PARC HB

OPAMPS SIMPLIFIED (with LTSpice)

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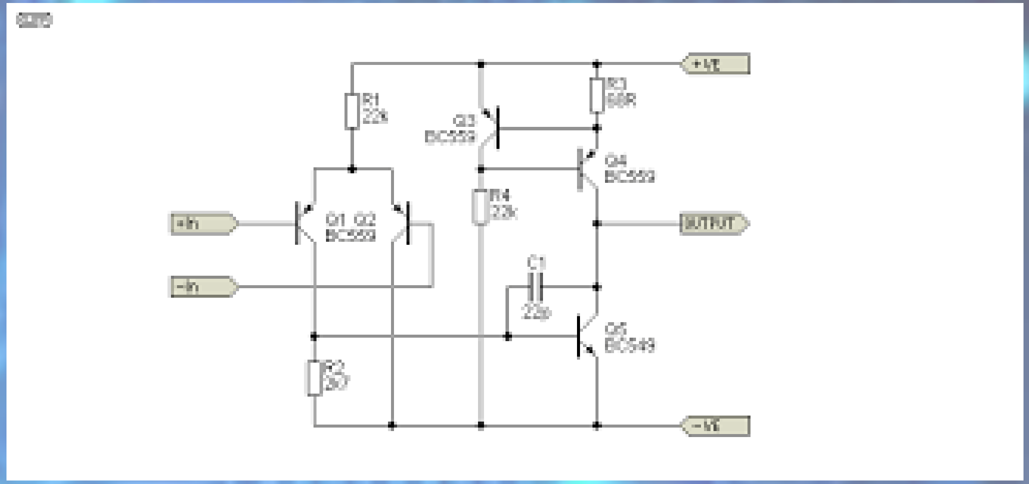
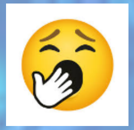
Feb 2021

FOLLOW AND LEARN

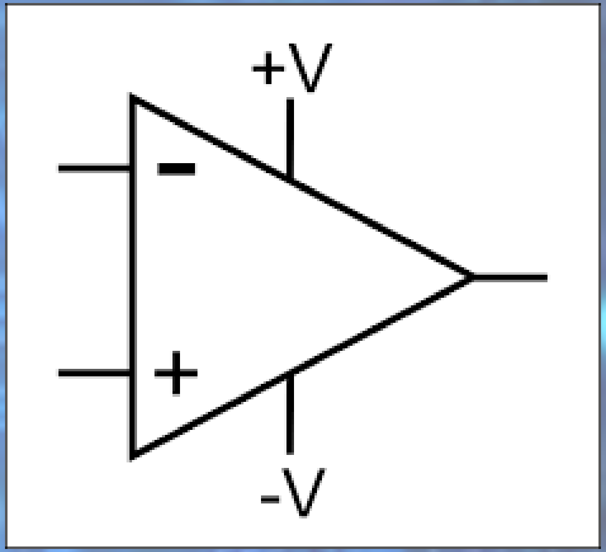
1. This is <u>not</u> a “traditional” tutorial
2. Its “Hands-On”, experimental approach.
3. Build experience using LTSpice
4. Present a “Principal” then clarify with experiment with LTSpice

FUNDEMANTALS





1. **Based on a bunch of transistors**
2. **Have 2 inputs + (non-inverting) and – (inverting)**
3. **Have Positive Supply (+V) and a Negative Supply (-V). Lets call this positive or negative voltage "rails"**
4. **Output is based on difference.**
   - **Output is 0 if difference between inputs is 0**
   - **Generally, output a voltage between voltage rails based on difference of inputs**



Principal 1: Input Offset Voltage

1. **If voltage at + input is greater than – input, output is set to Positive Rail**

2. **If voltage at - input is greater than + input, output is set to Negative Rail**

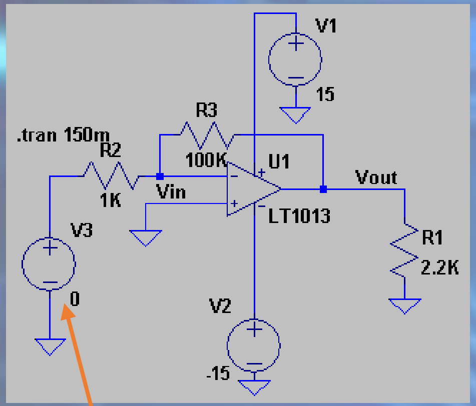
3. **Real opamp has input offset due to mismatched parts and tolerances.**
   - **0 voltage difference applied to both terminal does NOT produce 0 volts output**
   - **Typical offset between inputs to trigger output to hit Positive or Negative Rail**

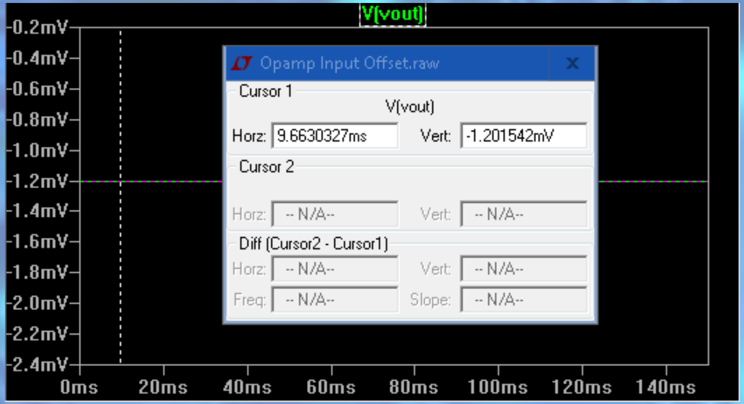
An ideal op-amp amplifies the differential input; if this input difference is 0 volts (i.e. both inputs are at the same voltage), the output should be zero. However, due to manufacturing process, the differential input transistors of real op-amps may not be exactly matched. This causes the output to be zero at a non-zero value of differential input, called the input offset voltage.

