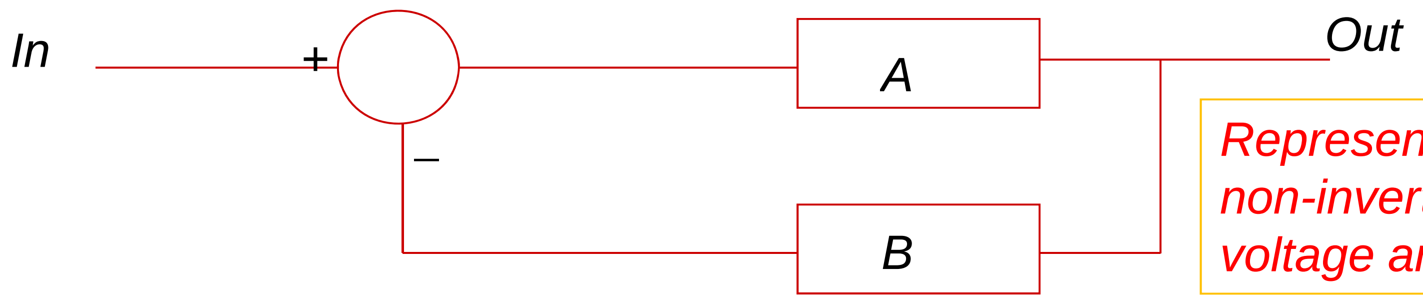
Physics 160
Lecture 15

R. Johnson

May 18, 2015

Negative Feedback Formalism



Representative of a non-inverting voltage amplifier

A= open loop gain (forward gain with no feedback), typically huge (e.g. 100,000)

B= gain of feedback network, typically < 1

AB= loop gain

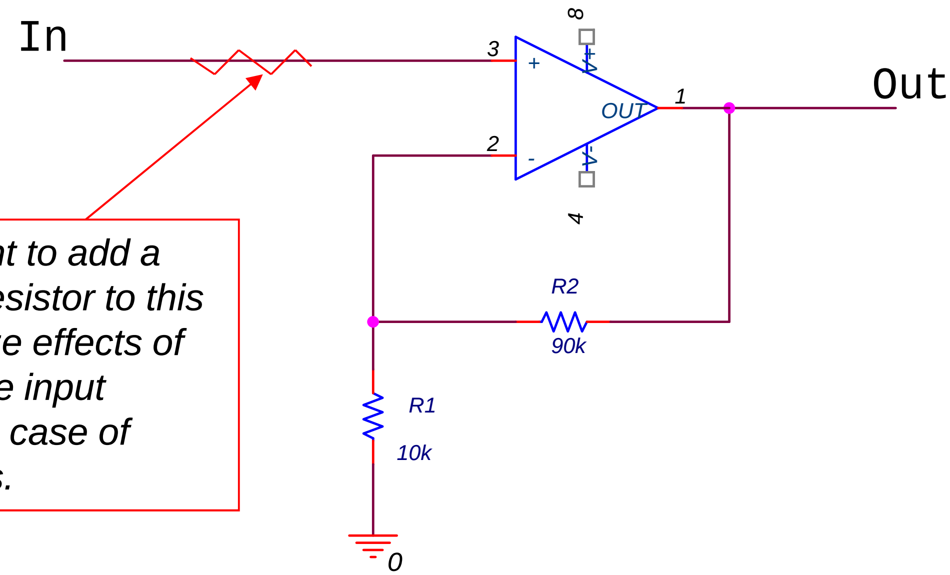
Feedback

$$V_{out} = A \cdot (V_{in} - B \cdot V_{out})$$

$$G = \frac{V_{out}}{V_{in}} = \frac{A}{1+AB} = \frac{1}{B}\left[\frac{1}{1+\left(1/AB\right)}\right]$$

Ideally, you want the loop gain AB to be large, so that G is determined by only the feedback network gain B.

Non-Inverting Amp, More Complete Analysis



You may want to add a 9.1k series resistor to this leg to equalize effects of non-negligible input current in the case of bipolar inputs.

Using the not-so-simplified analysis:

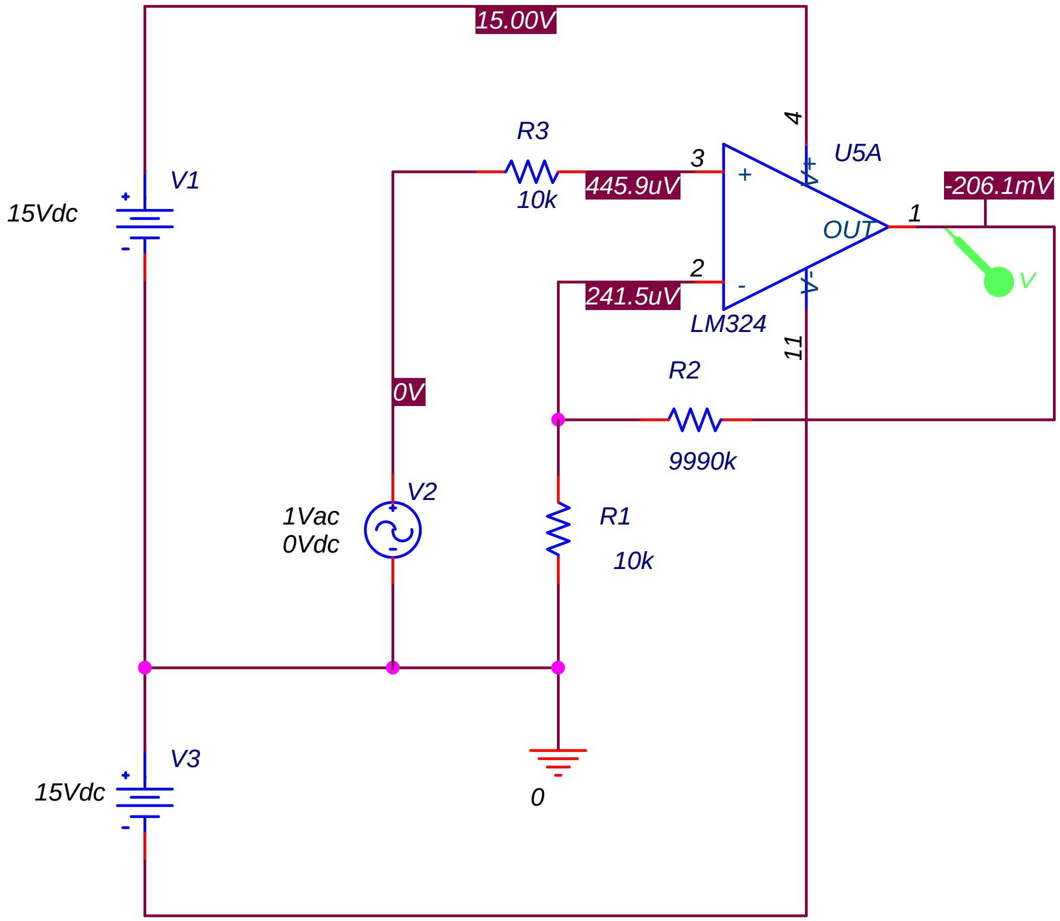
Suppose the forward gain is $A=10^5$ (fairly typical).

Here the feedback gain is $B=R_1/(R_1+R_2)=1/10$ (voltage divider).

Then the loop gain is $AB=10^4$.

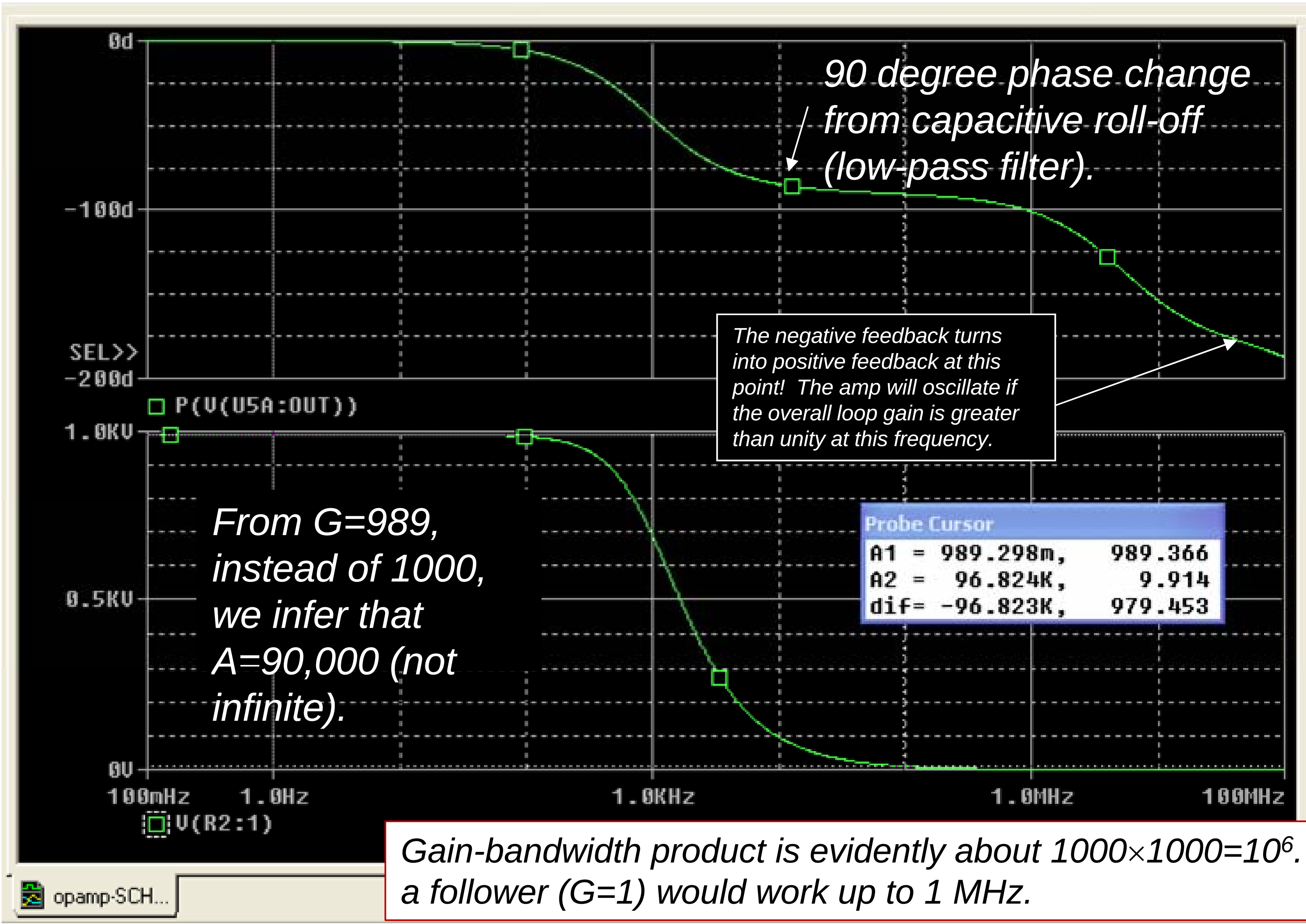
$$G = \frac{V_{out}}{V_{in}} = 10 \times \left(\frac{1}{1+10^{-4}} \right) = 9.999$$

