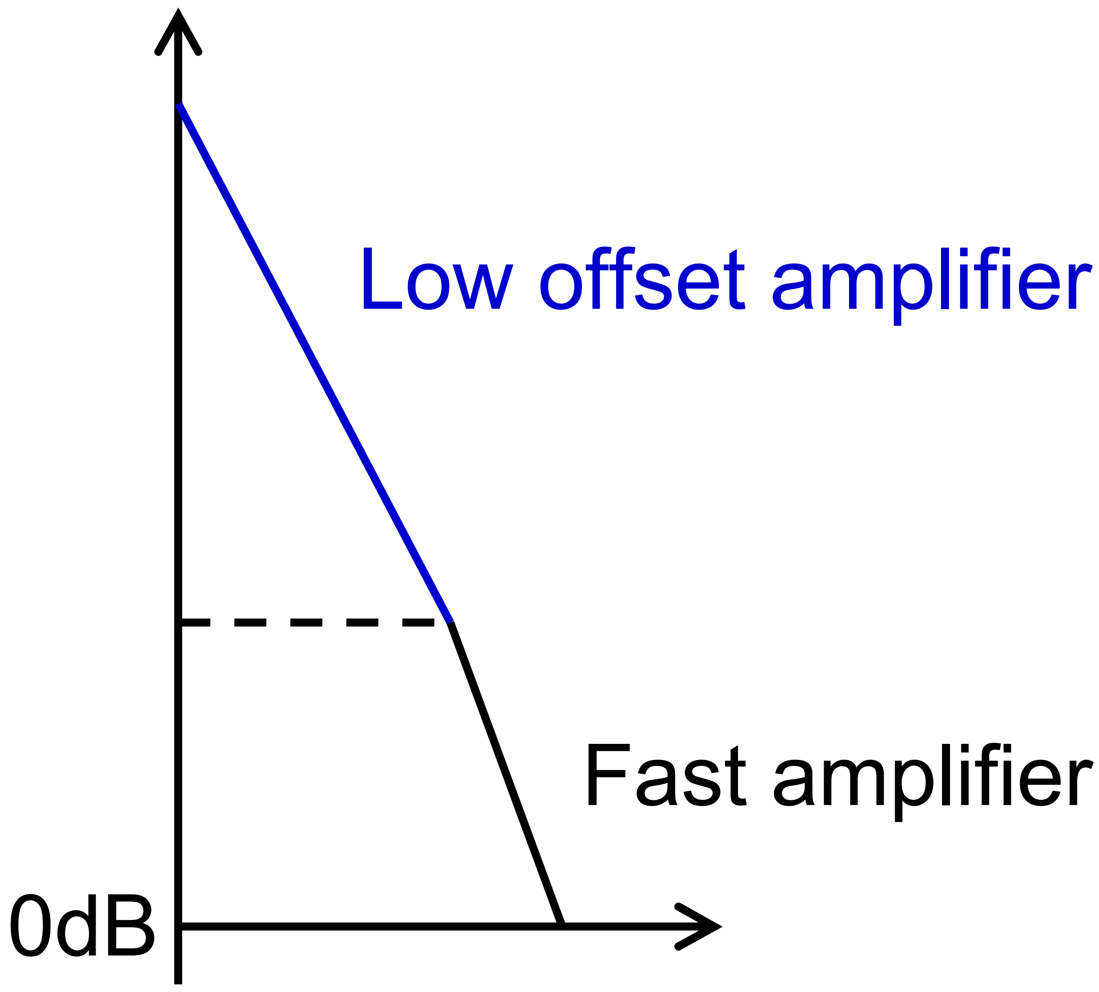


Compound Amp (Response)

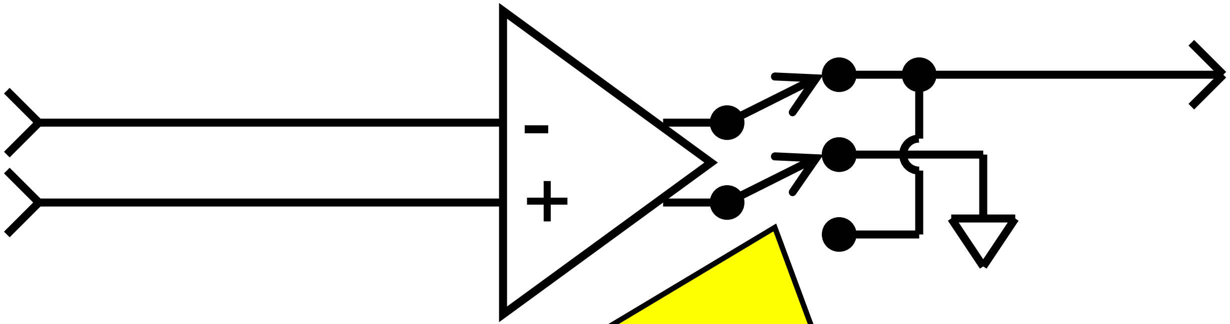
Fast amplifier



Compound Amp (Response)