SYMBOL	PARAMETER	CONDITIONS	LT1013AM/AC LT1014AM/AC MIN	TYP	MAX	LT1013C/D/I/M LT1014C/D/I/M MIN	TYP	MAX	UNITS
V_{OS}	Input Offset Voltage	LT1013		40	150		60	300	μV
		LT1014		50	180		60	300	μV
		LT1013D/I, LT1014D/I					200	800	μV

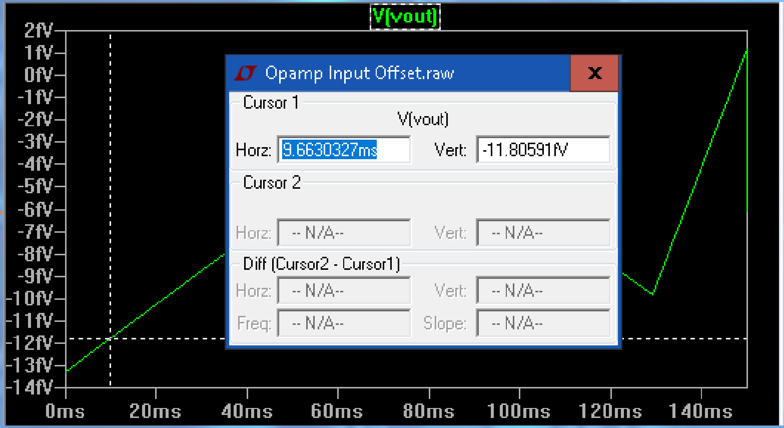
LT1013 is replacement of LM358

Experiment 1: Input Offset Voltage





Offset set to -12.0156µV



- **1.2mV at output. What input offset is needed?**
  - **For Gain = 100, input = 1.201542/100 mV = 12 uV**
- **An input offset of 12uV is needed to make output zero.**
- **This is a simulation. Data sheet says typically 40 – 150 uV and due to MANUFACTURING.**

SYMBOL	PARAMETER	CONDITIONS	LT1013AM/AC LT1014AM/AC MIN	TYP	MAX	LT1013C/D/I/M LT1014C/D/I/M MIN	TYP	MAX	UNITS
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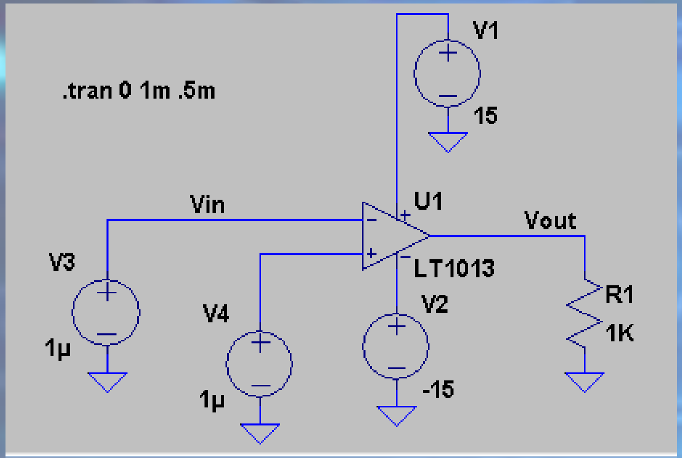
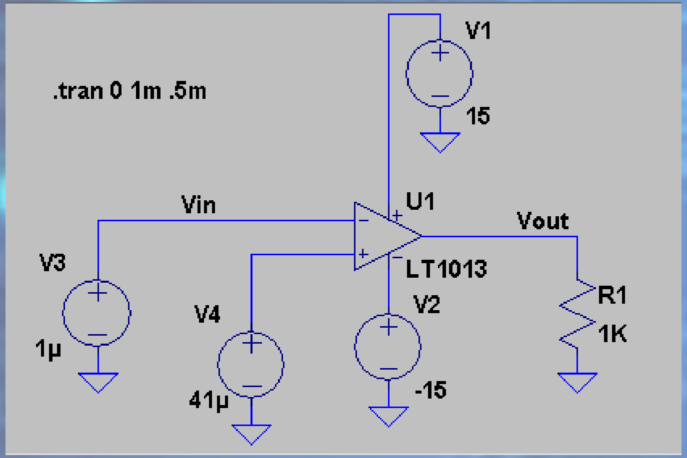
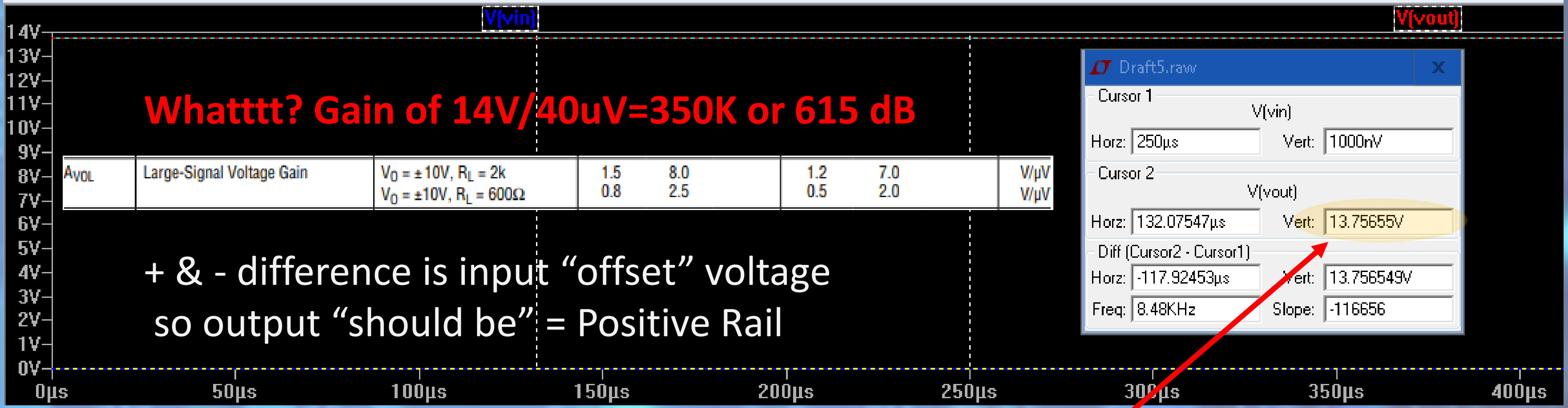
		LT1013D/I, LT1014D/I					200	800	µV

