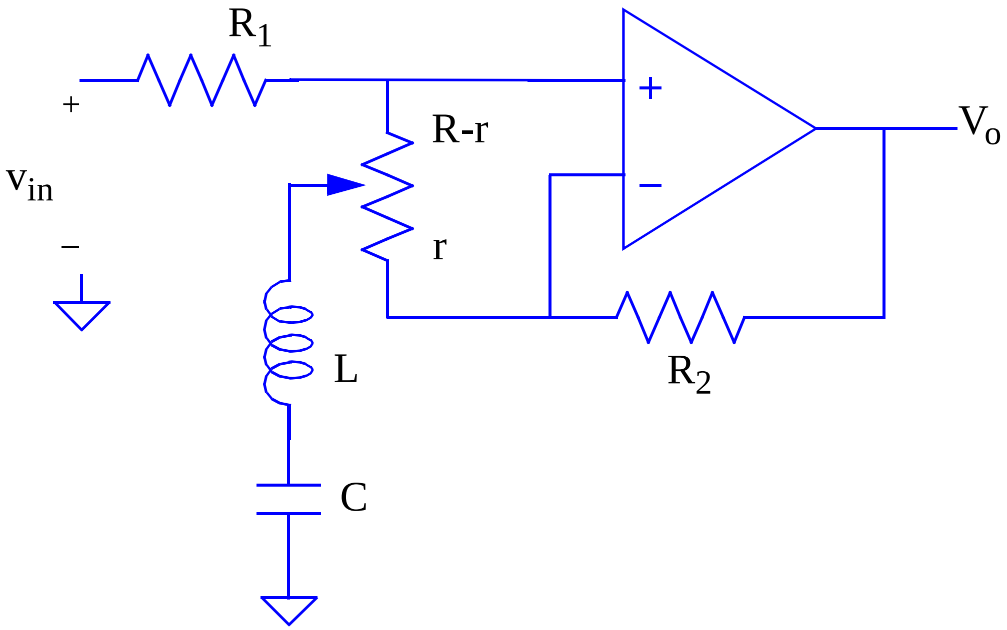
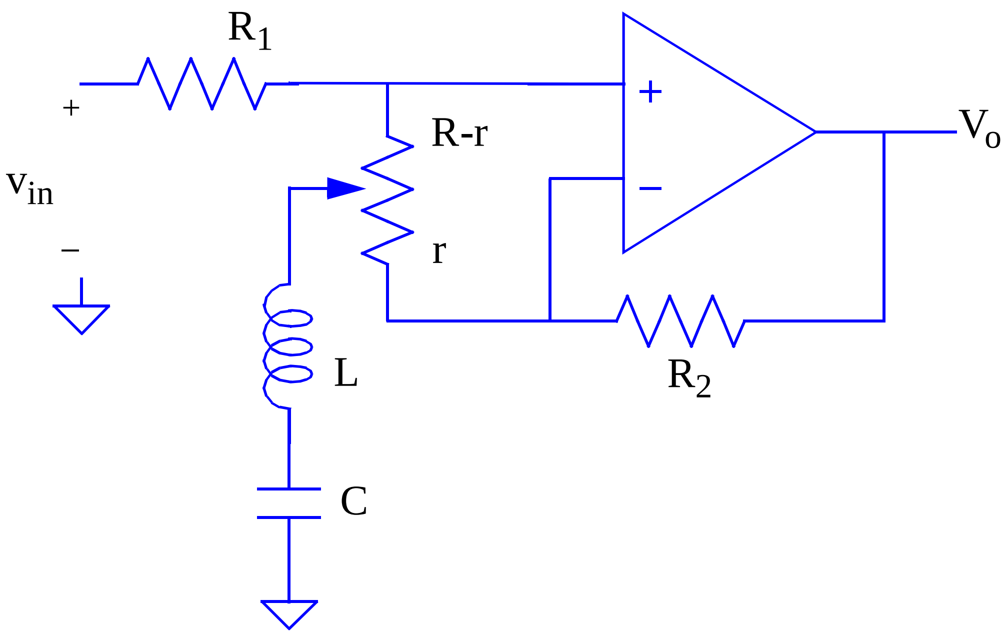
Combination Notch and Bandpass Filter

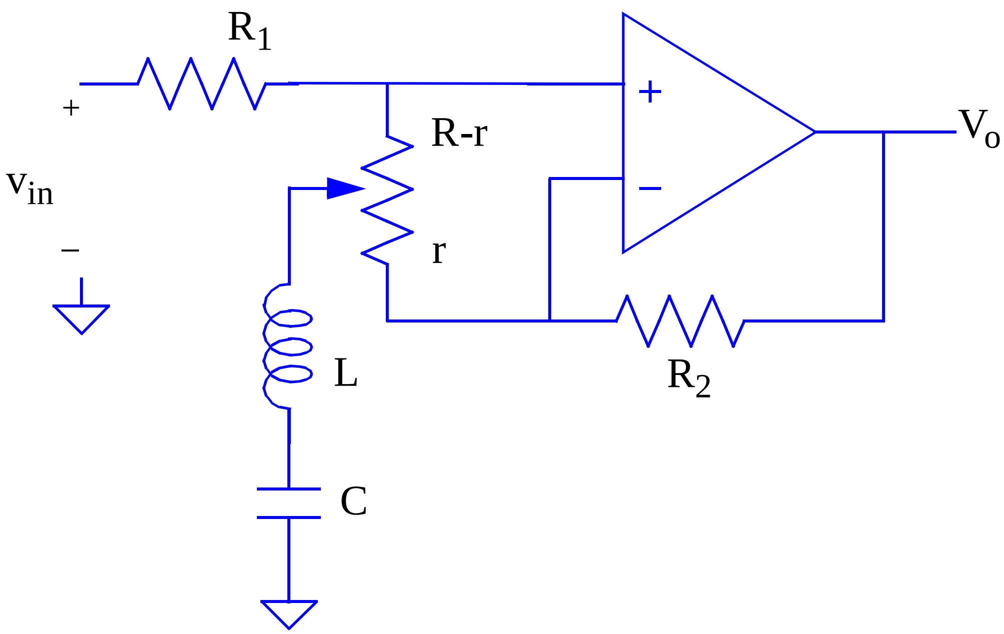
- Clever filter design for graphic equalizer can perform both notch and bandpass functions
- Gain or attenuation is controlled by a potentiometer for specific frequency bands