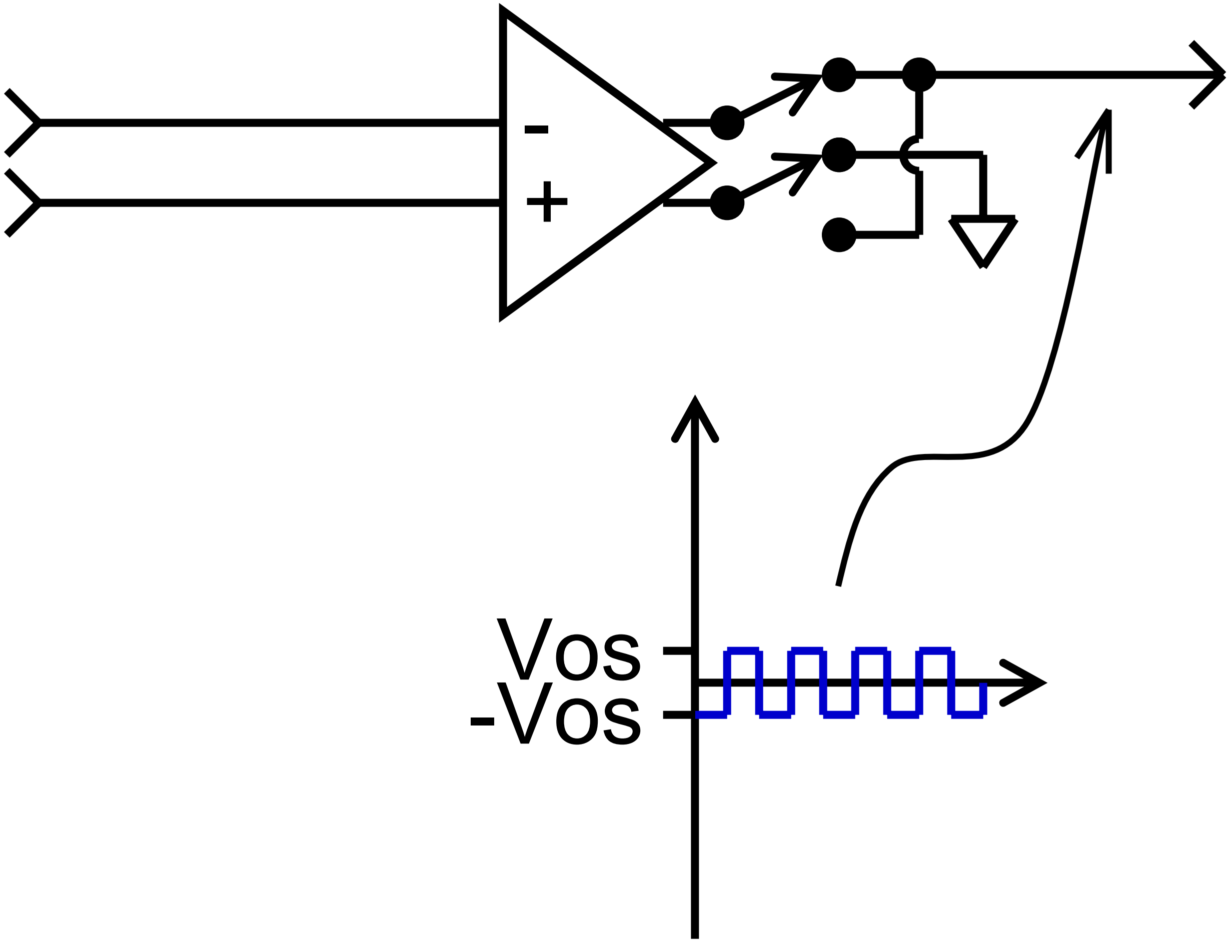


Synchronous Demodulation

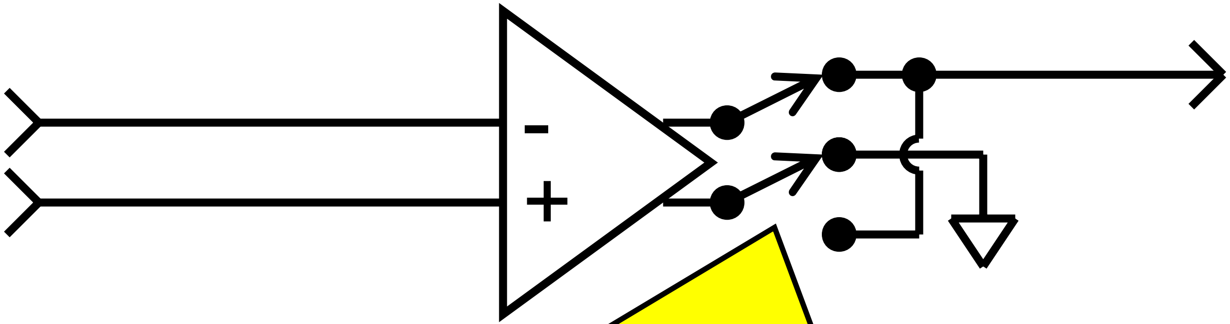


This pair of switches reverses the offset voltage of this amplifier. Offset becomes a square wave centered around zero (for a shorted input).