Example



$$G = \frac{V_{out}}{V_{in}} = 1000 \times \left[\frac{1}{1 + (1000/A)} \right]$$

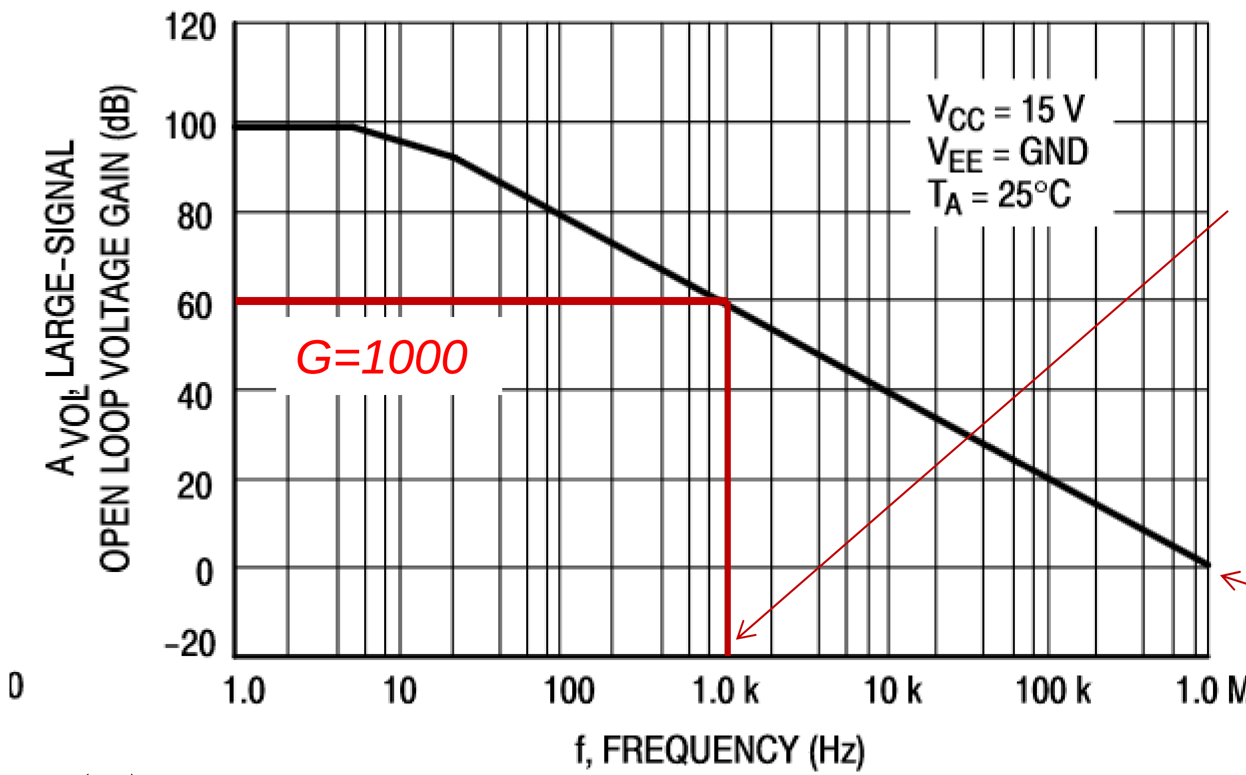
Non-Inverting Amp Output



Gain-bandwidth product is evidently about $1000 \times 1000 = 10^6$. So a follower (G=1) would work up to 1 MHz.

LM324 Data Sheet

http://www.onsemi.com/pub_link/Collateral/LM324-D.PDF



We expect a frequency limit of ~1 kHz

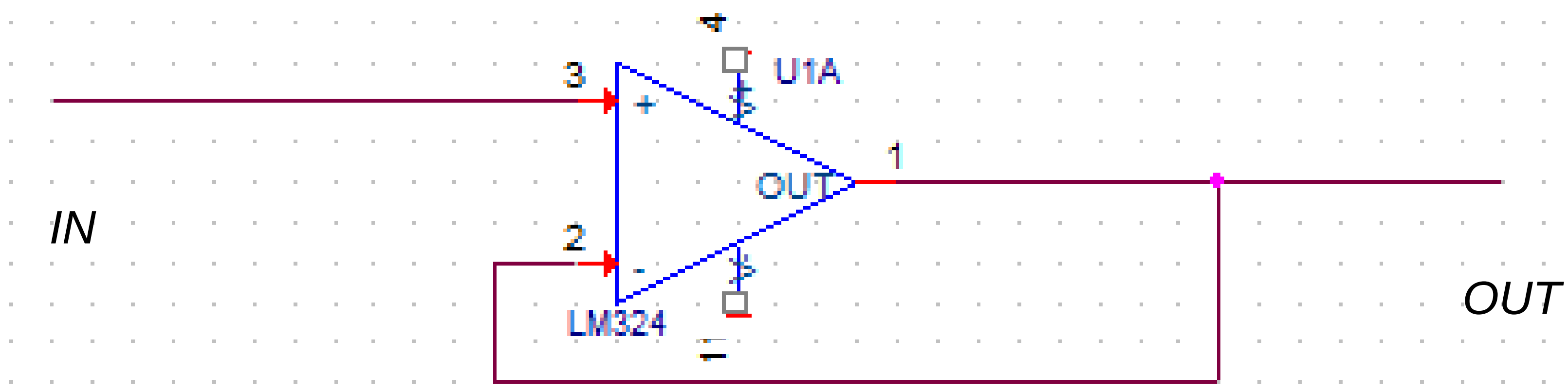
A follower (G=1) will work up to ~1 MHz.

Figure 6. Open Loop Frequency

$$\mathrm{dB} = 20 \cdot \log_{10}(G)$$

$$20 \cdot \log(90000) = 99\,\mathrm{dB}$$

Follower



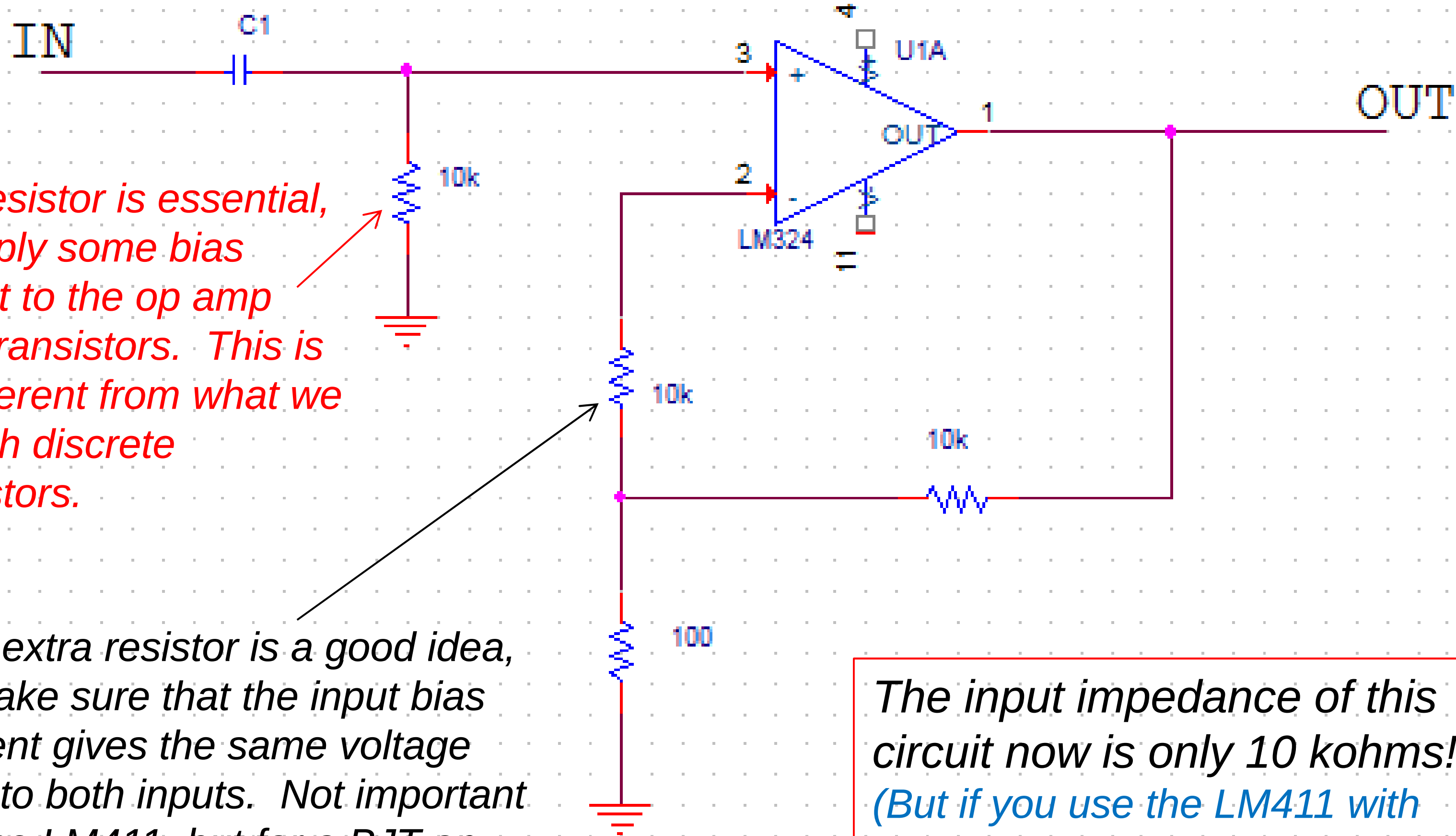
Non-inverting amp with 100% feedback. Be aware that the internal compensation capacitor is very important here to avoid high-frequency oscillations!

The LM324, like the LM411, has a large enough internal capacitor to enhance the Miller effect that it is stable when operated as a follower.

Some op amps require an external compensation capacitor, so you can optimize the operation.

AC Coupled Non-Inverting Amp

(The op amp here is assumed to be operated with dual power supplies, so that the signal can oscillate about ground.)