Experiment 2: Input "Offset" Voltage







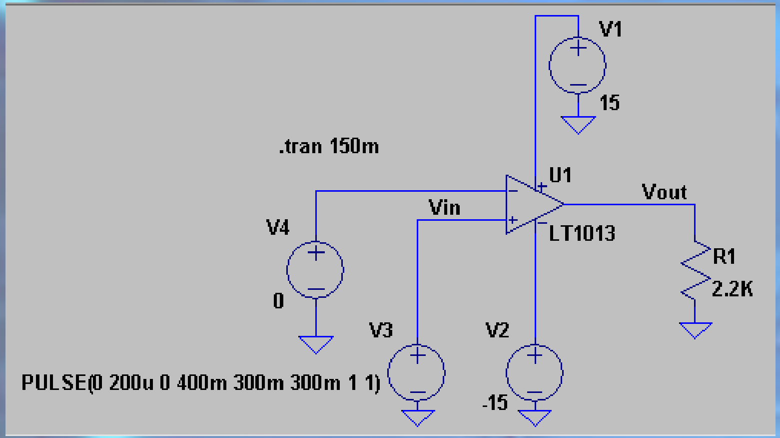
A_{VOL}	Large-Signal Voltage Gain	$V_O = \pm 10V, R_L = 2k$	1.5	8.0	1.2	7.0	V/µV
		$V_O = \pm 10V, R_L = 600\Omega$	0.8	2.5	0.5	2.0	V/µV

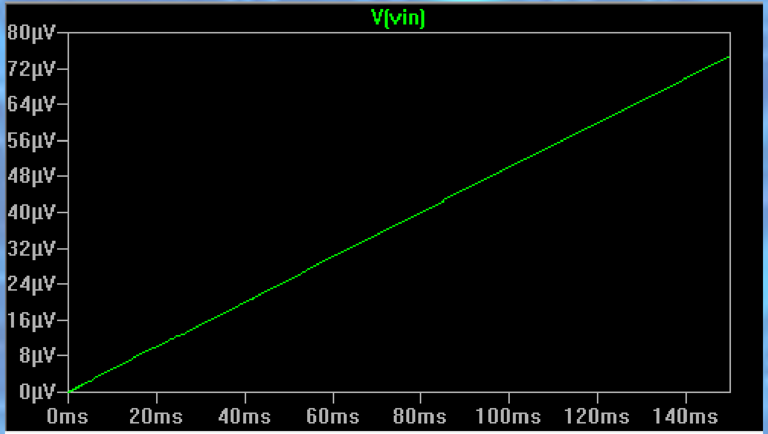
Huh?

HOMEWORK:

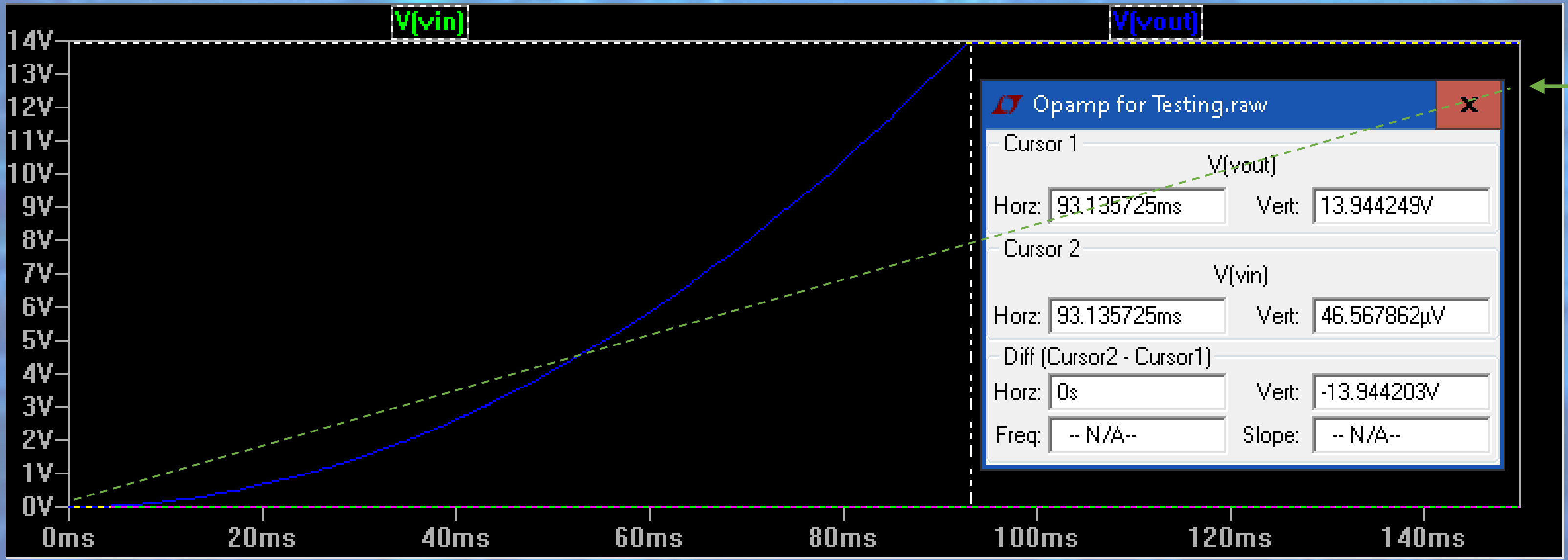
1. Vary the input. Is it linear between 0-40uV?
2. What happens if you ground the negative supply?

Experiment 3: Alternate View of "Offset"