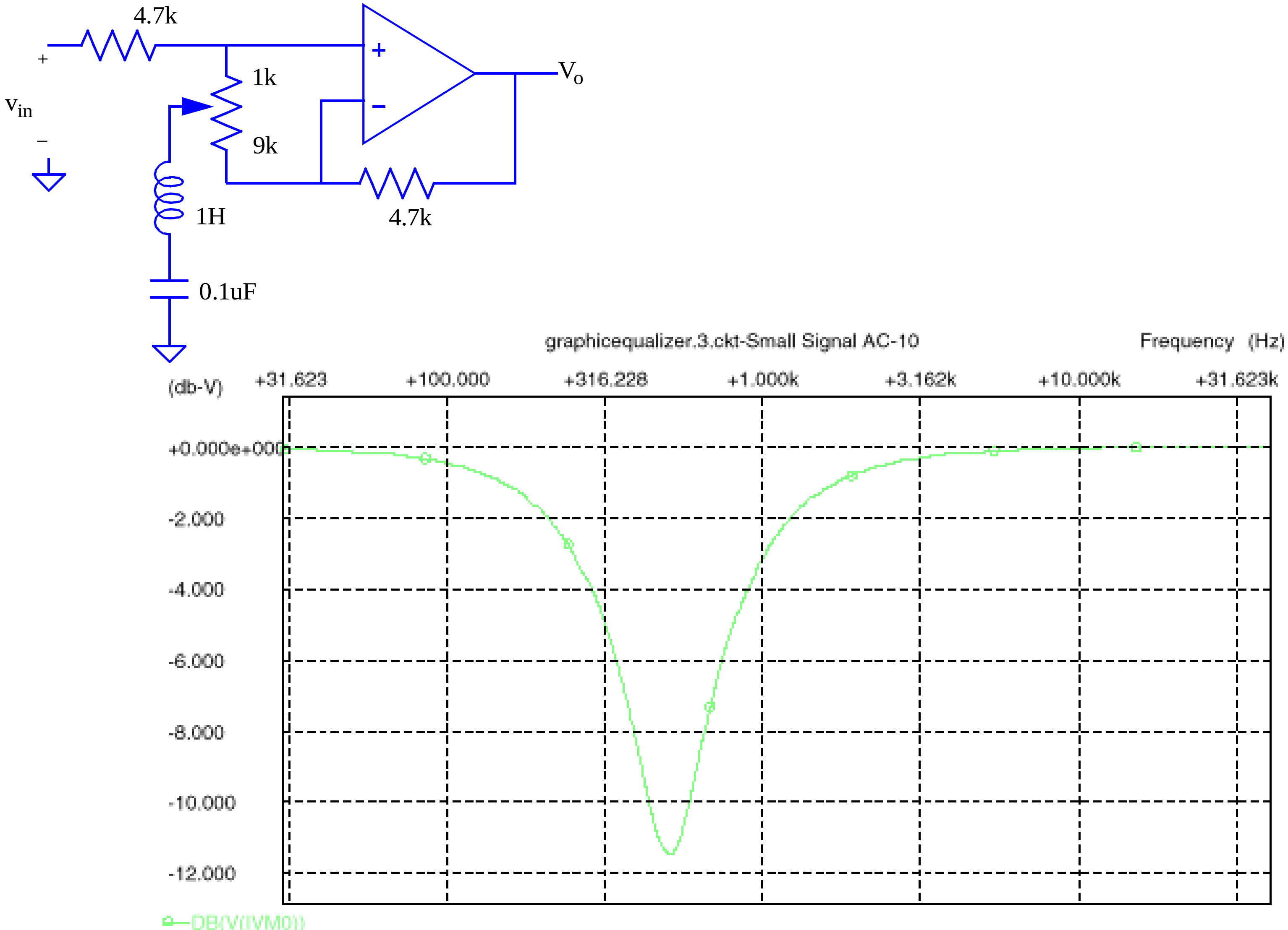
Combination Notch and Bandpass Filter



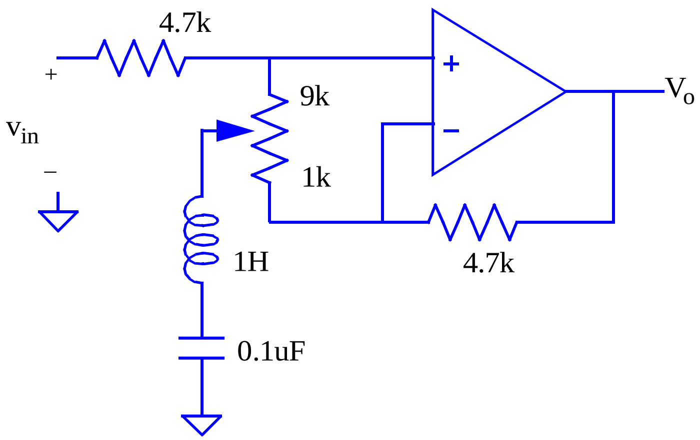
Combination Notch and Bandpass Filter

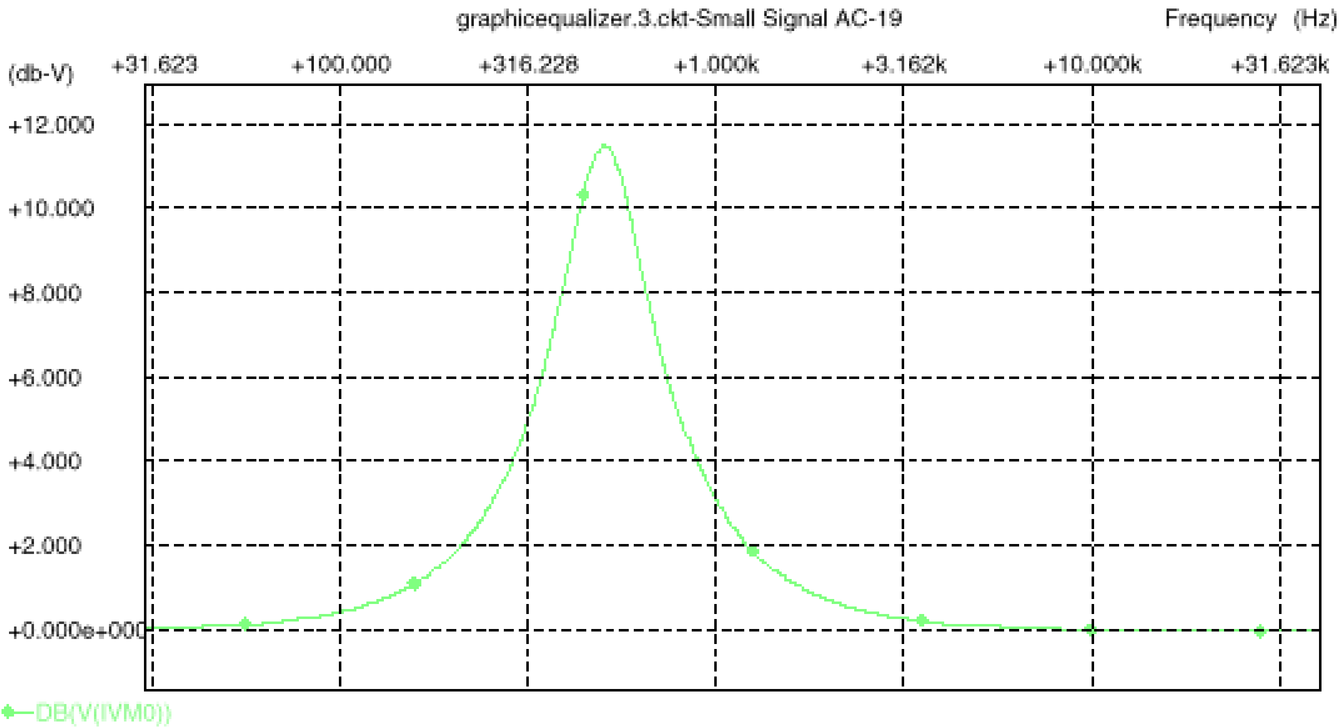


Combination Notch and Bandpass Filter



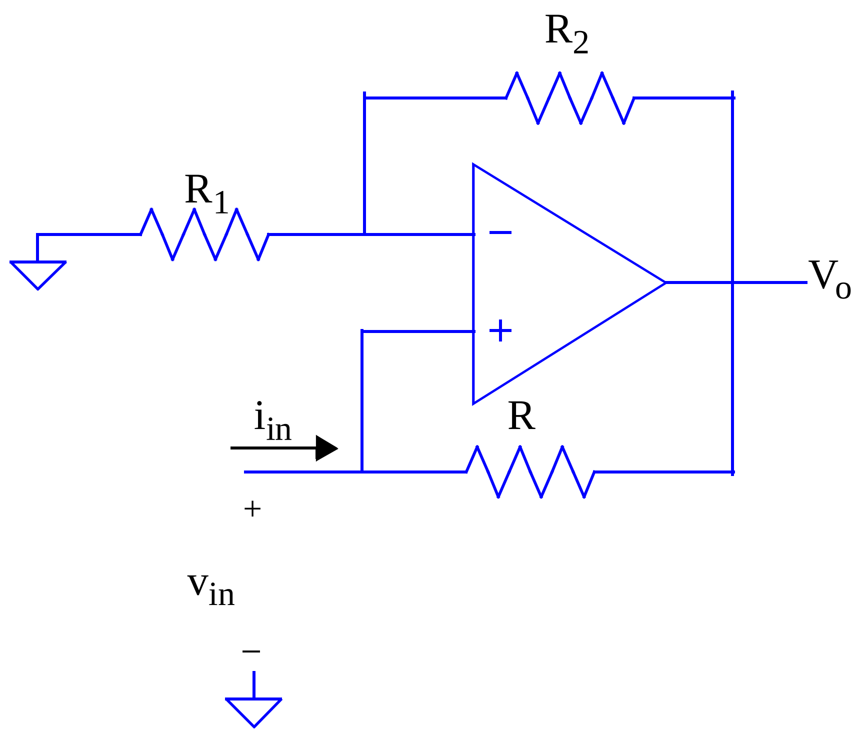
Combination Notch and Bandpass Filter





Integrator via Negative Impedance Converter

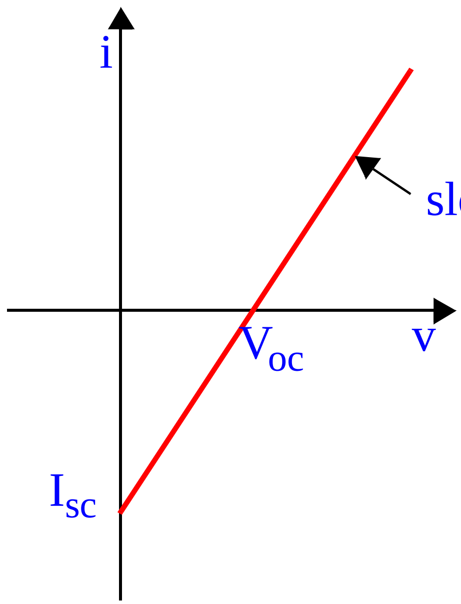
- Presents a negative resistance at the input terminals
- Best analyzed by applying a test voltage and measuring the input current

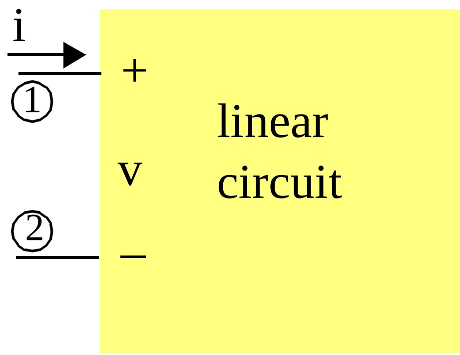


- If it is behaving like a linear circuit, we can calculate the Thevenin equivalent