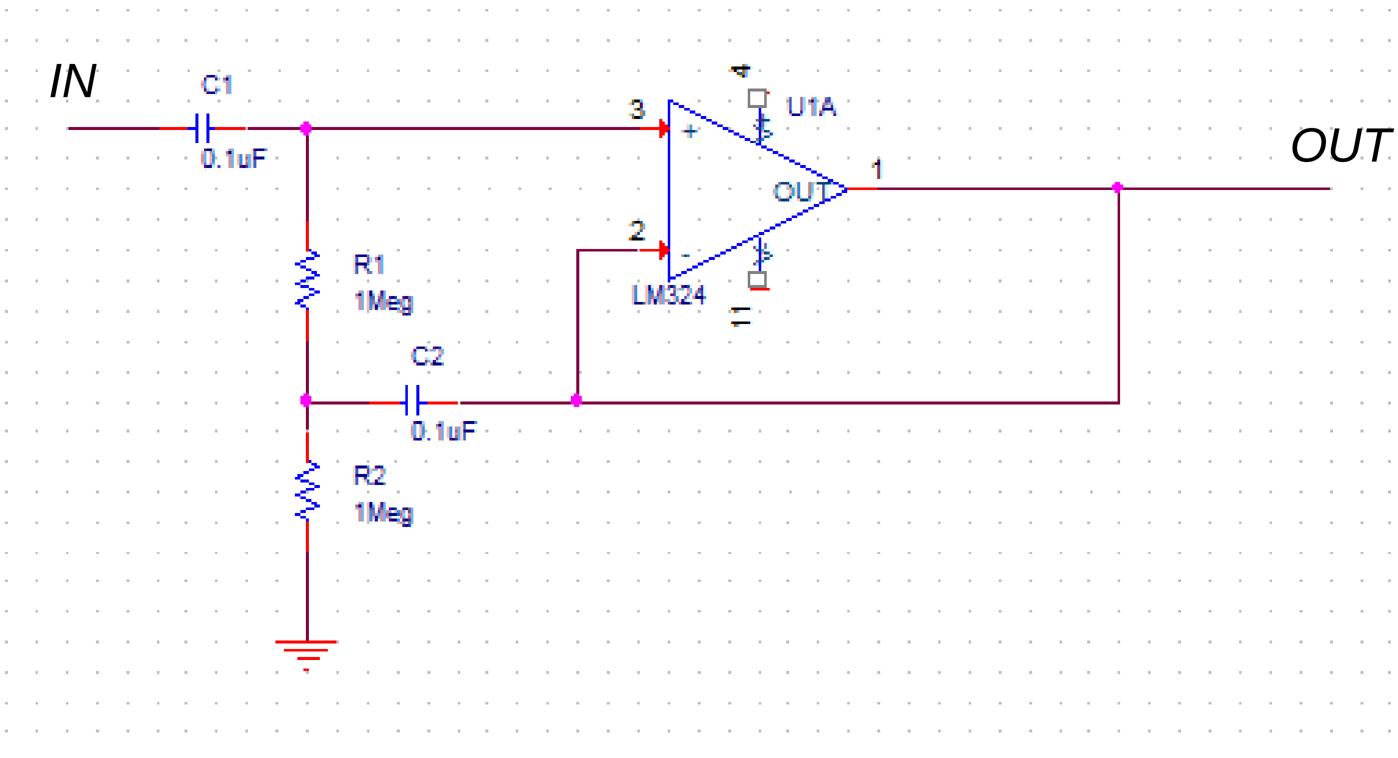


This resistor is essential, to supply some bias current to the op amp input transistors. This is no different from what we did with discrete transistors.

This extra resistor is a good idea, to make sure that the input bias current gives the same voltage shift to both inputs. Not important for the LM411, but for a BJT op amp like the LM324 it can be very important.

The input impedance of this circuit now is only 10 kohms!
(But if you use the LM411 with JFET inputs, the resistor can be much, much bigger.)

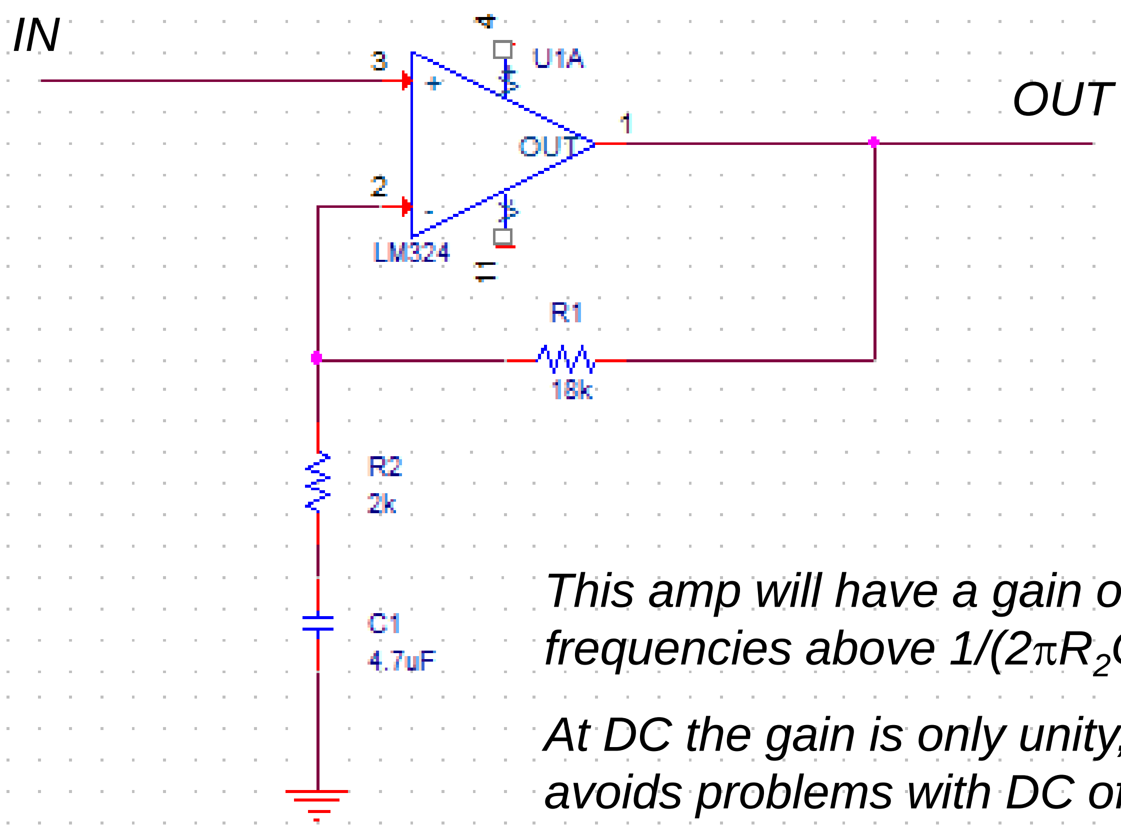
AC Coupled Follower with Bootstrap



If necessary, for a follower the bias network can be bootstrapped as shown here, in exactly the same way as we did for the emitter-follower. *(Note that this example is for an amplifier with both positive and negative supplies, so the inputs and outputs can be centered on ground potential.)*

AC Non-Inverting Amplifier

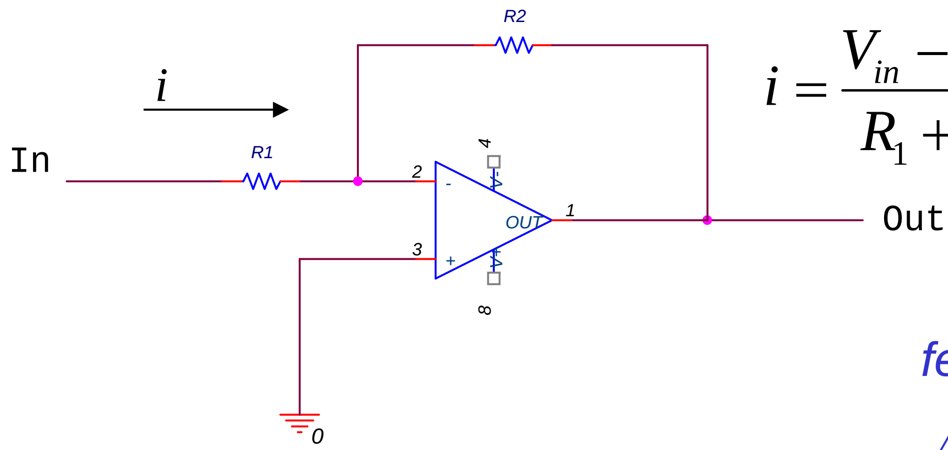
An alternative to using a coupling capacitor, or a good idea even if the input is AC coupled.



This amp will have a gain of 10 at frequencies above $1/(2\pi R_2 C_1)$.

At DC the gain is only unity, which avoids problems with DC offsets getting amplified.

Inverting Amp, More Complete Analysis



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

Without R1 this is a transresistance amplifier.

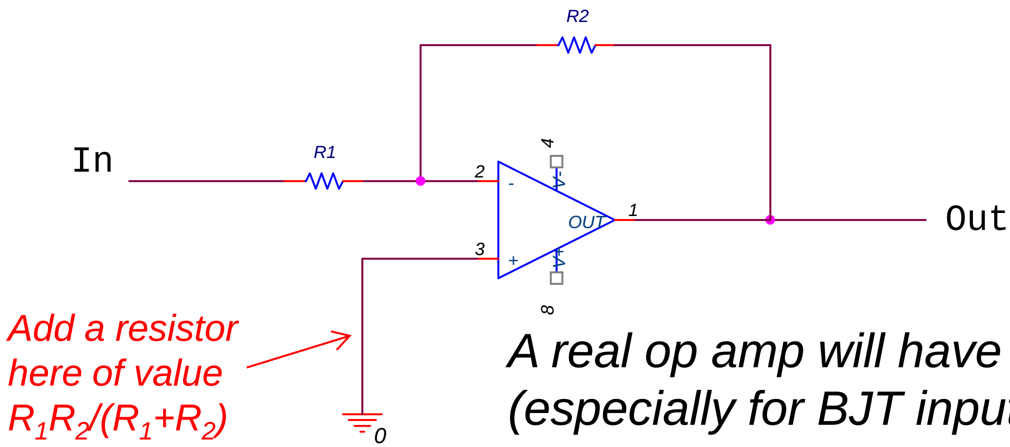
feedback

$$V_- = V_{in} - iR_1 = V_{in} - (V_{in} - V_{out}) \cdot B \quad \textit{where} \quad B \equiv \frac{R_1}{R_1 + R_2}$$