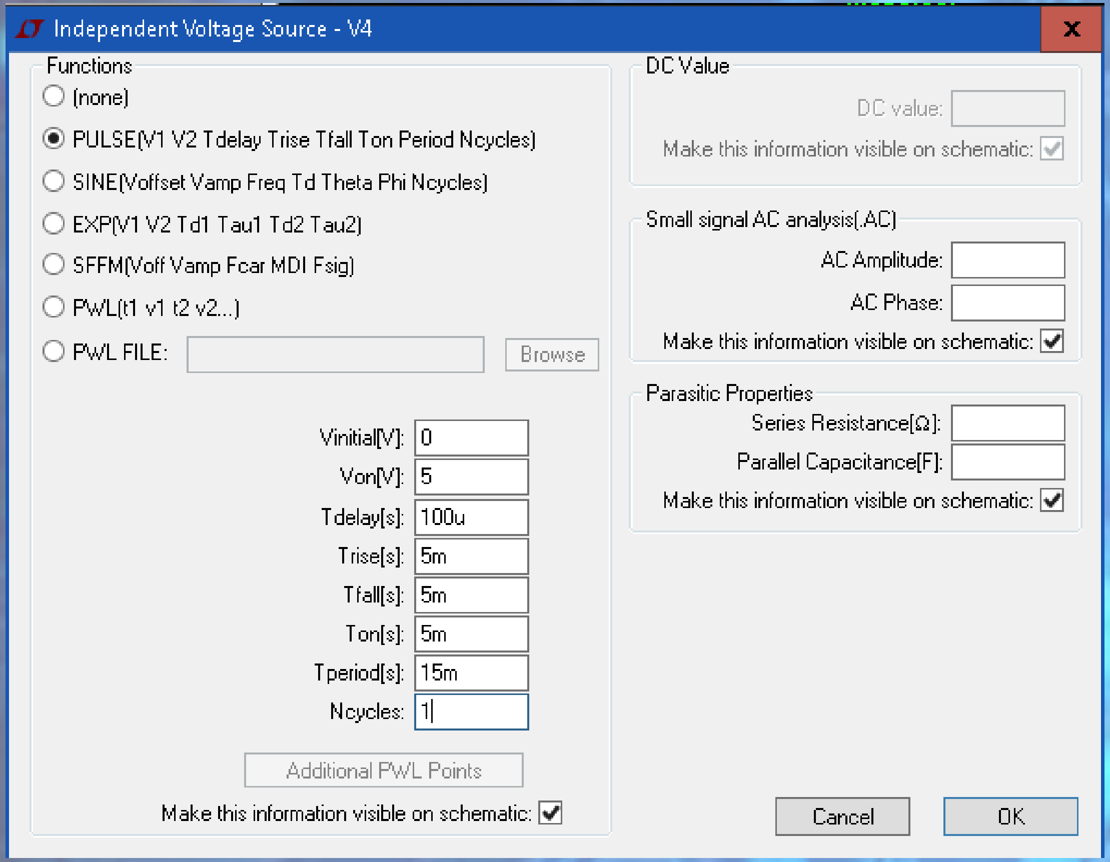


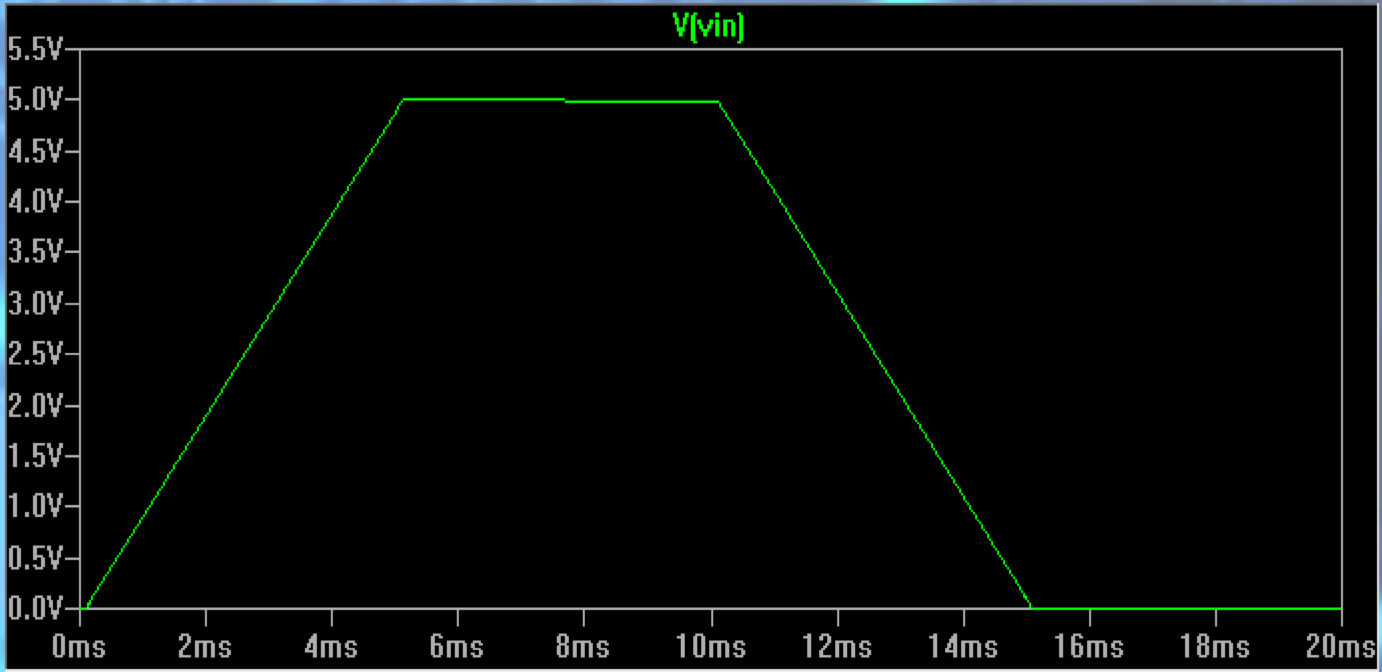
Opamp <u>DOES NOT</u> set output to positive or negative rail with a small offset. Huh?



CONDITIONS	LT1013AM/AC LT1014AM/AC MIN	TYP	MAX
LT1013		40	150
LT1014		50	180
LT1013D/I, LT1014D/I			

LTSPICE MINUTE: PULSE SOURCE





Rail to Rail

V_{OUT}	Output Voltage Swing	$R_L = 2k$	±13	±14	±12.5	±14	V

1. **Many opamps don't swing to the voltage rails. This reduces the useful limit of an opamp. BEWARE!!**