- If it's passive, we can simply calculate its impedance (resistance in this case)

Thevenin/Norton Equivalents

- By definition, a linear circuit has a straight-line i-v characteristic

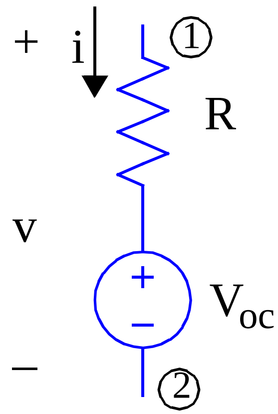




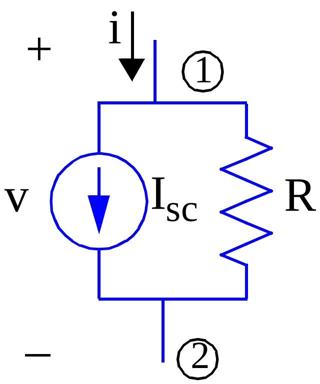
$$v = Ri + V_{oc}$$

$$i = \frac{v}{R} + I_{sc}$$

Which can be represented by

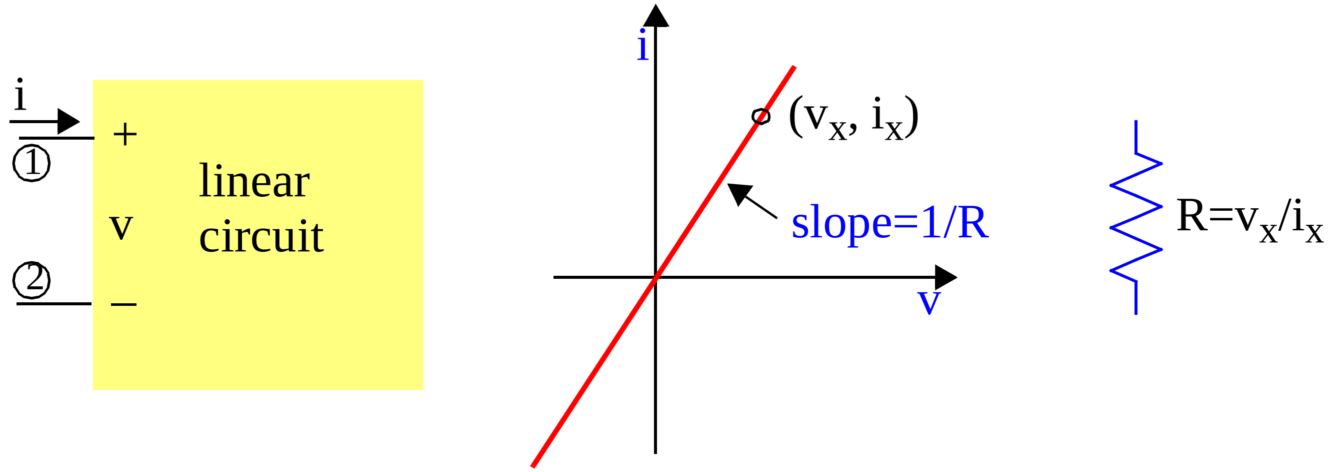


or

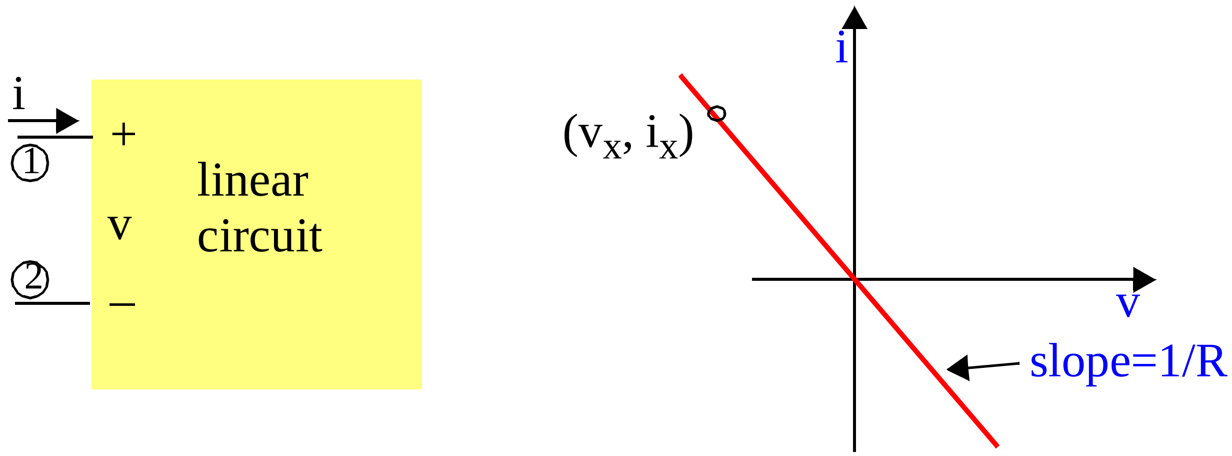


Thevenin/Norton Equivalents

- If the line passes through the origin, then it is a passive linear circuit --- a single impedance
- Only one (v_x, i_x) point is needed to determine the slope