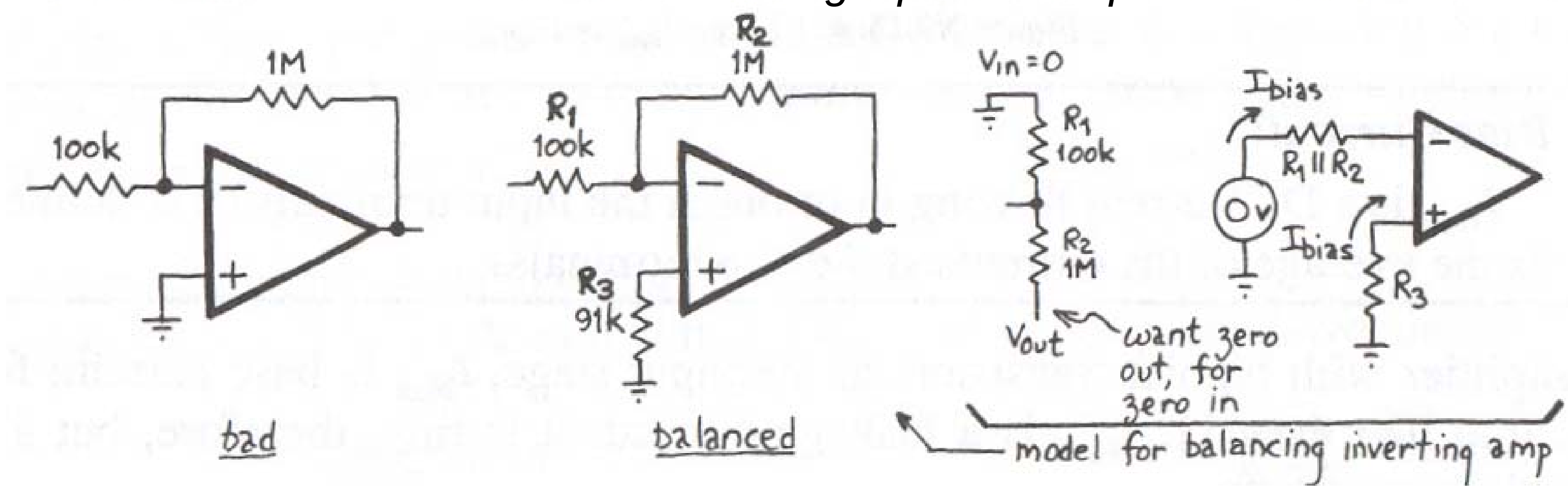
$$V_{out} = A \cdot (V_+ - V_-) = -AV_-$$ *Forward gain*

$$\text{Eliminate } V_- : \qquad \text{G} = \frac{V_{\text{out}}}{V_{\text{in}}} = -\left[\frac{(1/B) - 1}{1 + 1/AB}\right] \approx -\frac{R_2}{R_1}$$

Inverting Amp, Input Current Compensation



A real op amp will have some input bias current (especially for BJT input). The current flowing through R1 and R2 will shift the voltage at the inverting input. We should add a resistor to the non-inverting input to compensate:



Analog Computing

Analog computing:

- *Integrator*
- *Differentiator*
- *Summing amplifier*
- *Log amp*

Op-amps provide nearly ideal performance for these devices, far, far beyond what can be achieved with passive components.

(Note: historically analog computers were widely used, but by now digital computers have such high performance and low cost that analog computers are largely obsolete.)

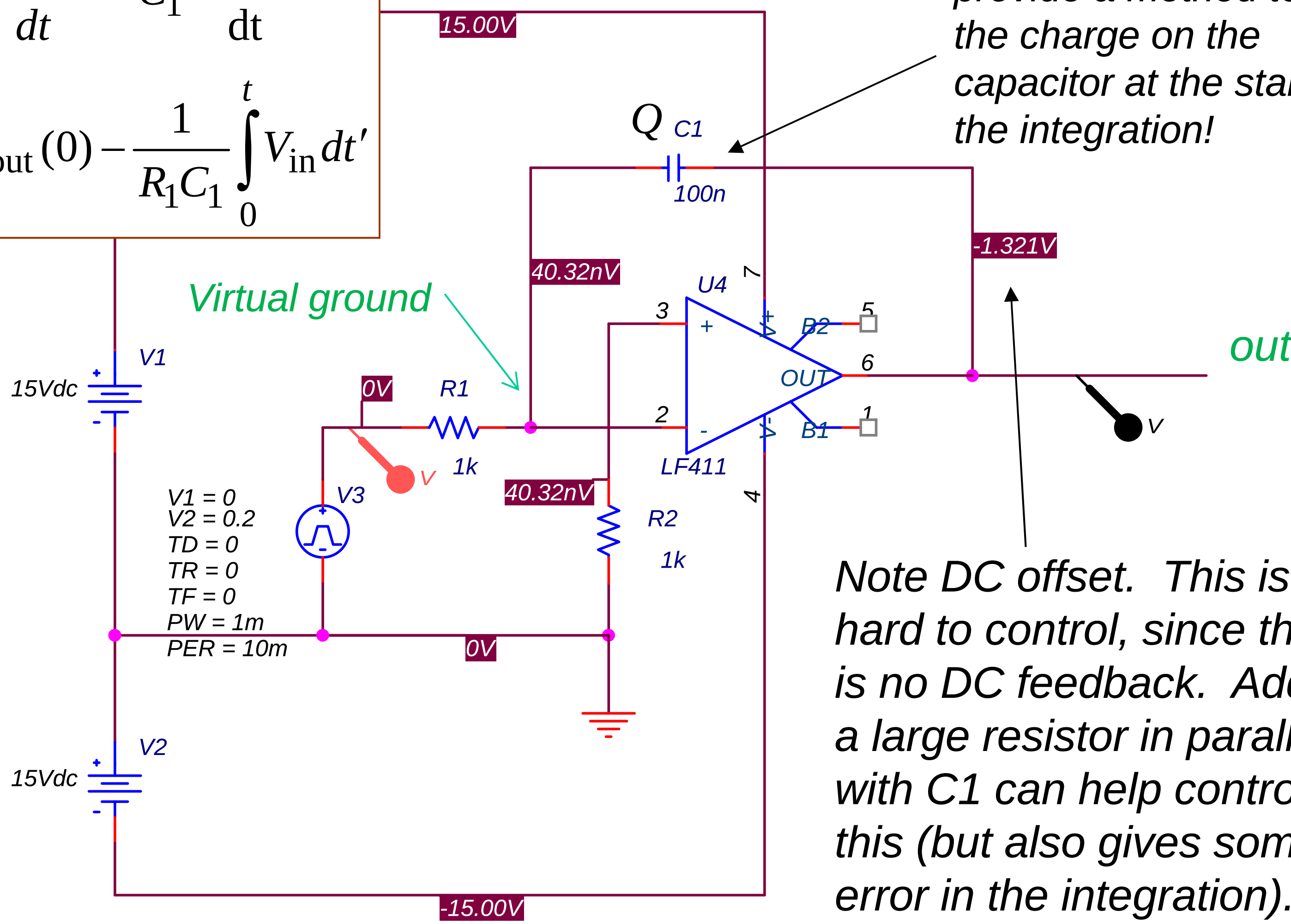
A 1960 Newmark analog computer, made up of five units. This computer was used to solve differential equations and is currently housed at the Cambridge Museum of Technology (from Wikipedia).

Integrator Example

$$i_{\text{in}} = \frac{V_{\text{in}}}{R_1} = \frac{dQ}{dt} = -C_1 \frac{dV_{\text{out}}}{dt}$$

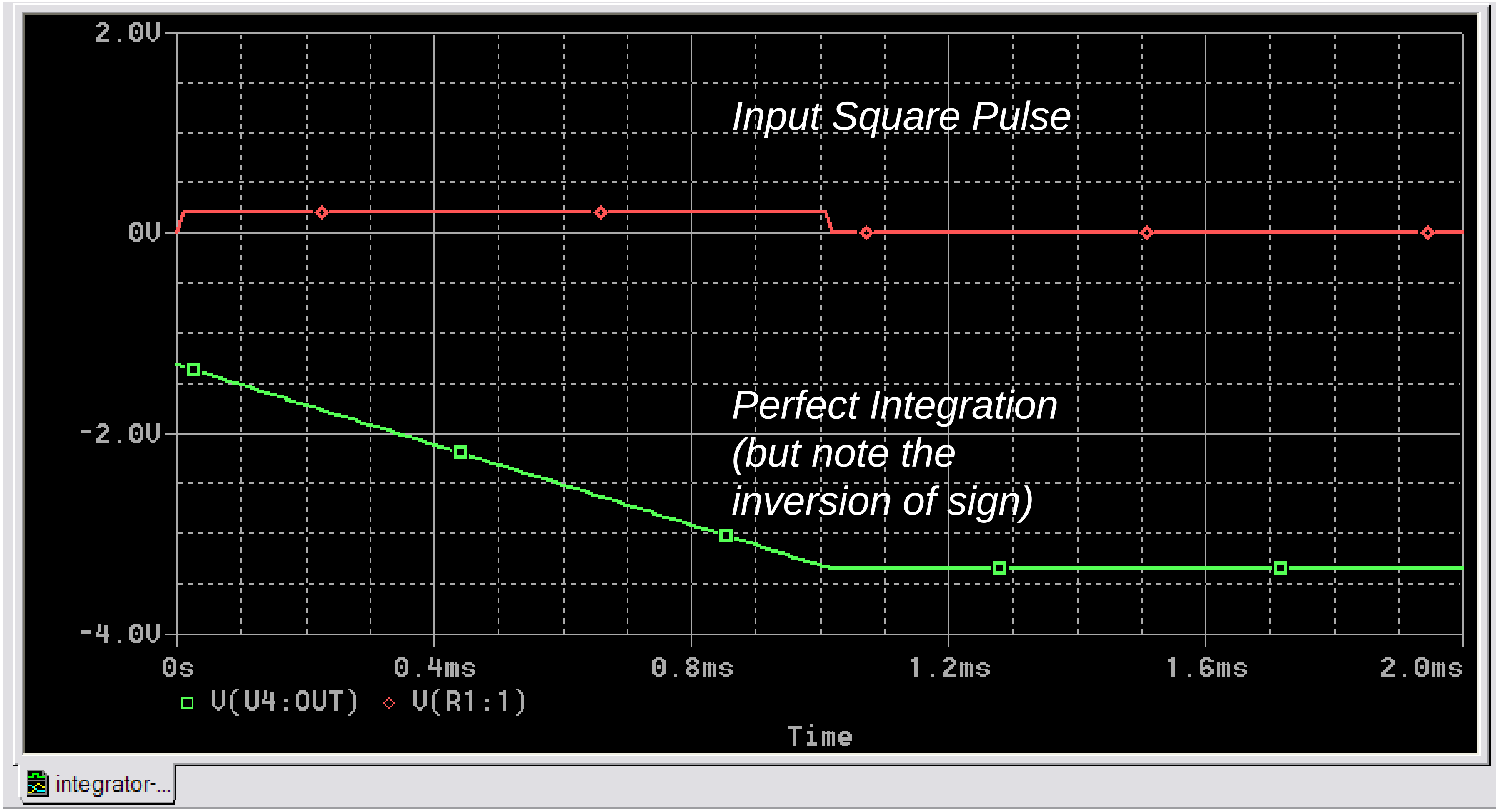
$$V_{\text{out}}(t) = V_{\text{out}}(0) - \frac{1}{R_1 C_1} \int_0^t V_{\text{in}}\, dt'$$

A real circuit will have to provide a method to zero the charge on the capacitor at the start of the integration!