Synchronous Demodulation

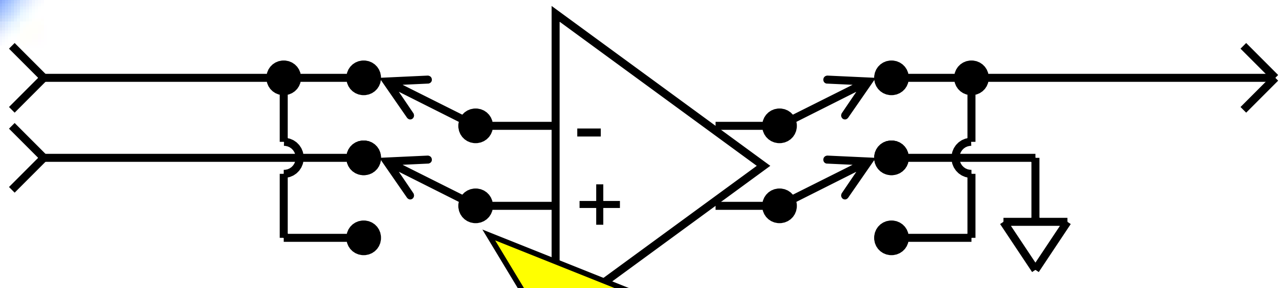


Synchronous Demodulation



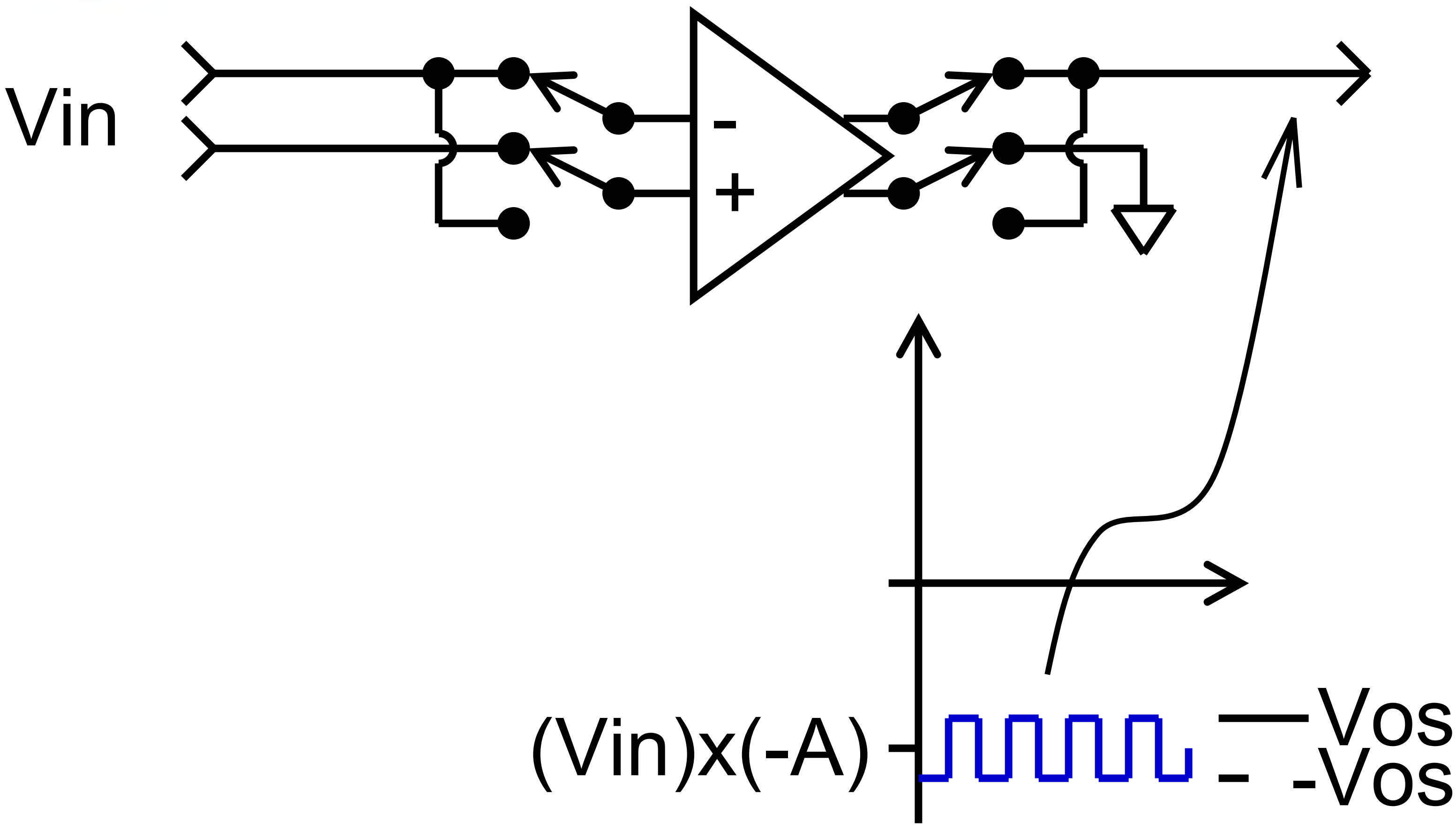
Note that any signal at the main amplifier input would also get filtered out.