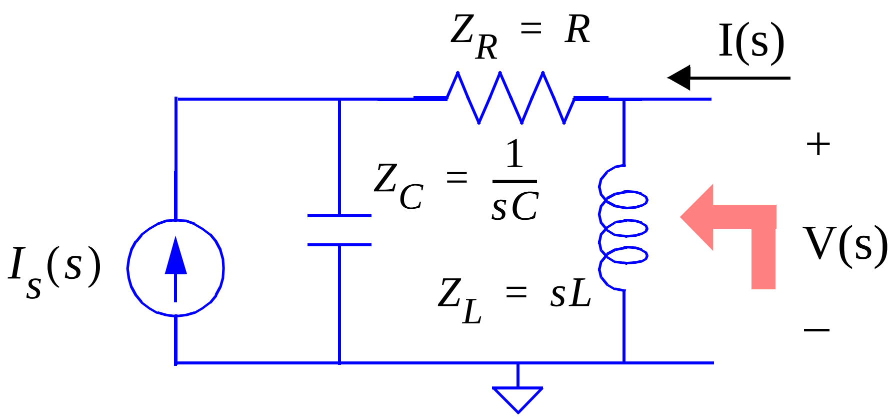


- A negative resistance is recognized by a negative slope (*with directions shown*)



Thevenin/Norton Equivalents

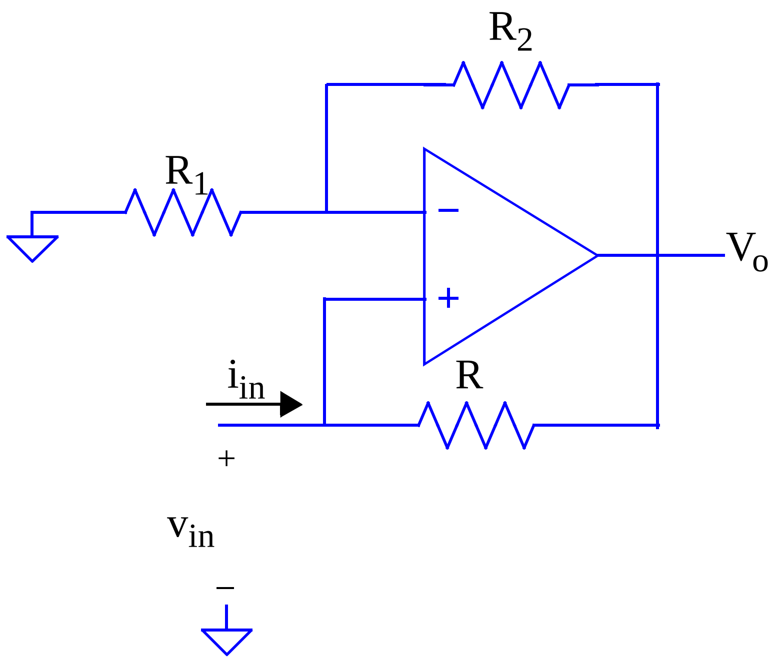
- Note that the same Thevenin/Norton conversion steps --- applying test voltages and measuring test currents --- works for complex impedances too



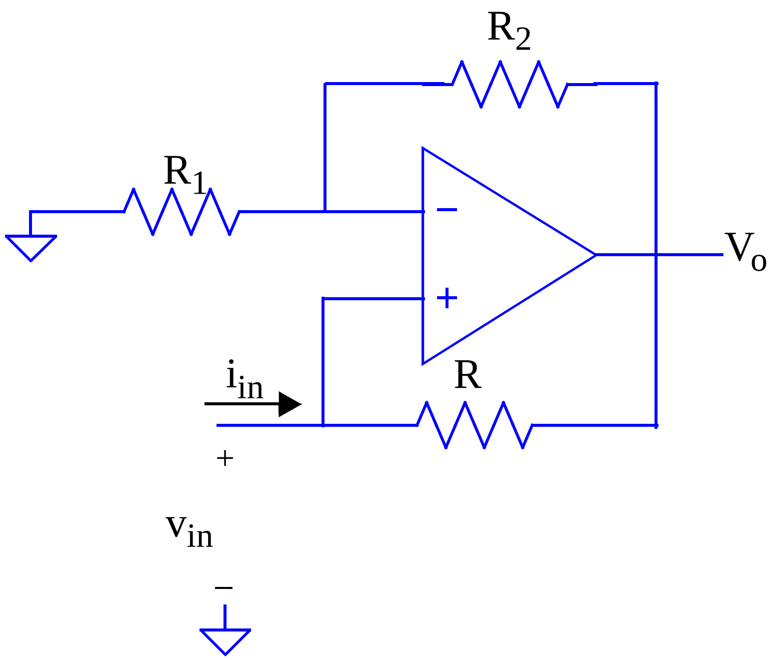
- We just can’t draw them as two dimensional i-v characteristics

Negative Impedance Converter

- Calculate v_{in}/i_{in}

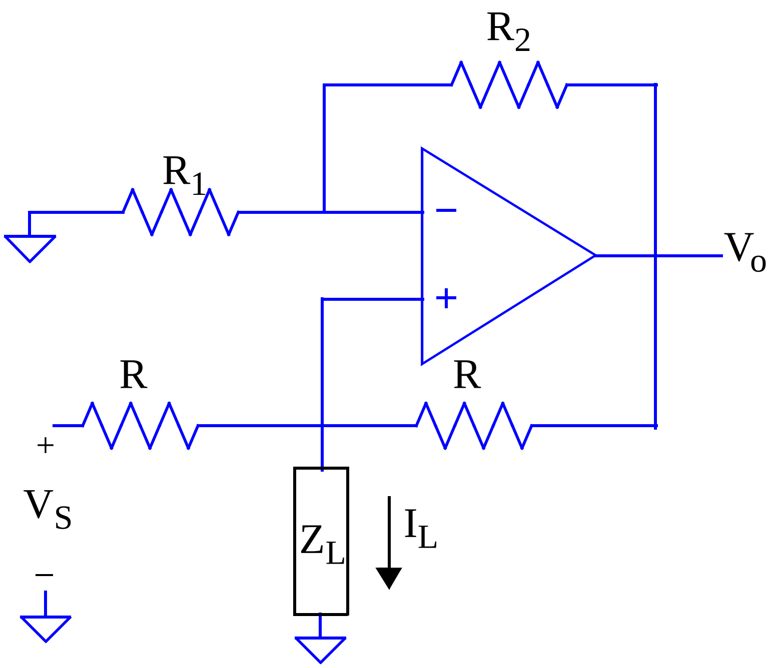


Negative Impedance Converter

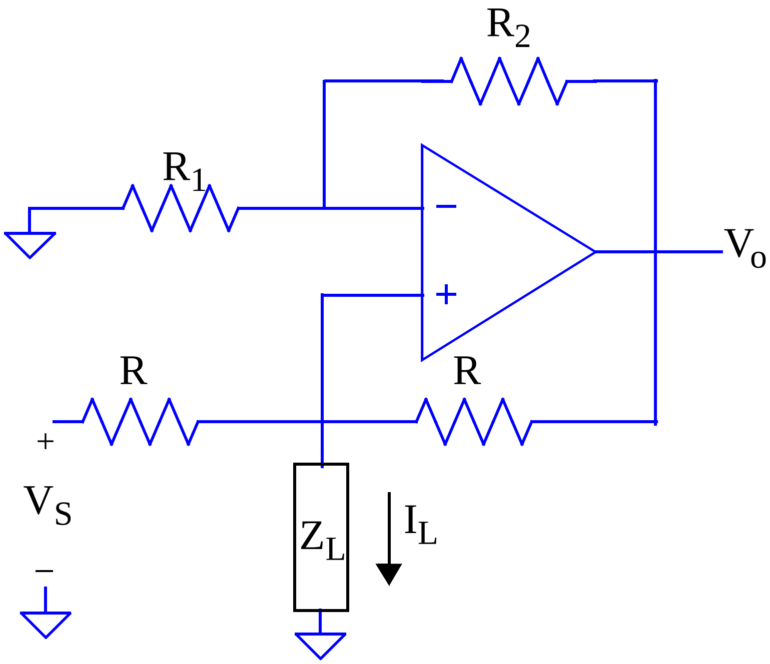


Voltage-to-Current Converter

- The negative impedance converter can be used to create a voltage-to-current converter where the output load current is independent of the load impedance