Note DC offset. This is hard to control, since there is no DC feedback. Adding a large resistor in parallel with C1 can help control this (but also gives some error in the integration).

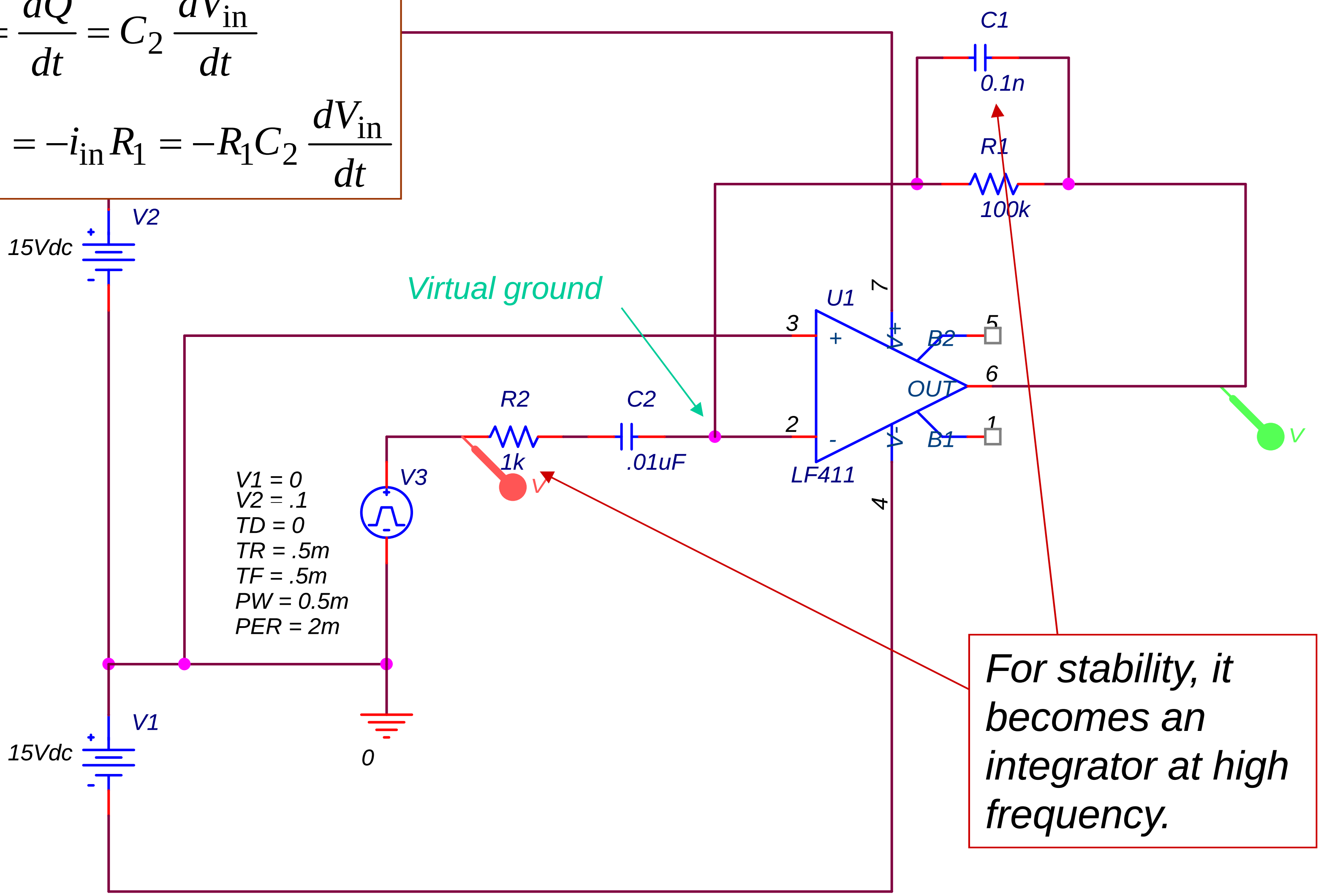
Integration Example



Differentiator

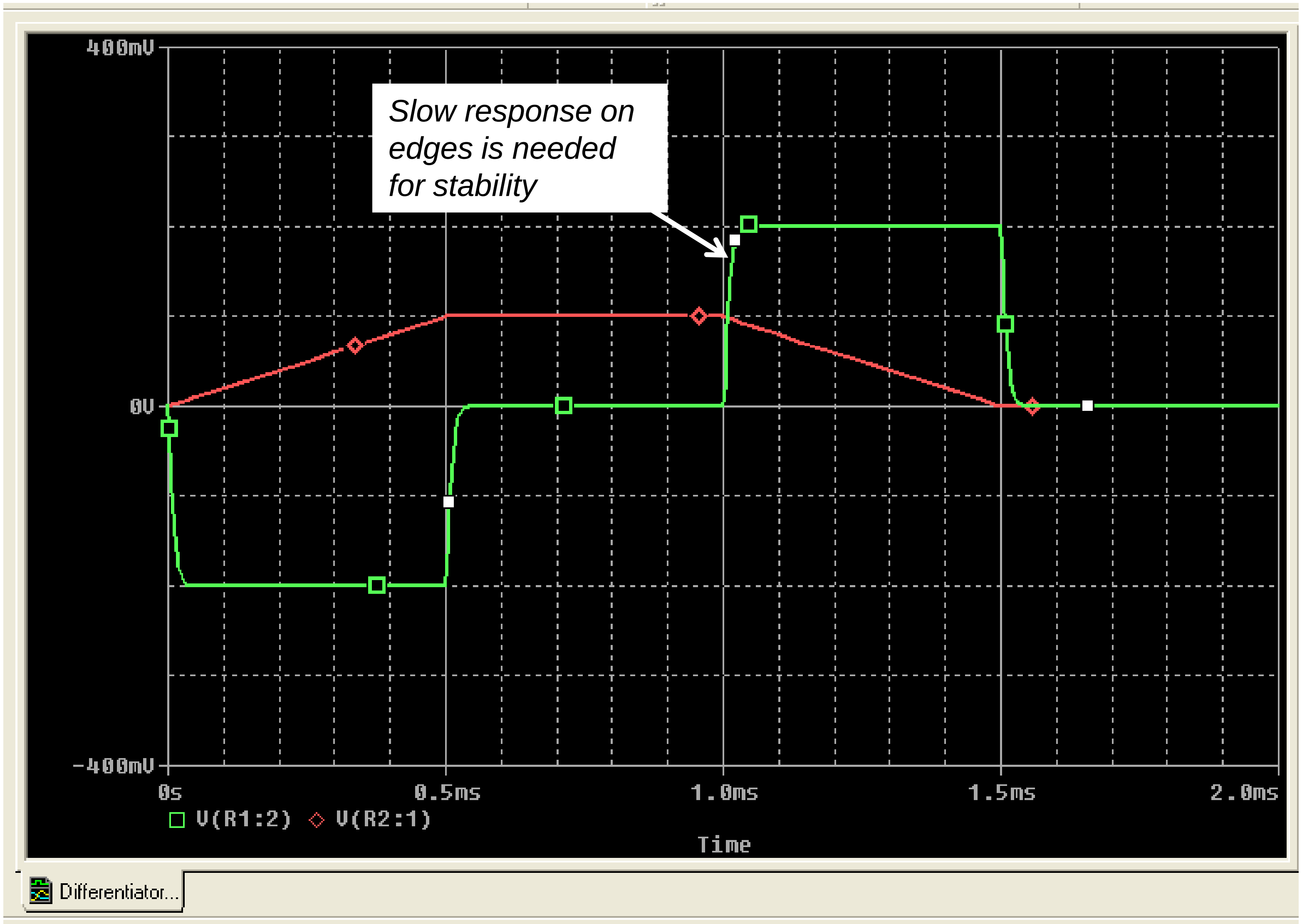
$$i_{\text{in}} = \frac{dQ}{dt} = C_2 \frac{dV_{\text{in}}}{dt}$$

$$V_{\text{out}} = -i_{\text{in}} R_1 = -R_1 C_2 \frac{dV_{\text{in}}}{dt}$$



For stability, it becomes an integrator at high frequency.