Synchronous Demodulation

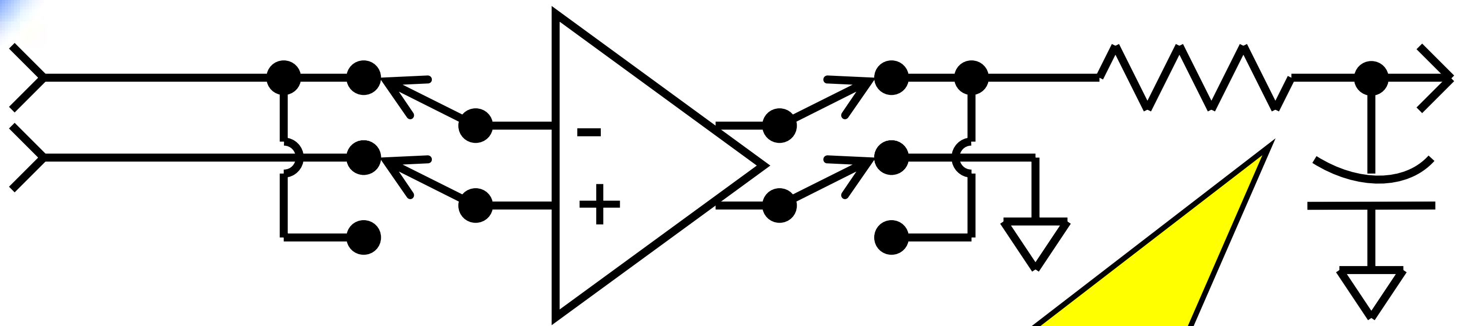


So add these switches to reverse the input polarity synchronously with the output switches.