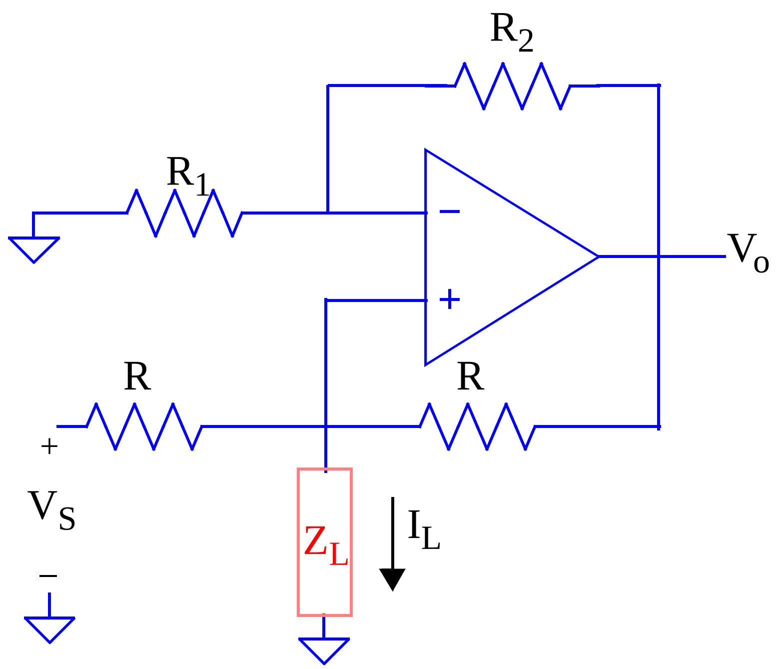
Voltage-to-Current Converter



- We could also write out all of the current equations and get the same result

Integrator

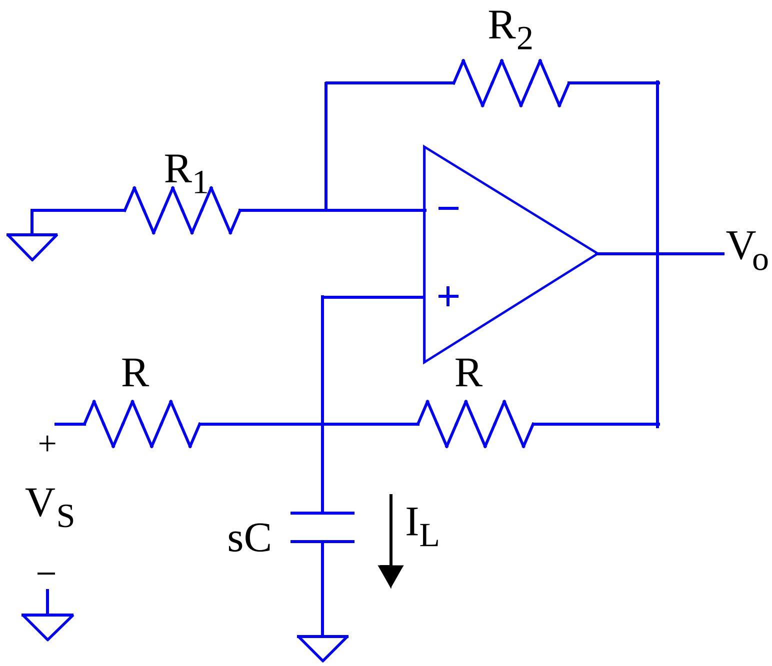
- Use the voltage-to-current converter to design an integrator



Integrator

- Need a low output impedance for this circuit -- why?

- If the output impedance is not low enough, what is another design option?



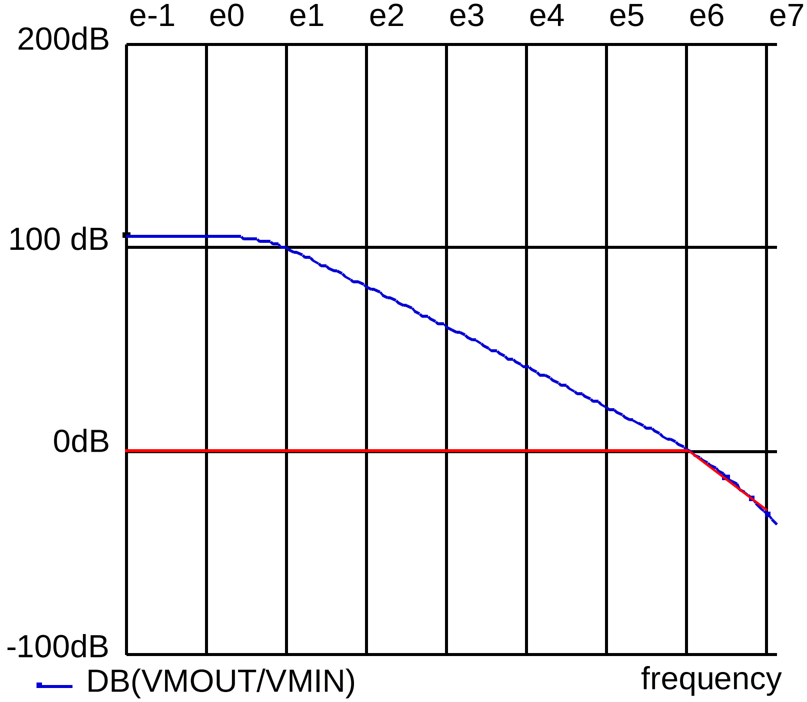
More Nonidealities

- Along with the frequency dependence of the gain, and the finite output/input impedances of the devices, there are other nonidealities associated with opamps that can cause distortion
- Saturation: the output is really limited to a voltage that is 1 to 3 volts less than VCC
- Slew Rate: limited gain of transconductance input amplifier can cause severe distortion in the output
- CMRR: the signal component that is common to both differential inputs is amplified somewhat, and the CMRR specifies the quality with which this phenomenon is rejected
- dc Offset Voltage: the input differential voltage required to set the output to zero when no other signals are applied
- Finite Input/Output Impedances: the input resistance/impedance of the inputs and the limited current sourcing capability of the output
- dc Input Bias Current: small currents required to bias the transistors at the input stage of the opamp