Differentiation Example



Stability Issues

- **Integrator:**
  - *voltage gain* ***falls*** *at 6 dB per octave as frequency increases.*
  - *inherently* **stable** *against oscillations even with an uncompensated op-amp.*
  - *the feedback itself looks like Miller-effect frequency compensation.*
- **Differentiator:**
  - *voltage gain* ***rises*** *at 6 dB per octave as frequency increases.*
  - *inherently* **unstable** *against oscillations.*
  - *the gain must be rolled off at high frequency by introducing an integration, or oscillation is guaranteed!*

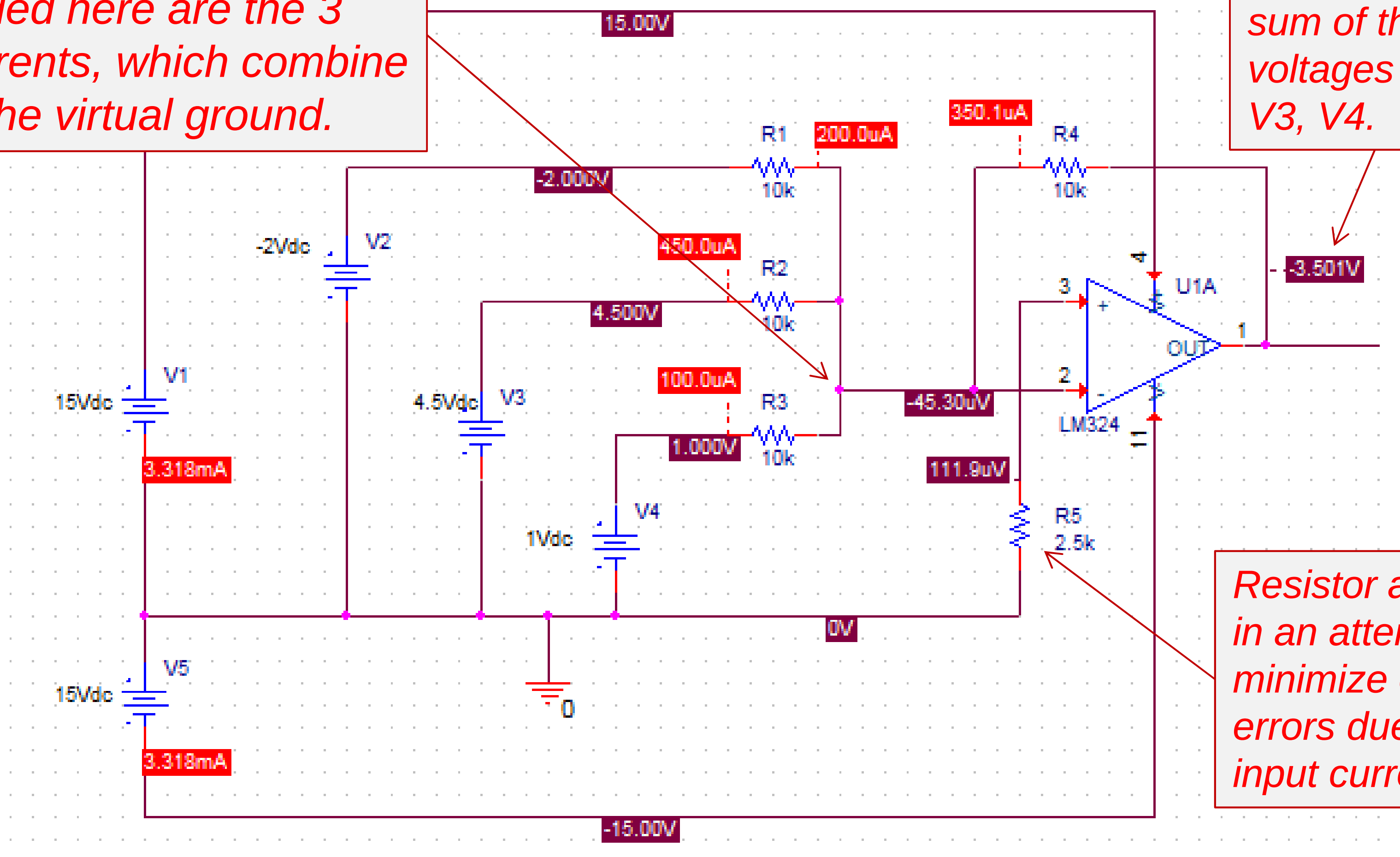
$$\text{Integrator: } G = -\frac{1}{j\omega RC}$$

$$\text{Differentiator: } G = -j\omega RC$$

Sum (or Subtraction) Amp

What are really being added here are the 3 currents, which combine at the virtual ground.

Inverse of the sum of the 3 voltages V2, V3, V4.

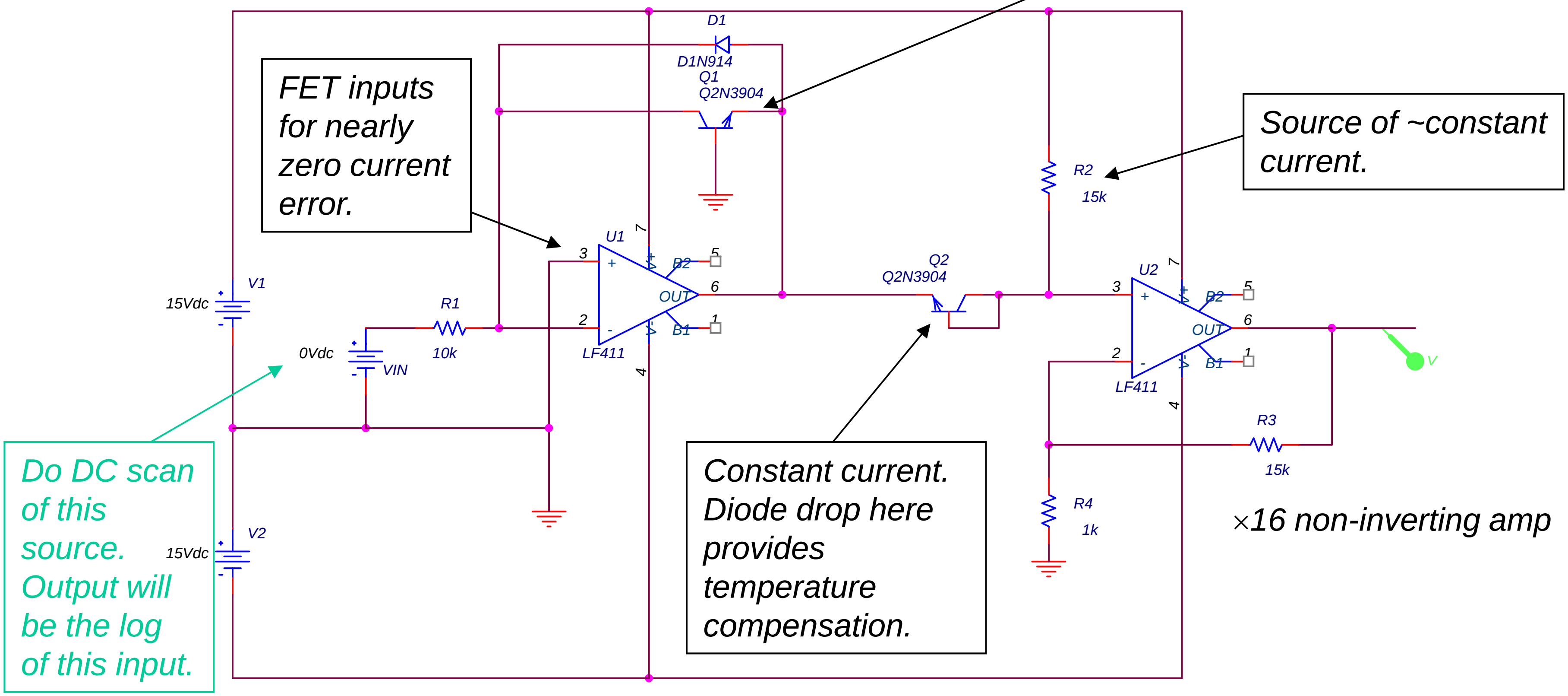


Resistor added in an attempt to minimize offset errors due to input current.

Log Amp

Diode is to protect against base-emitter breakdown in case input goes negative.

Emitter voltage is logarithm of collector current.



With a log amp you can do analog multiplication and division!

Ebers-Moll: $V_{BE} = V_T \cdot \log(I_C + I_S) - V_T \cdot \log I_S$ But $I_C >> I_S$

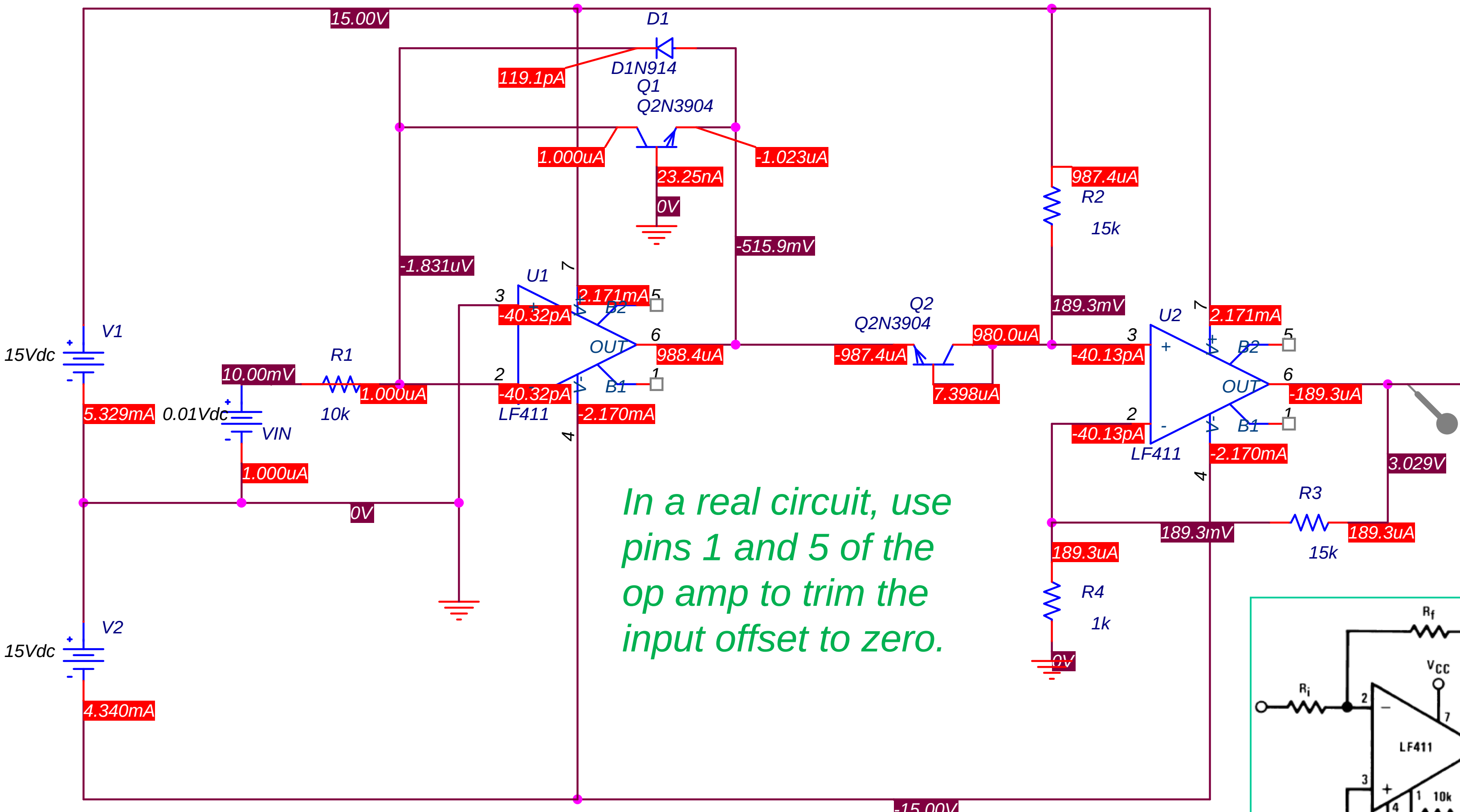
$I_C = V_{in} / R_1$

$$V_{out} = C + V_{BE} \cdot 16 \approx C - 0.96\text{ V} \times \log_{10}\left(I_C / I_S\right)$$