Synchronous Demodulation

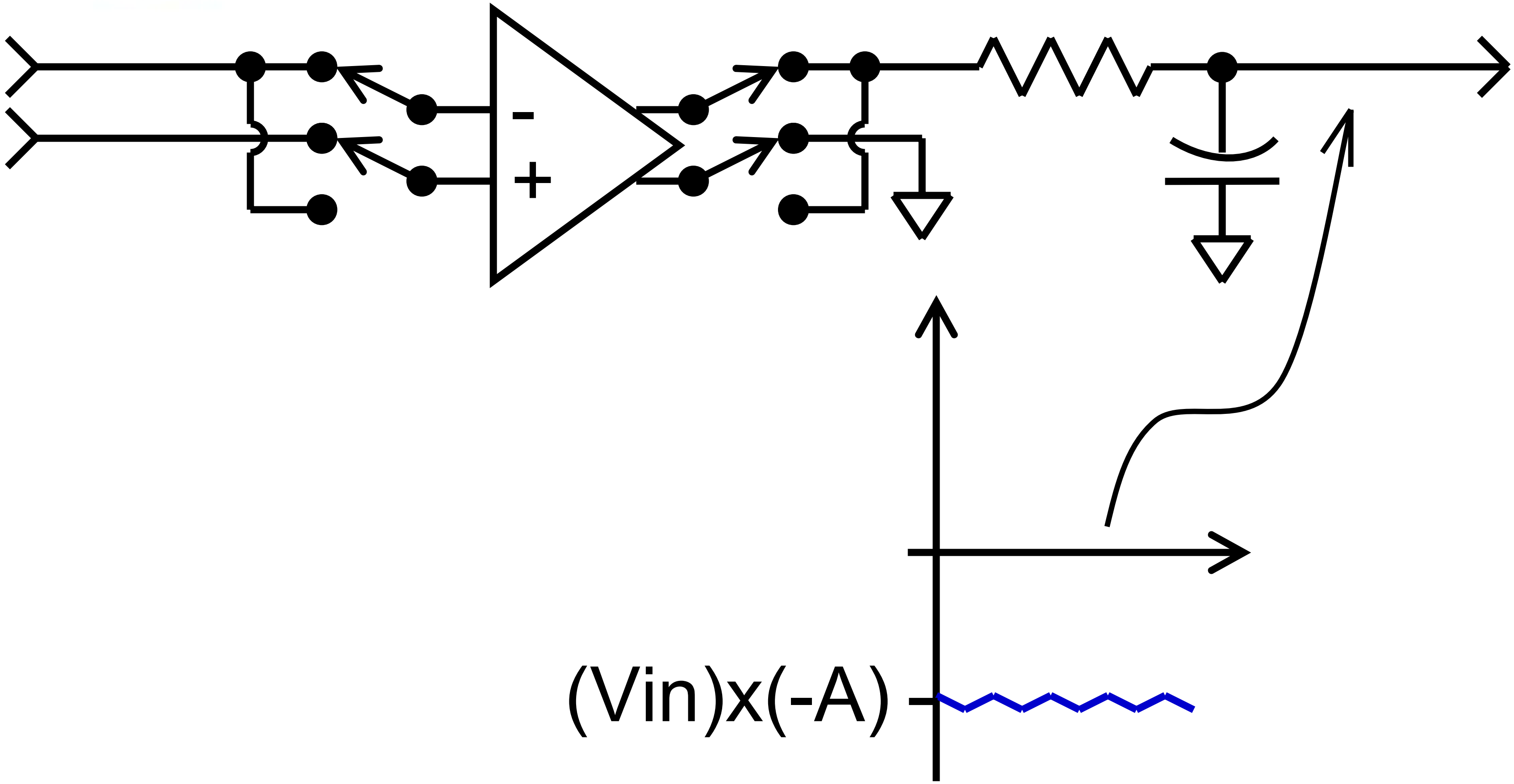


Synchronous Demodulation

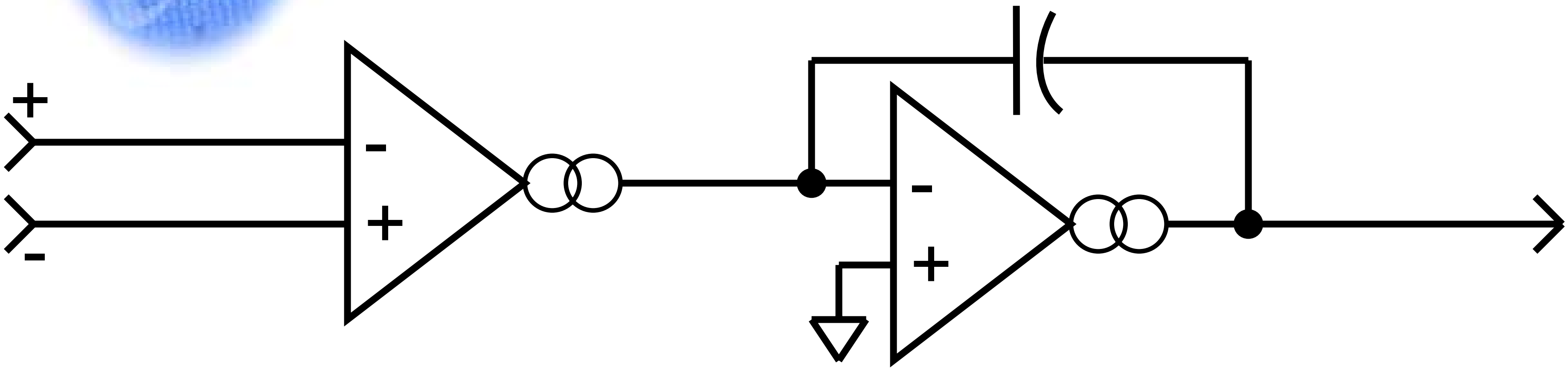