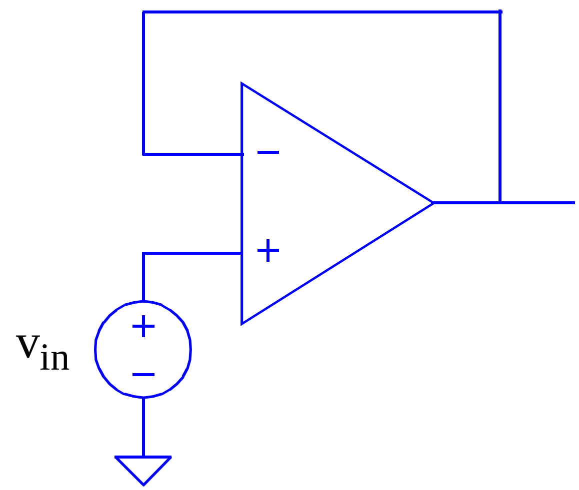
Slew Rate Limitations

- We know that an opamp behaves like a low pass filter due to the frequency dependence of the gain
- A unity gain amplifier has a bandwidth of ω_t

741 Open Loop Characteristics

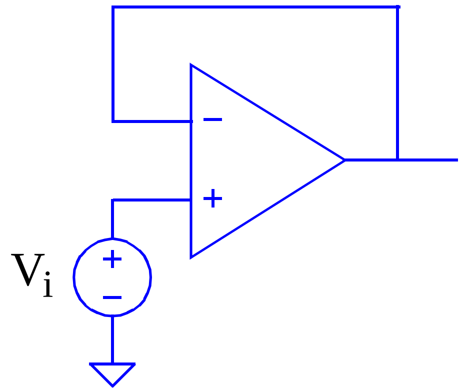


$$A(s) = \frac{A_o}{1 + \frac{s}{\omega b}}$$



Slew Rate Limitations

- So we can write an expression for the closed-loop gain as:



$$\frac{V_o}{V_i} = \frac{1}{1 + \frac{s}{\omega_t}}$$

- Which is like a STC with a time constant of $\frac{1}{\omega_t}$
- In the time domain we'd expect a step response of the form:

$$v_o(t) = V\left(1 - e^{-\frac{t}{\tau}}\right)$$

- Which has a maximum possible change in output voltage of

$$\frac{dv_o(t)}{dt} = \frac{V}{\tau}$$

Slew Rate Limitations

- If the output wants to change faster than this, it will not be able to do so
- This is especially difficult for large signals; e.g. when V is large
- The maximum switching speed is limited by ω_t, which is due to the compensation capacitor in this case, but all capacitors in the circuit in general
- The open loop roll-off with frequency is due to the limited current sourcing capability of the amplifier and these capacitors

$$\frac{\Delta V}{\Delta t} \Rightarrow \frac{I_{max}}{C}$$

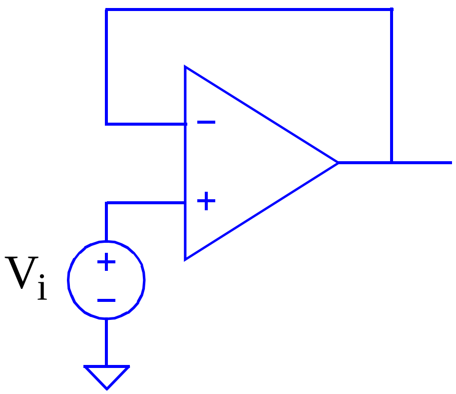
- So the maximum current sourcing capability and the compensation capacitor, for example, may determine the slew rate

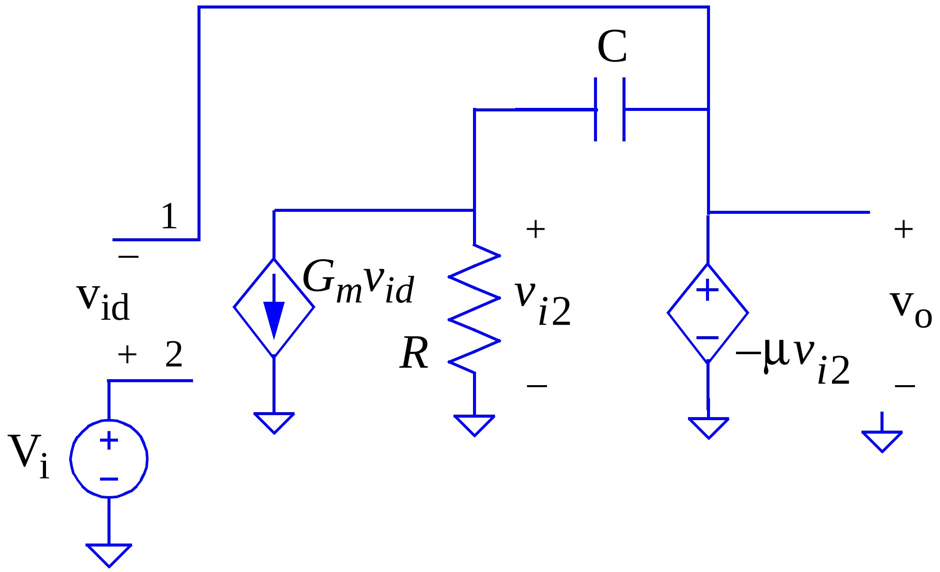
$$SR = \left.\frac{dV_o}{dt}\right|_{max} \qquad \text{(volts/}\mu\text{s)}$$

- A smaller change in voltage can go to higher frequencies before encountering the SR limitation

Opamp Macromodels

- We can look at this limited current sourcing capability of the opamp in terms of the opamp macromodel

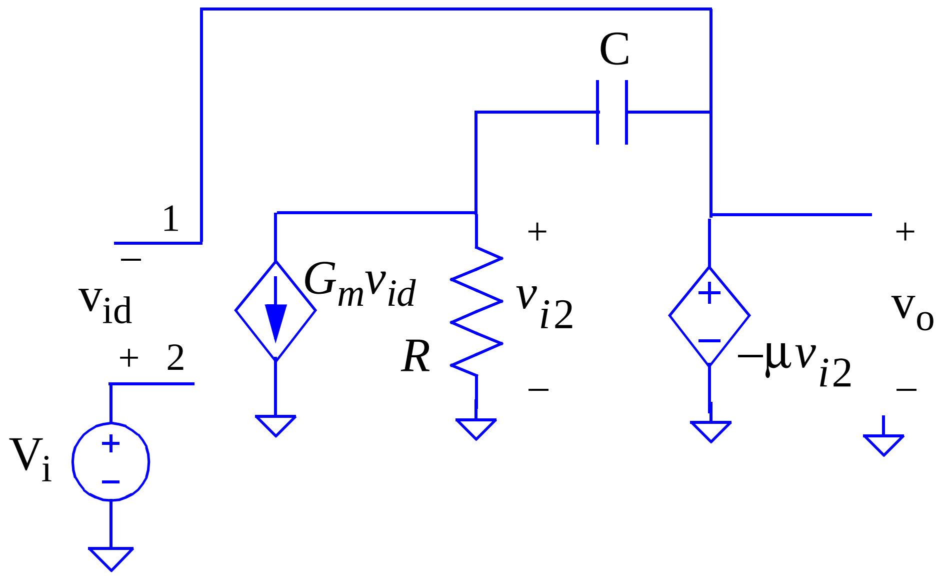




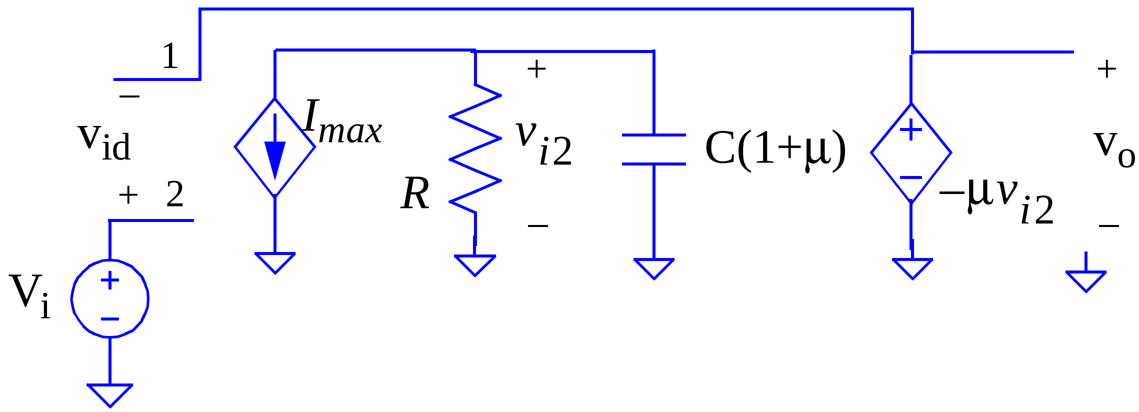
- When change in v_{id} is sudden, G_m can only supply a limited amount of current, I_{max} for a real input transconductance amplifier