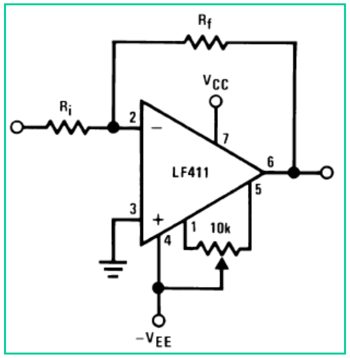
$0.026 \times 16 \times \ln(10) = 0.96$

Log Amp DC Bias Example

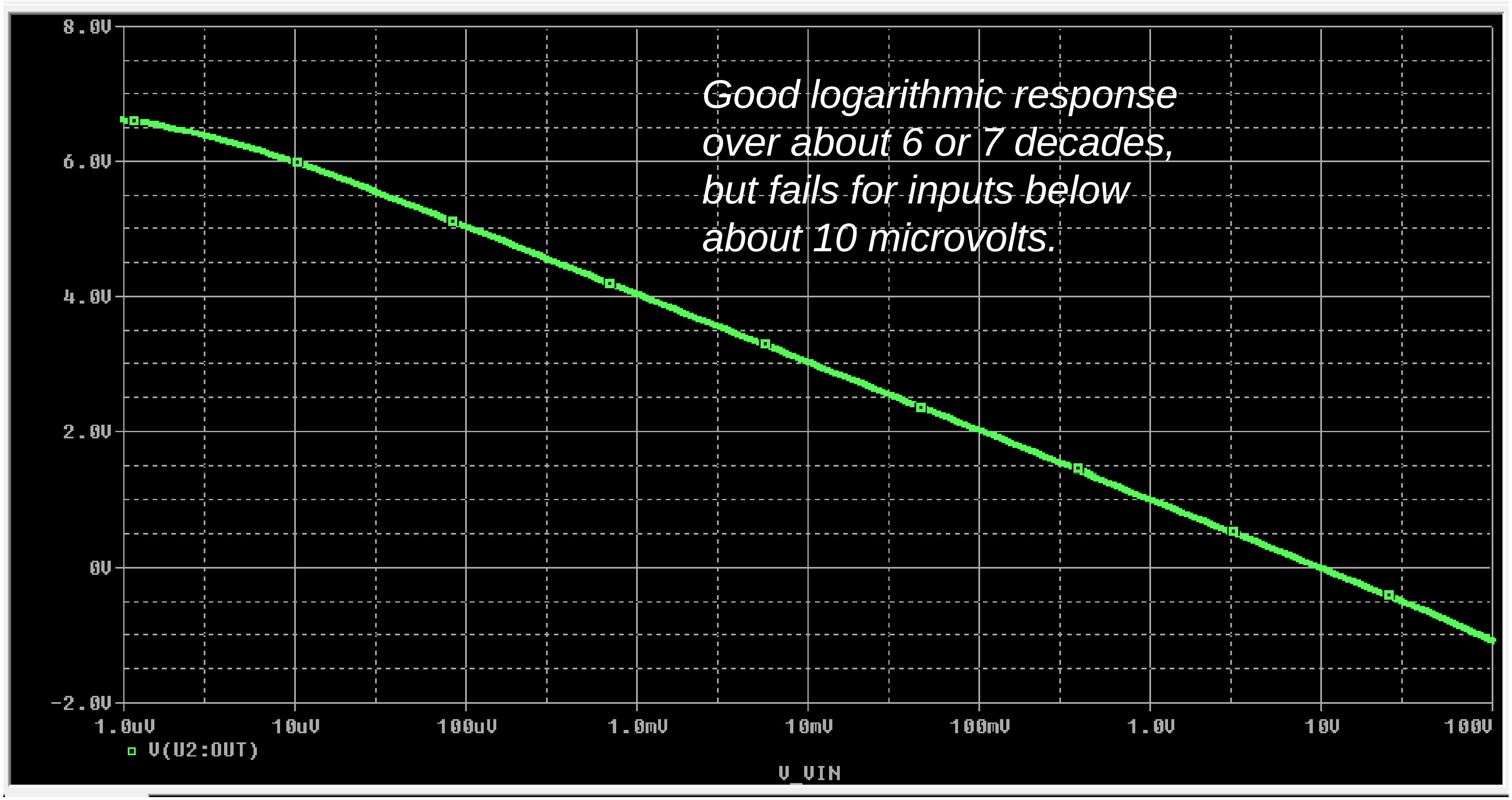
In a real circuit, put a capacitor in parallel with the diode, for stability.



In a real circuit, use pins 1 and 5 of the op amp to trim the input offset to zero.



Log Amp Simulation



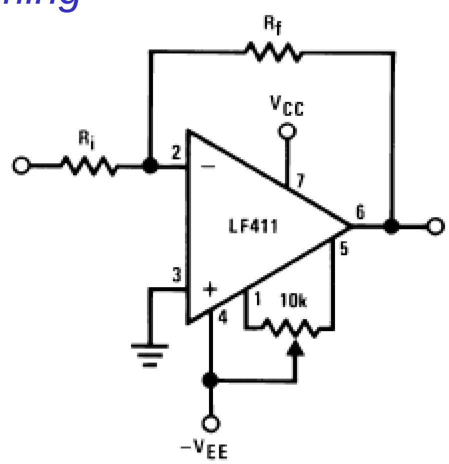
Behavior, Limitations of Real Op-amps

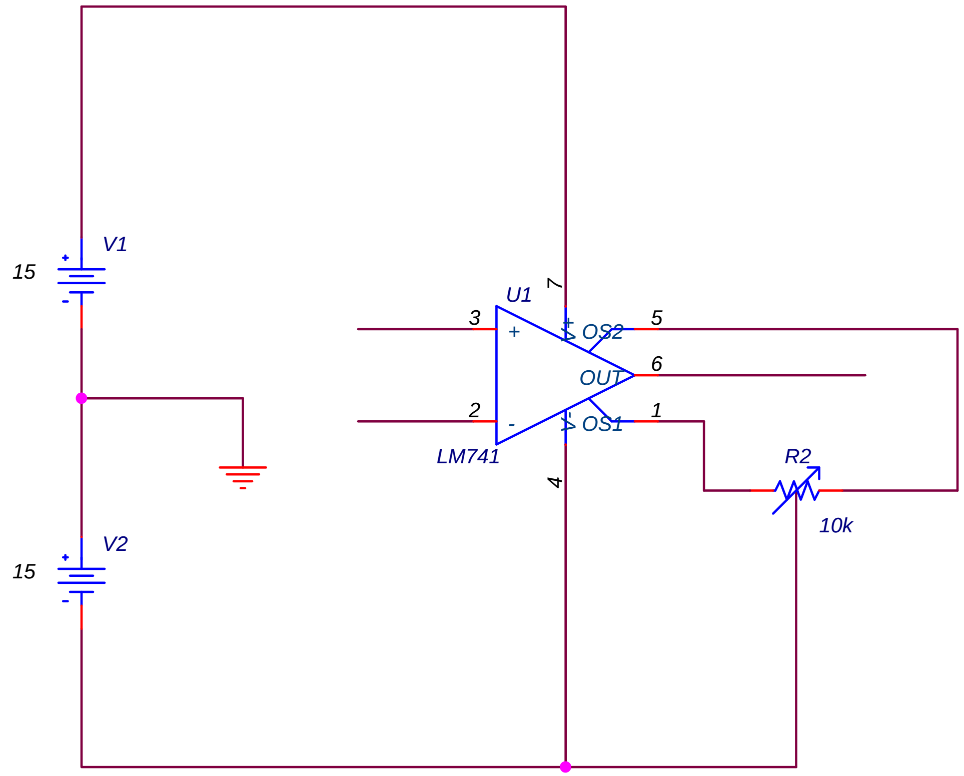
- *Input offset voltage*
- *Input current, and input-current mismatch*
  - *Design to minimize voltage offsets from this current*
  - *Input offset current*
- *Temperature dependences*
- *Slew rate*
  - *e.g. correcting crossover distortion*
- *Frequency range (gen. purpose op amps are not for high frequencies)*
- *Voltage gain and phase shift*
  - *Stability!*
- *CMRR and Common-mode input range*
- *Input impedance with negative feedback is extremely high*
- *Output impedance with negative feedback is very low*
  - *What is really relevant is the limitation on output current drive*
- *Output range (how close can the output get to the supply rails?)*
  - *Single-supply op amps; can the output slew all the way to zero?*

See the data sheet for the LF411 (posted on the course web page).

Offset Voltage and Input Current

- *Offset voltage*
  - *2 mV max. for the 411*
    - *This is the effective mismatch at the input. At the output it gets multiplied by the gain!*
  - *Trimming*