To remove the AC offset add a Low-Pass Filter

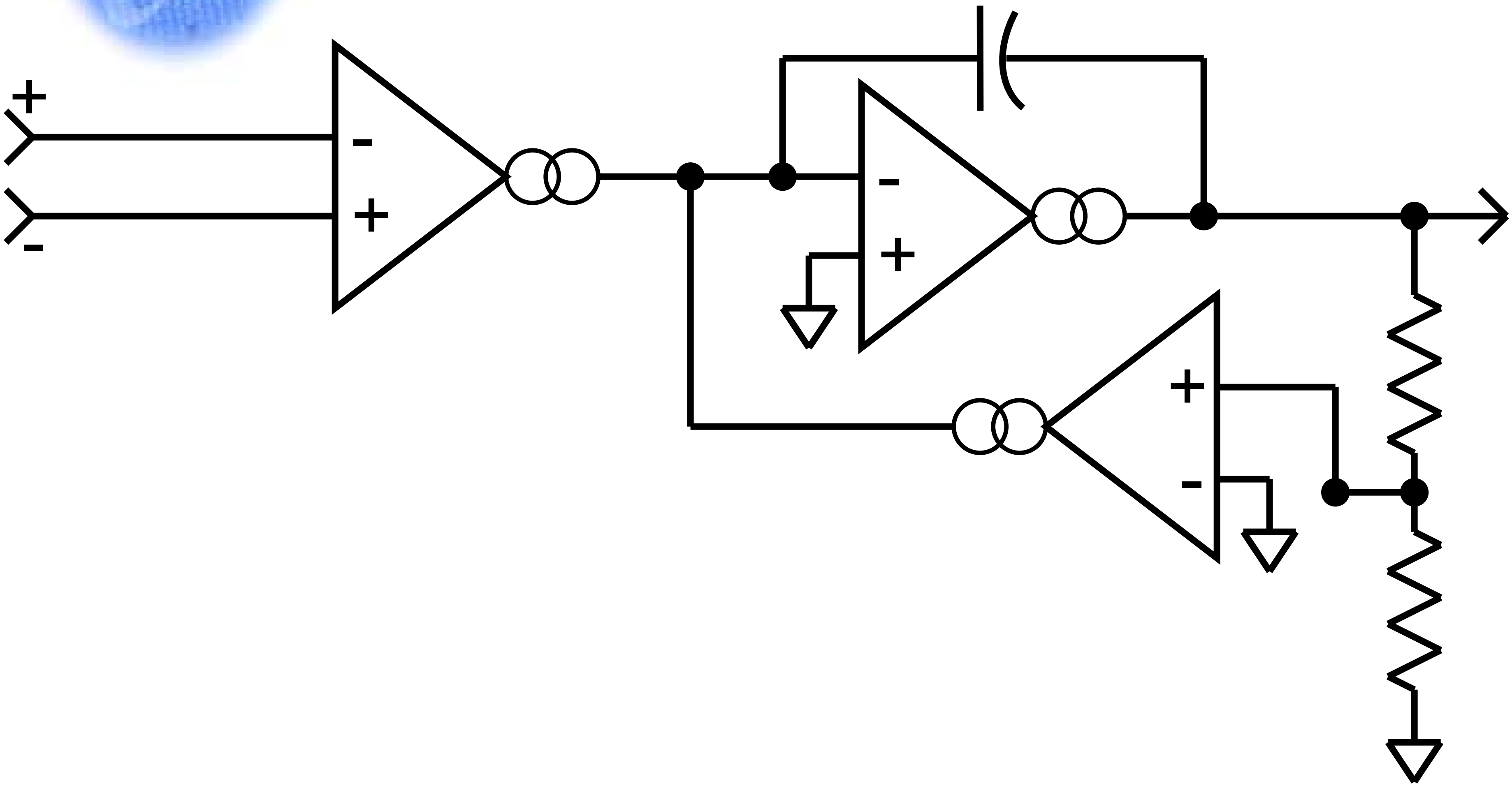
Synchronous Demodulation



Compound Amp (Fast section)



Compound Amp (Kill DC gain)