Slew Rate Limited Response

- At the slew rate limit the output can only ramp up with a slope of $I_{max}/C(1+\mu)$



For a sudden change in the input voltage, v_{id}

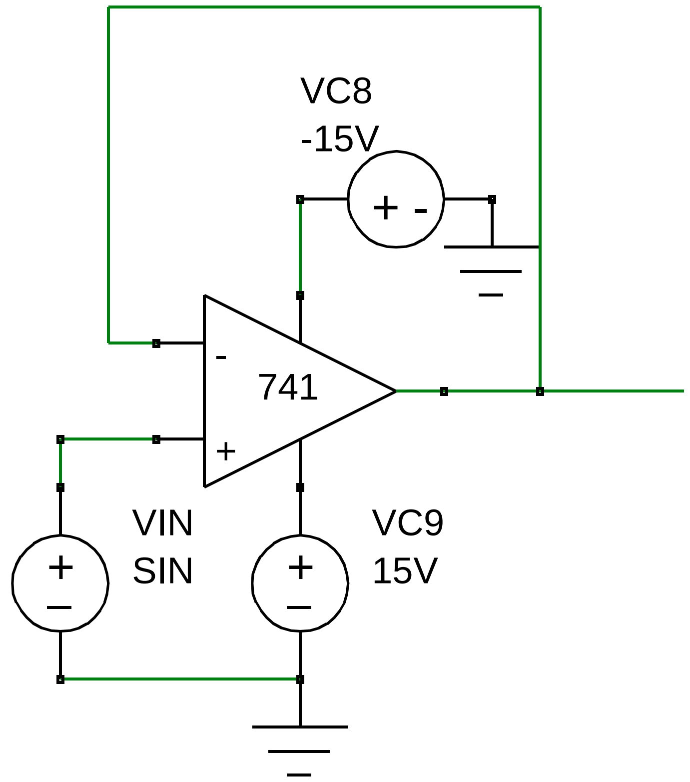


741 Example

- Slew Rate for a 741 is 0.63V/μs
- For a sinusoidal signal, the maximum change occurs near the zero crossing, so this is where we will notice the first signs of slewing

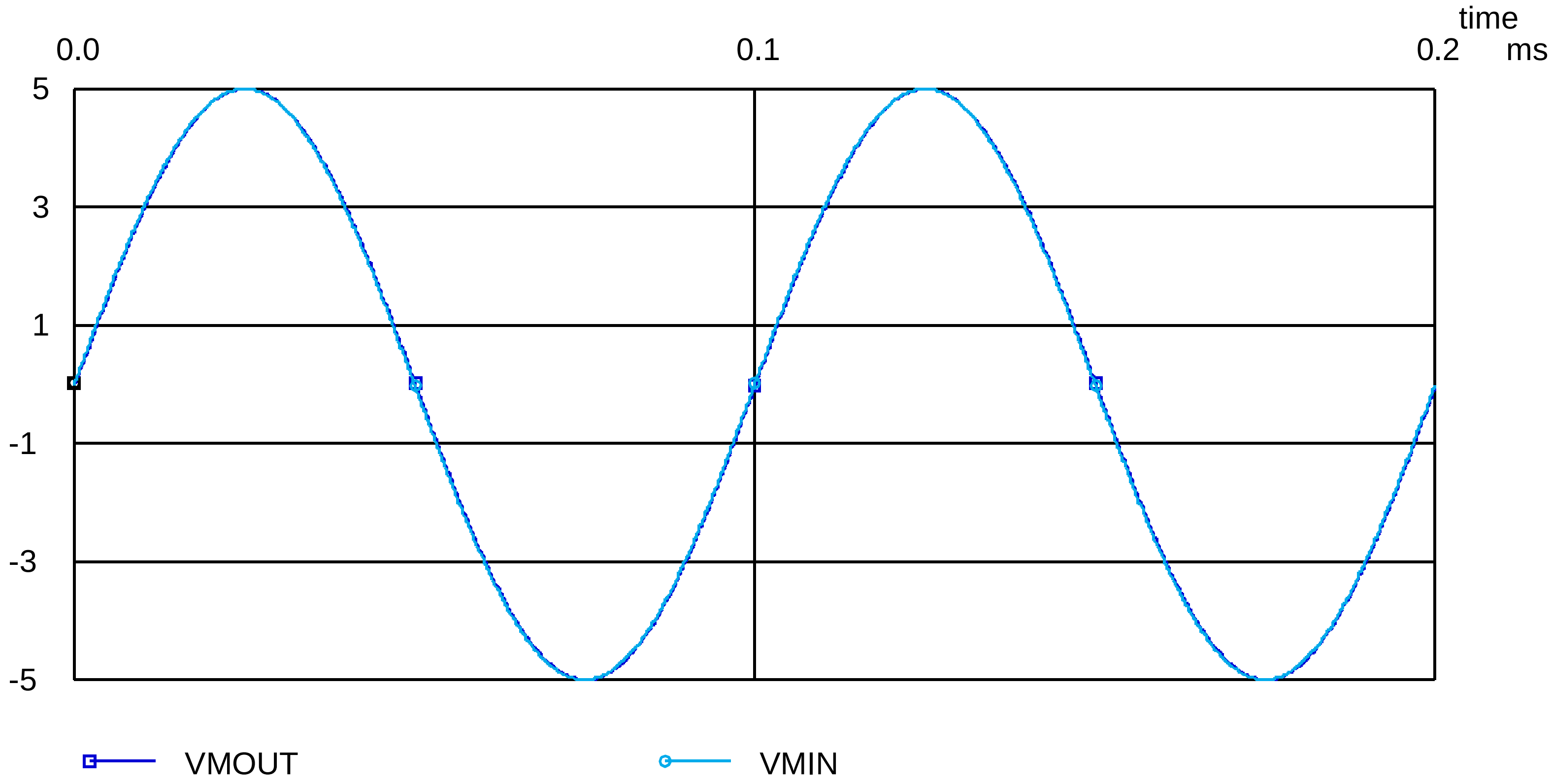
$$\left.\frac{dV_o}{dt}\right|_{max} = \omega V$$

- What's the maximum allowable frequency for a peak sinusoidal input voltage of 5.0 volts?