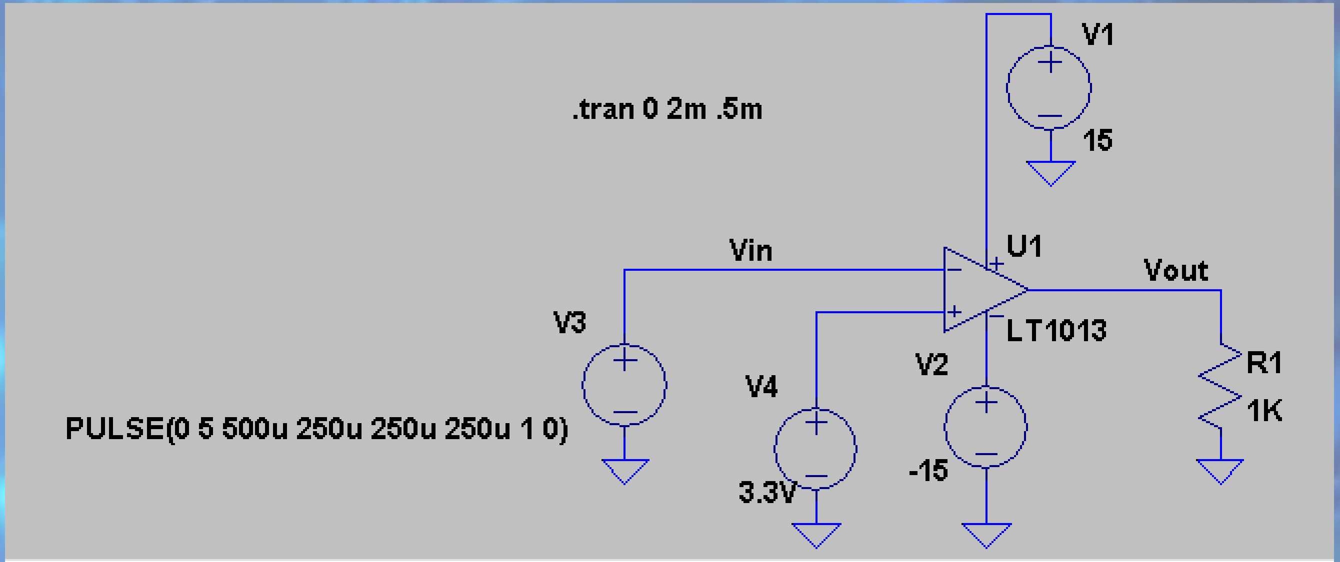
2. **Opamps that swing to both rails are called "rail-to-rail" opamps**

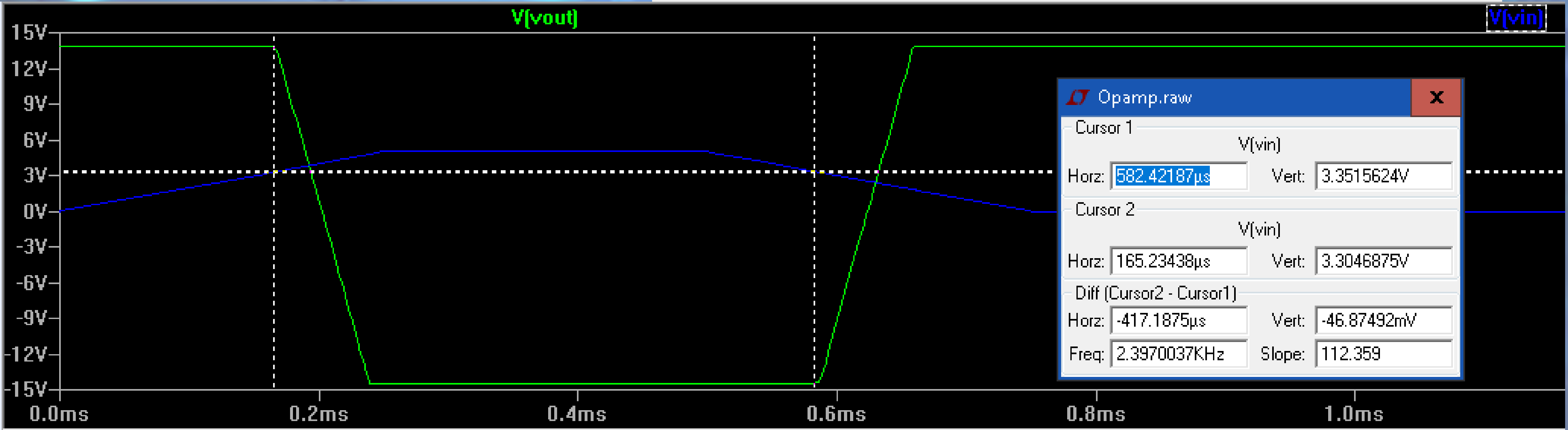
FINDING 1:

- **Opamps have a HUGE gain!**
- **Small input voltage can create output close to or equal to rail voltage**

Experiment 4: Comparator

Can be used to identify when a voltage is below, at or above a reference voltage



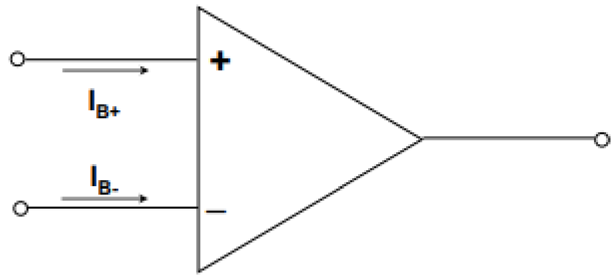


Principal 2: Input Bias Current

1. **Ideal Opamps have a infinite input impedance**

2. **Ideal Opamps should therefore have <u>NO</u> current should flow at inputs**

Ideally, no current flows into the input terminals of an op amp. In practice, there are always two *input bias currents*, I_{B+} and I_{B-} (see Figure 1).