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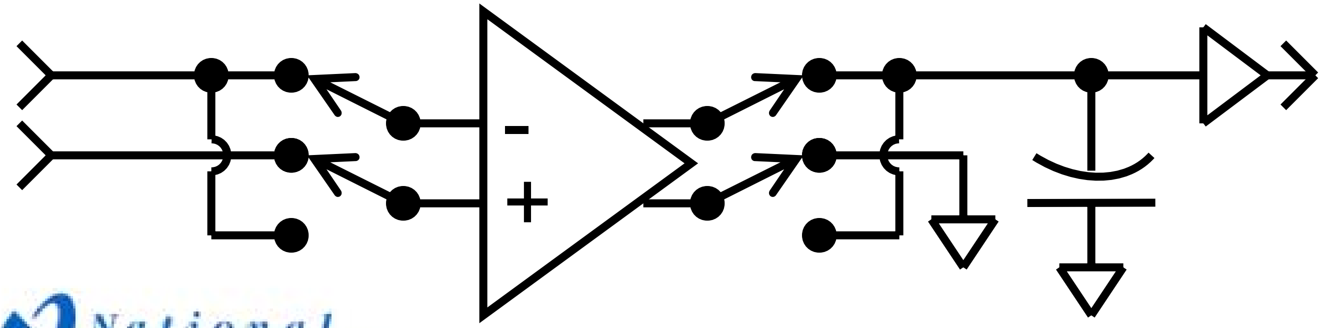
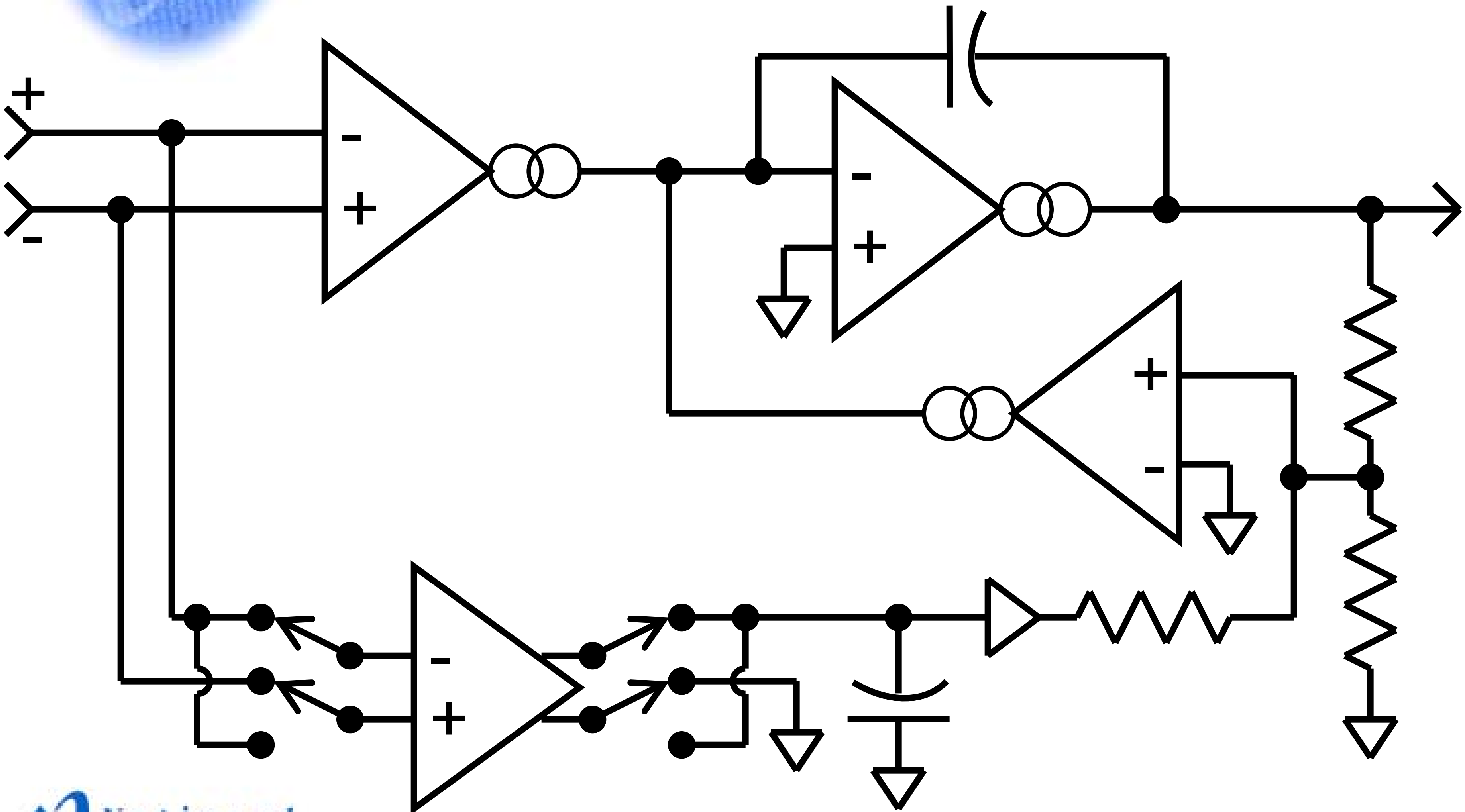
Compound Amp (DC path)