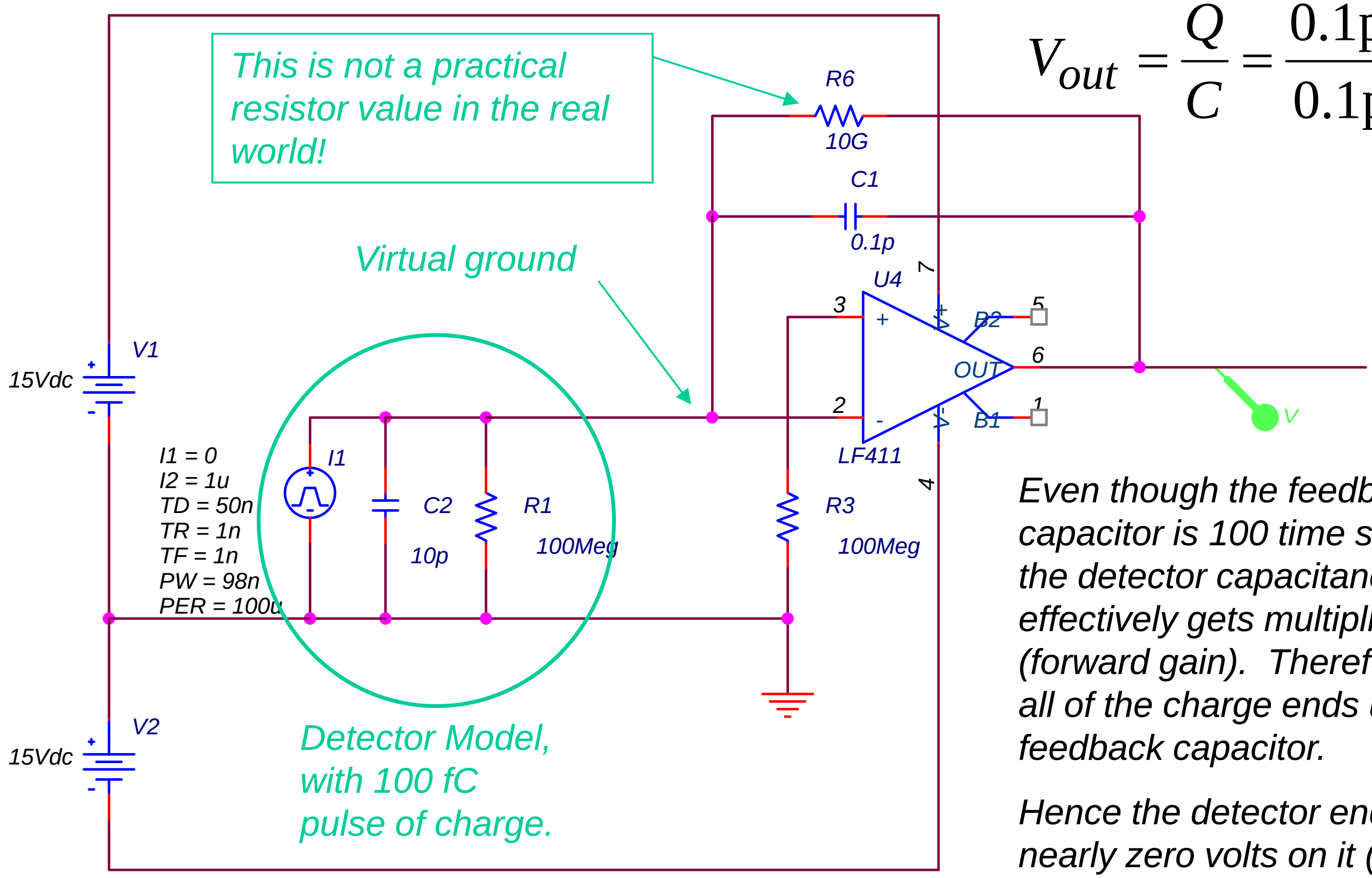


  - *Temperature and time drifts*
- *Input currents (esp. for BJTs)*
  - *Balancing resistors on inputs*
  - *Input offset current*
- *A/C Amp: reduce DC gain to unity to minimize offset effects*

Charge Sensitive Amp

- *Integrate the pulse of current from a detector to produce an output voltage proportional to the total charge.*

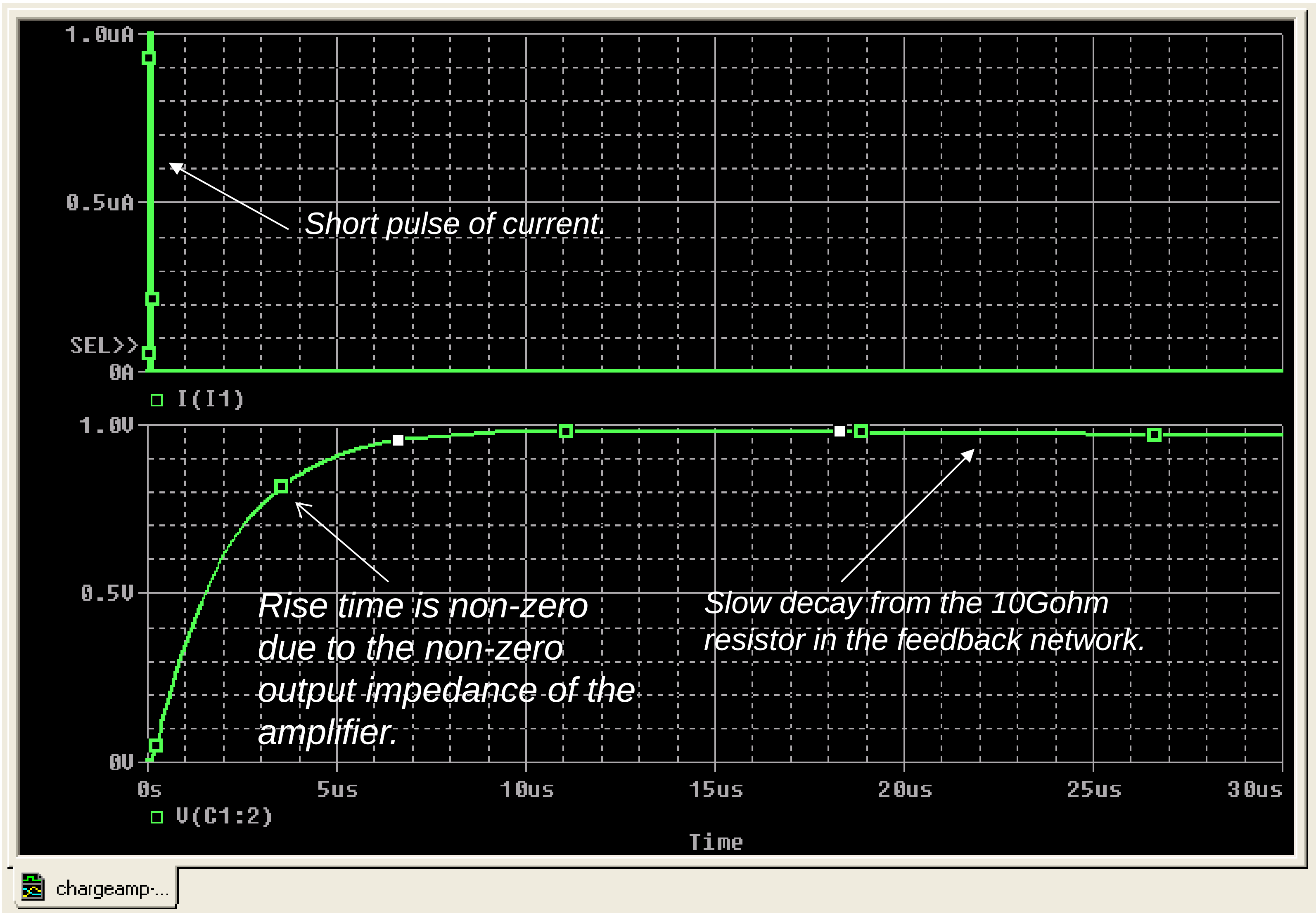
$$V_{out} = \frac{Q}{C} = \frac{0.1\text{pC}}{0.1\text{pF}} = 1\,\text{V}$$



Even though the feedback capacitor is 100 time smaller than the detector capacitance, it effectively gets multiplied by A (forward gain). Therefore, almost all of the charge ends up on the feedback capacitor.

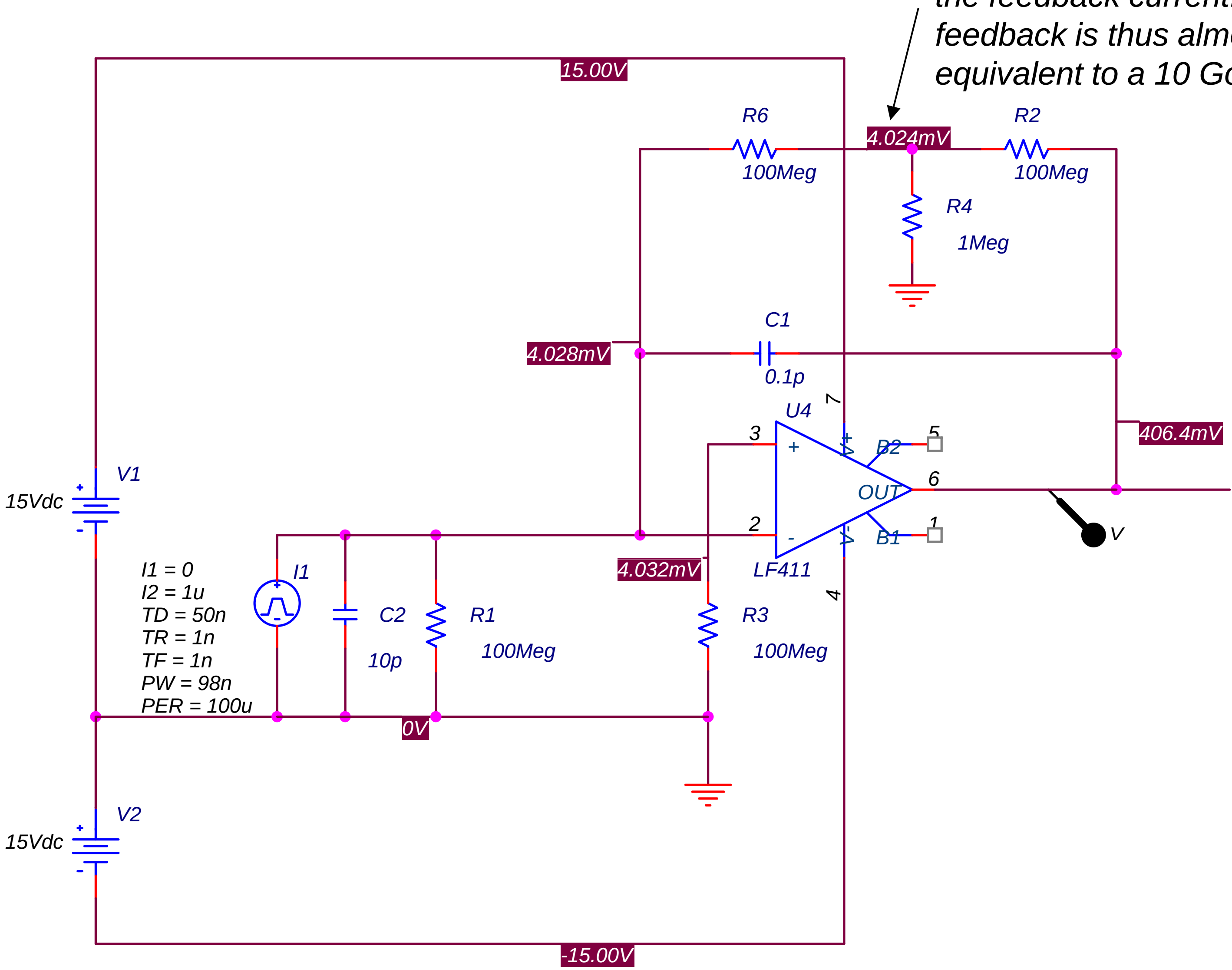
Hence the detector ends up with nearly zero volts on it (virtual ground).

Charge Amp Example



T Network

Voltage divider divides the output by 100, correspondingly reducing the feedback current. The DC feedback is thus almost equivalent to a 10 Gohm resistor.



Charge Amp with T Network