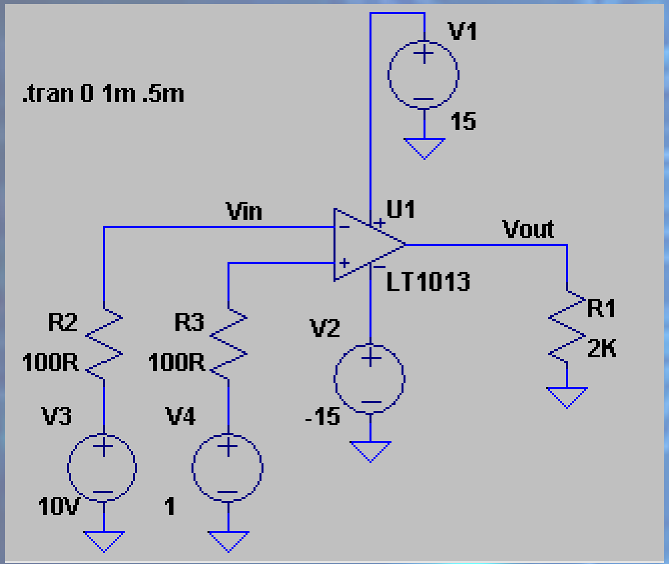


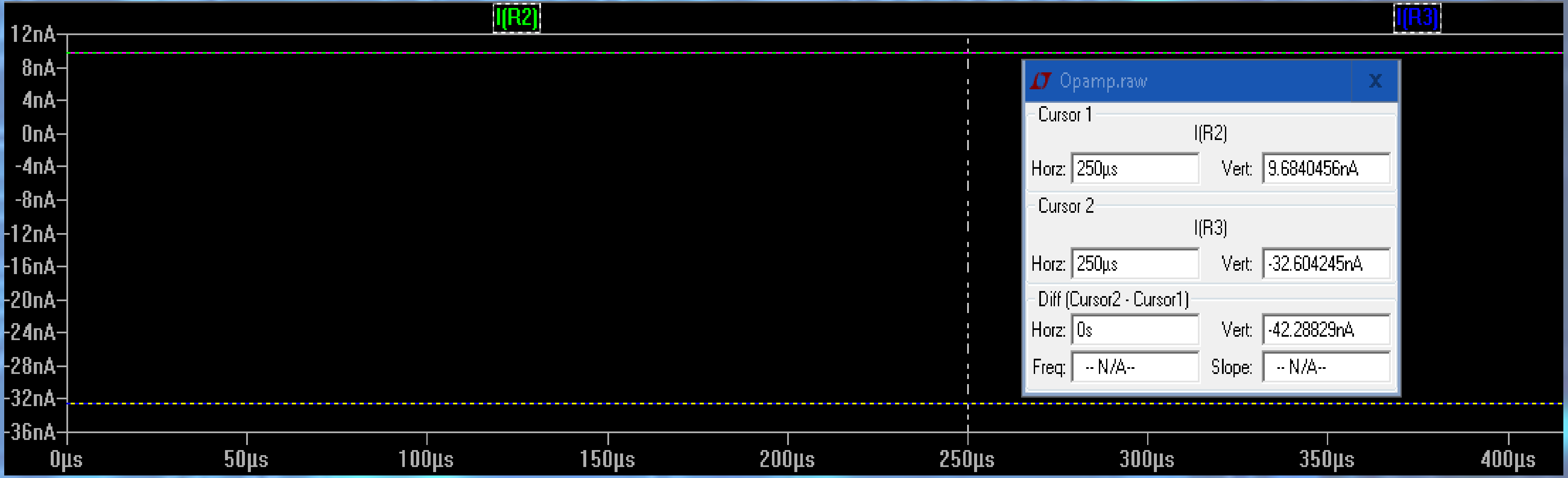
I_B	Input Bias Current			12	20		15	30	nA
	Input Resistance – Differential Common Mode	(Note 2)	100	400 5		70	300 4		MΩ GΩ

- Differential Mode: Input voltages relative to each other. Voltage different at terminals
- Common Mode: Input voltages relative to ground. Same voltage at inputs

Note 2: This parameter is guaranteed by design and is not tested.

Experiment 5: Input Bias Current



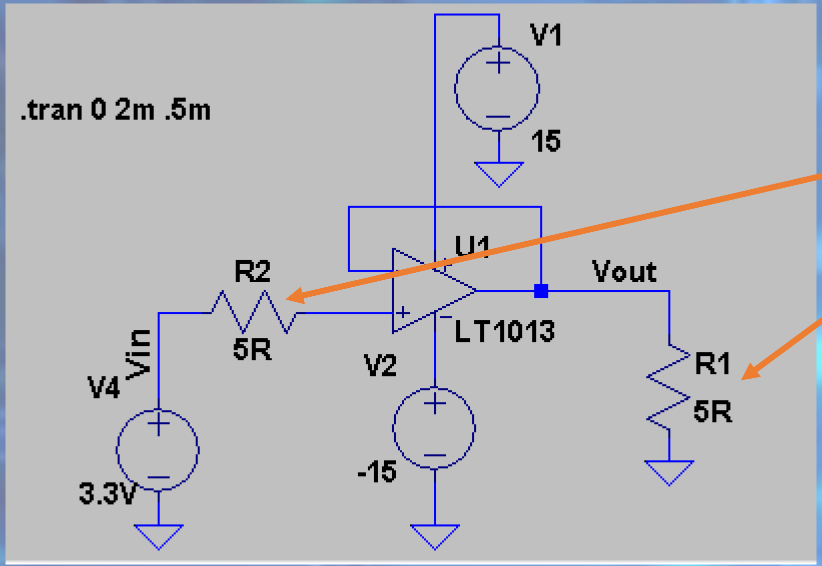


I_B	Input Bias Current		12	20	15	30	nA

FINDING 2:

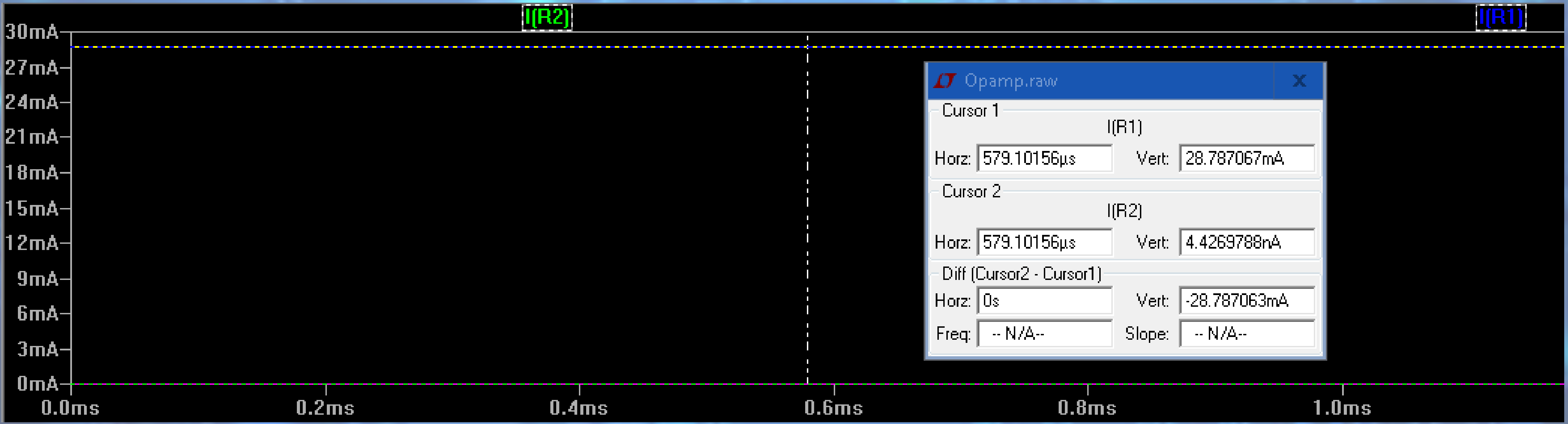
- Opamps consume negligible amount of current at input – this makes math EASY!!