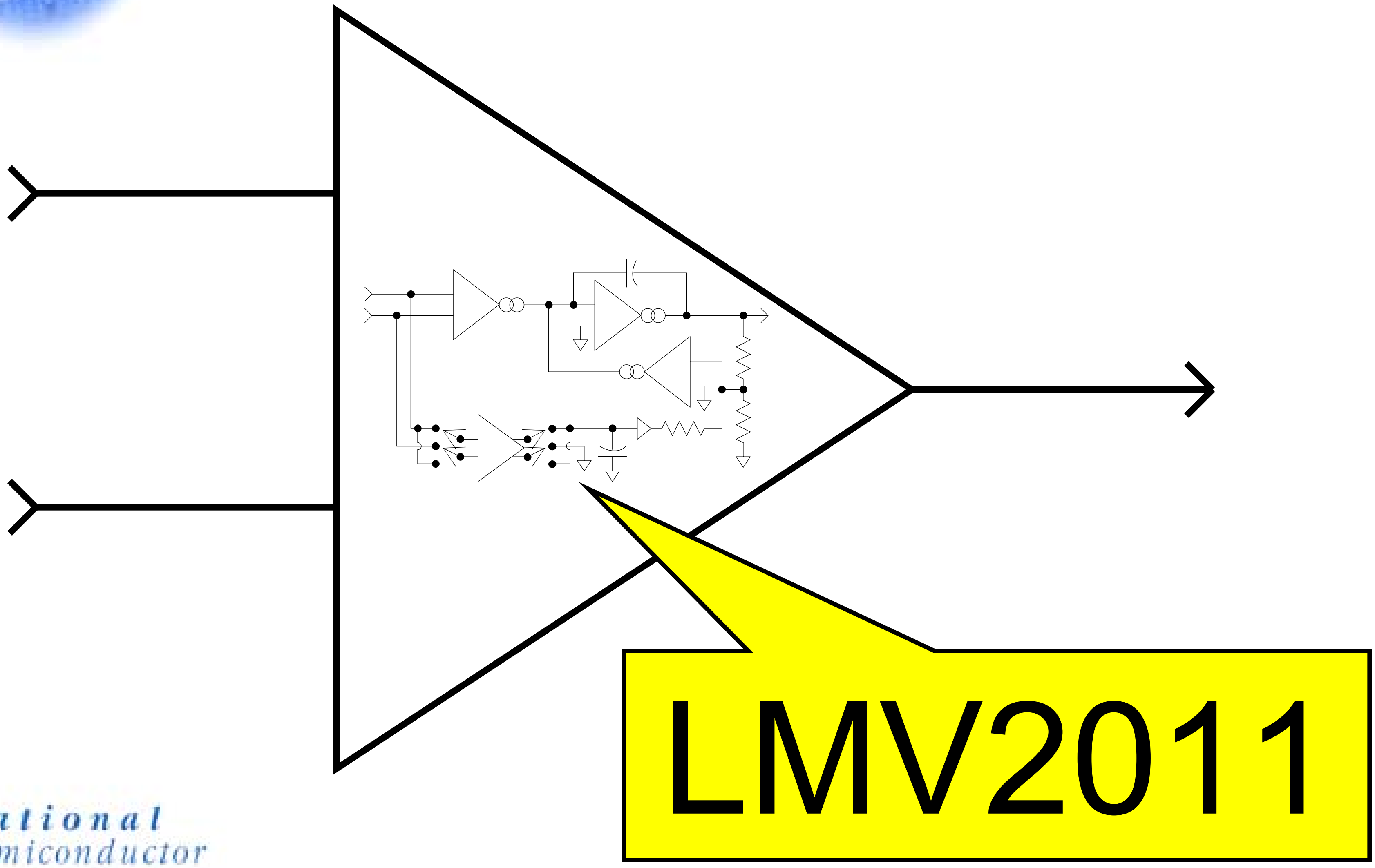


Compound Amp (Complete)



Except for the stuff I stole from Martin Giles
(Precision Op Amps)

Compound Amp (Buy one!)



How low is the offset?

• LMV2011	~ 0.8 microvolts
• AD8551	~ 1 microvolts
• TLC2652AI	~ 0.5 microvolts
• OPA735	~ 1 microvolt
• LTC2050	~ +/- 0.5 microvolts
• MAX4238	~ 0.1 microvolts

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What runs the switches?

- **A fixed clock**
- **A variable clock**
- **A spread-spectrum clock**

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What is the frequency?

- 25 kHz for the LMV2011
- 20 kHz for the MAX4238
- 7.5 kHz for the LTC2050
- 18 kHz for the OPA734
- 4 kHz for the AD8551

Disadvantages

- **Clock noise.**
- **Slow Speed.**
- **Cost (until we started making them).**
- **Variable Input AC impedance.**

Thank You!

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