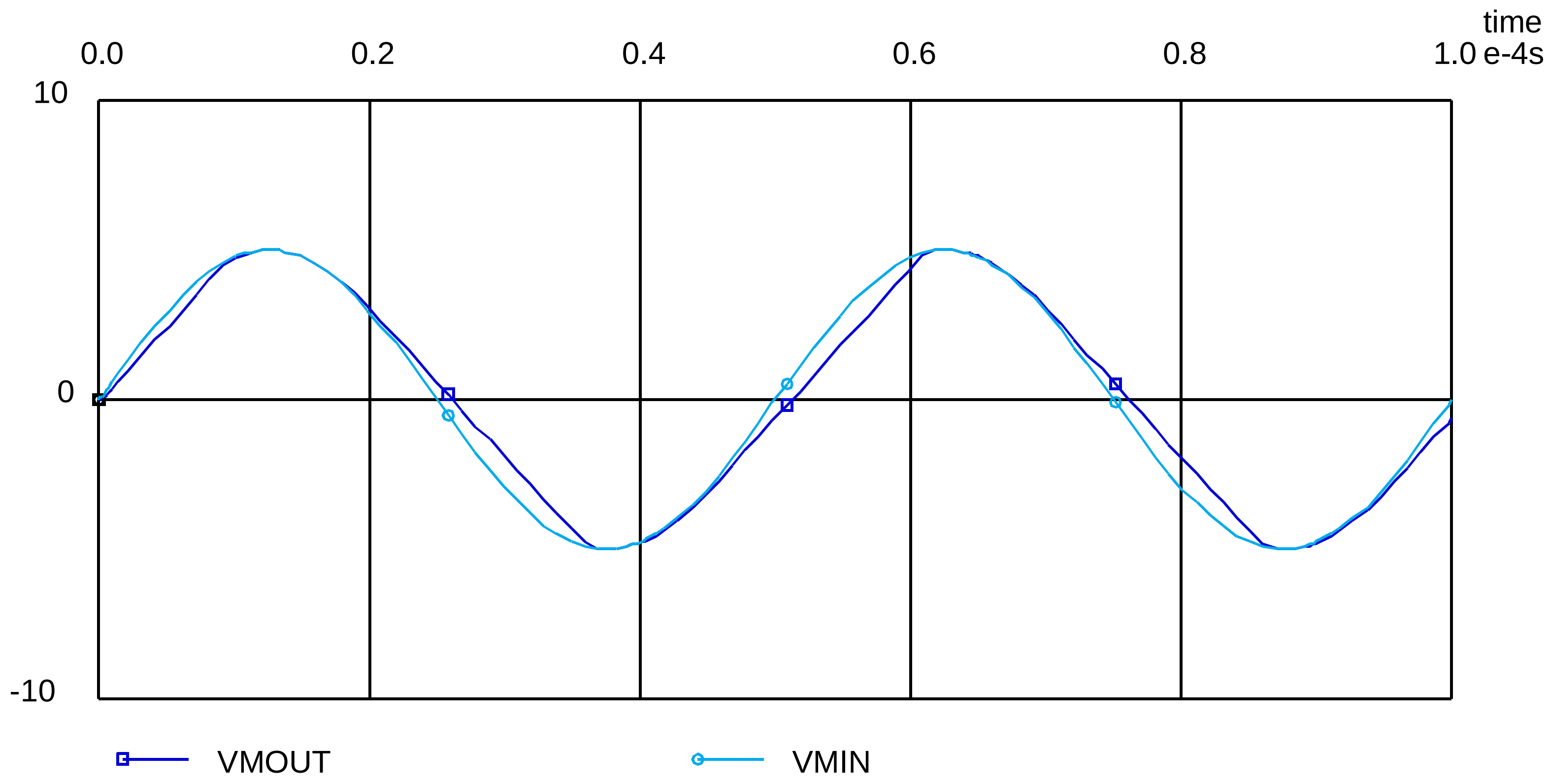
741 Example

- Input and output voltage for a 5 volt peak, 10kHz frequency



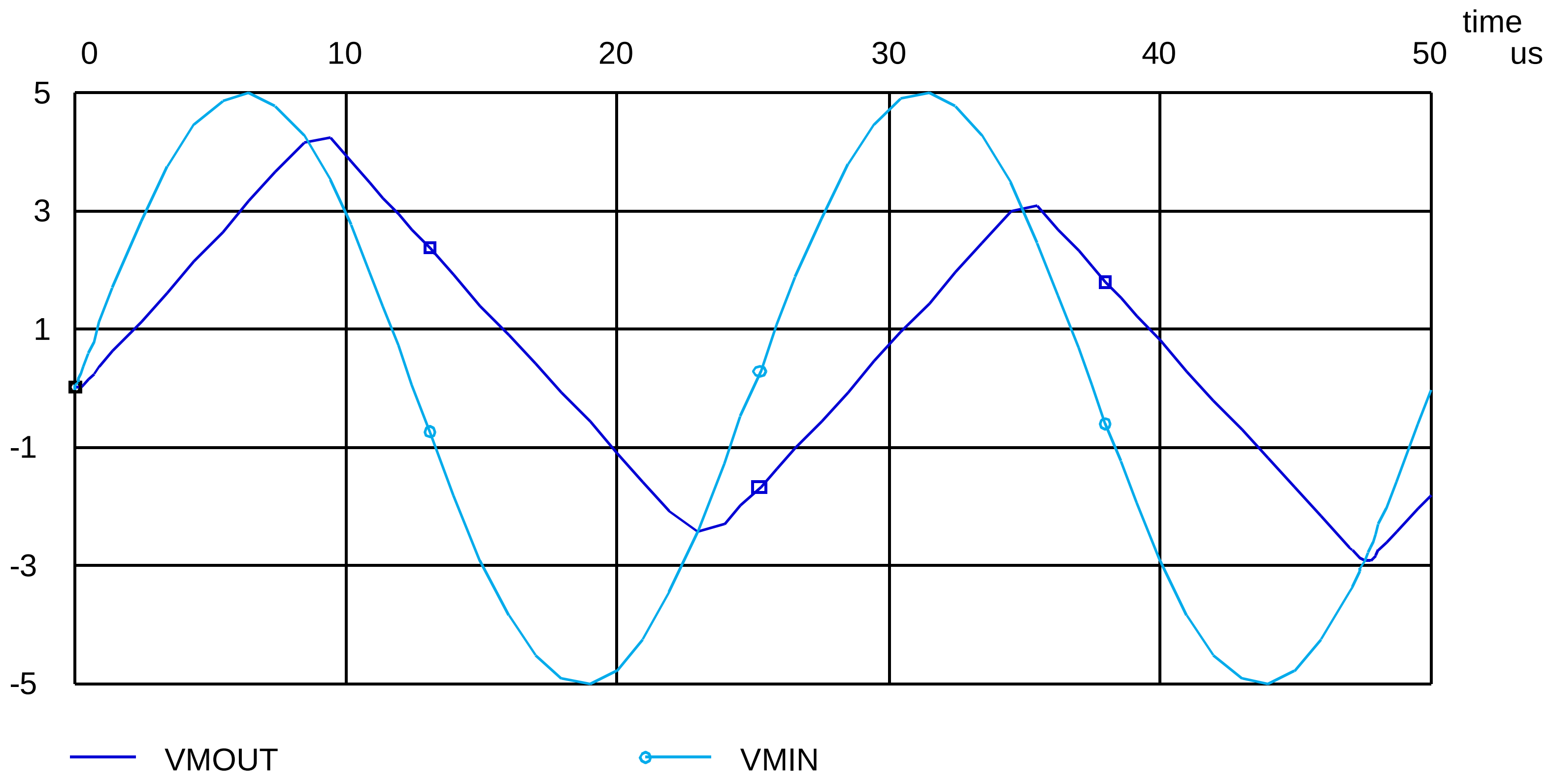
741 Example

- Input and output voltage for a 5 volt peak, 20kHz frequency



741 Example

- Input and output voltage for a 5 volt peak, 40kHz frequency



741 Example

- Note that the frequency response of the opamp does not affect the input signal at 20kHz
- It is a slew rate limitation that depends on the magnitude of the input voltage (has I_{max} of the input transconductance amplifier been reached?)