Experiment 6: Output Current



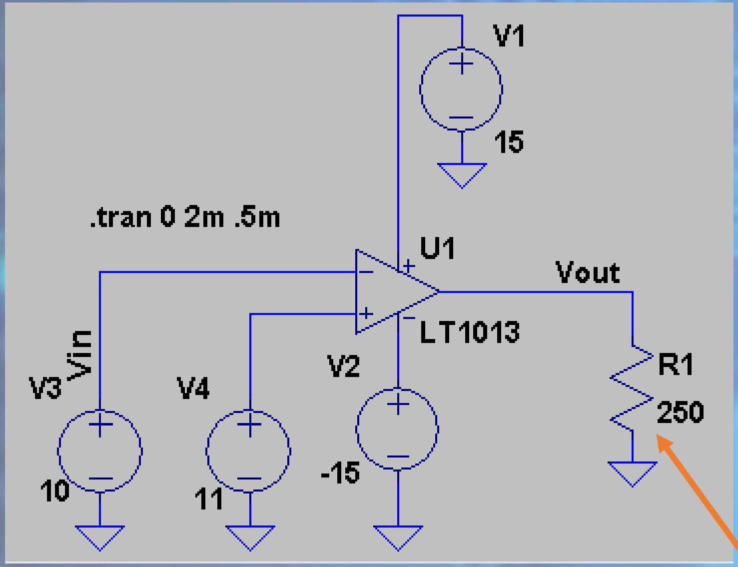
Use 2 current sensing resistors to measure input and output current.

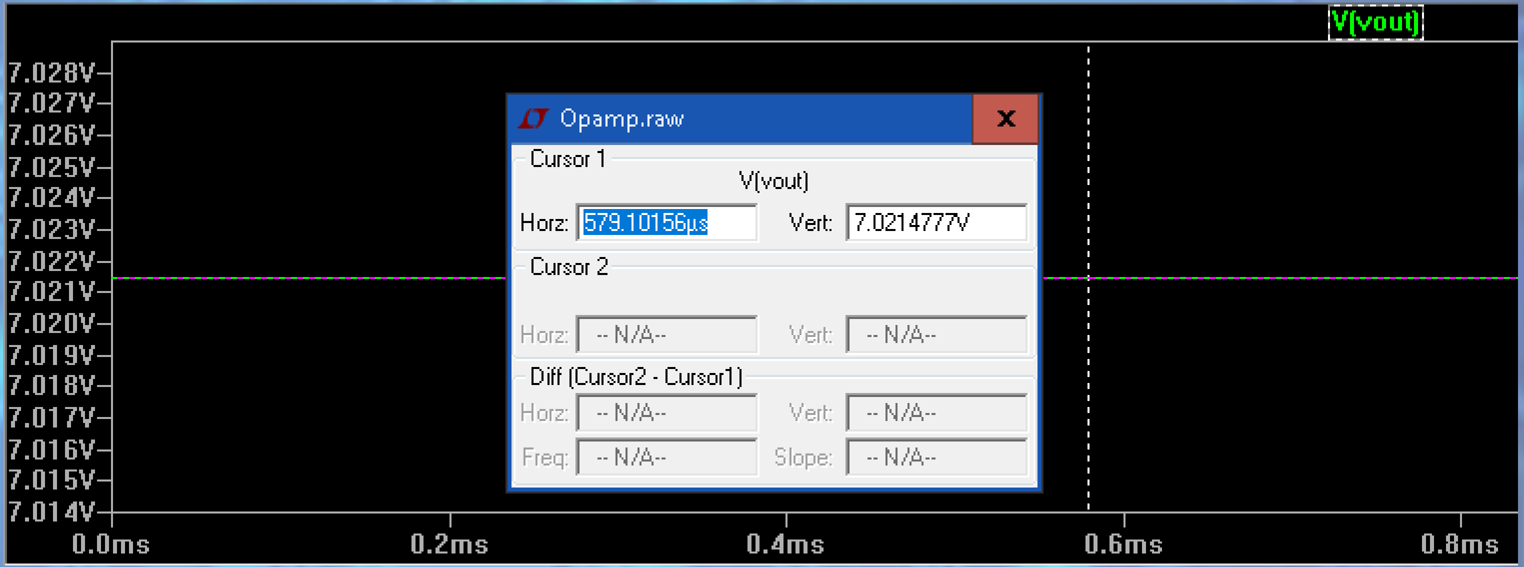
FINDING 4: Opamps can have huge current gain!



Experiment 7: Output Impedance

The overall op amp circuit output impedance is normally low and usually purely resistive. However aspects like the drive capability of the op amp need to be carefully considered as most chips have a very limited capability as they are not expected to drive large loads. Where large loads and high currents are needed, additional components can be added to provide the additional capability, or high power op amp chips can be used.



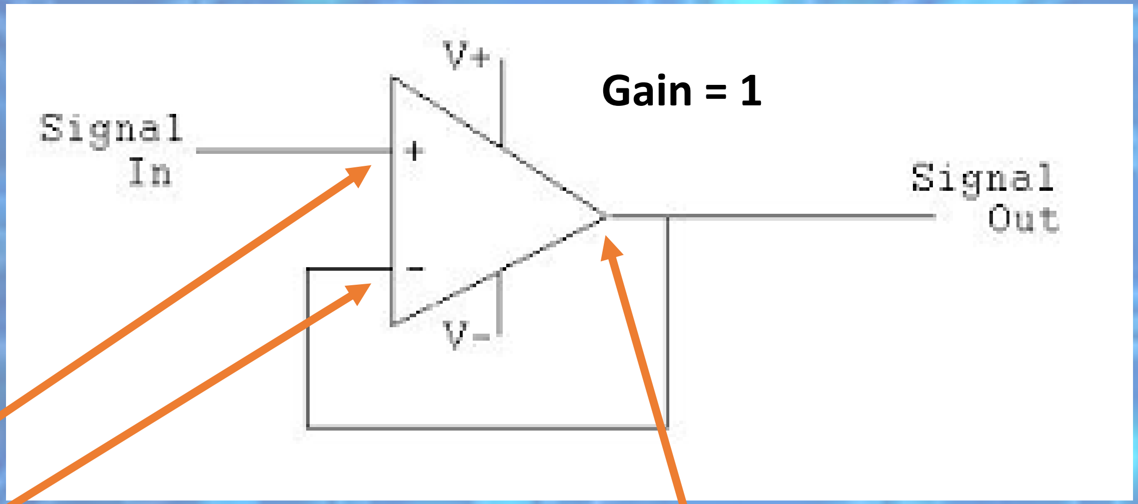


Change load resistor until you get ½ of maximum output (Rail voltage ~ 14V)

Principal 2: Negative Feedback

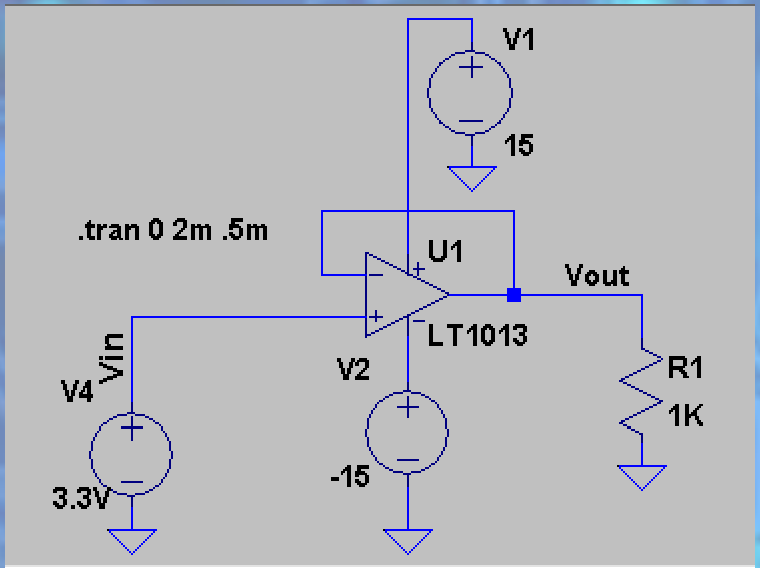
1. **Can use negative feedback to control the gain.**

2. **With feedback, the opamp alters output so that input offset is between (+) and (-) input are the same**



If (+) > (-), output raises to positive rail. Once output is within "Input Offset Voltage" of (+), then output = (+)

Experiment 8: DC Voltage Follower or Buffer



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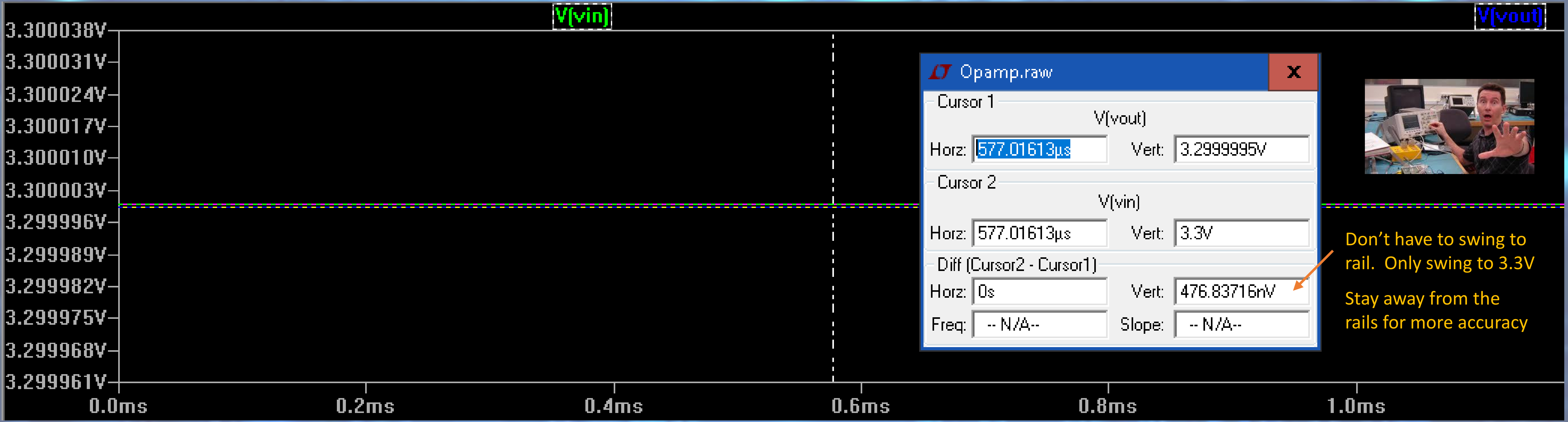
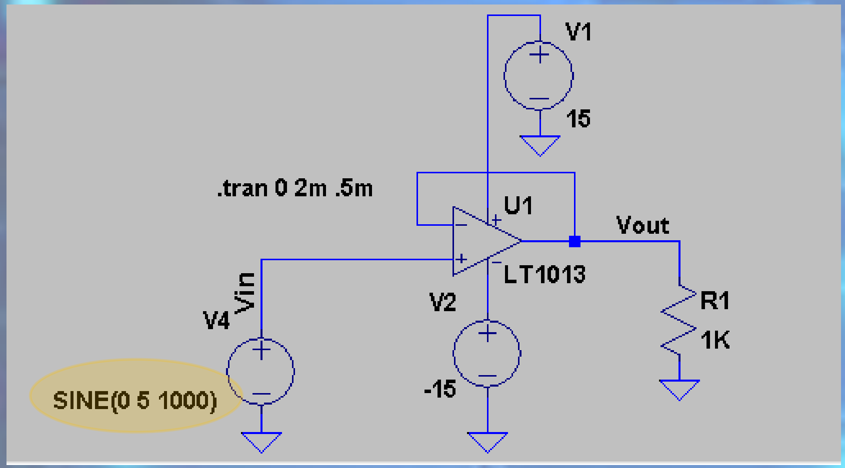
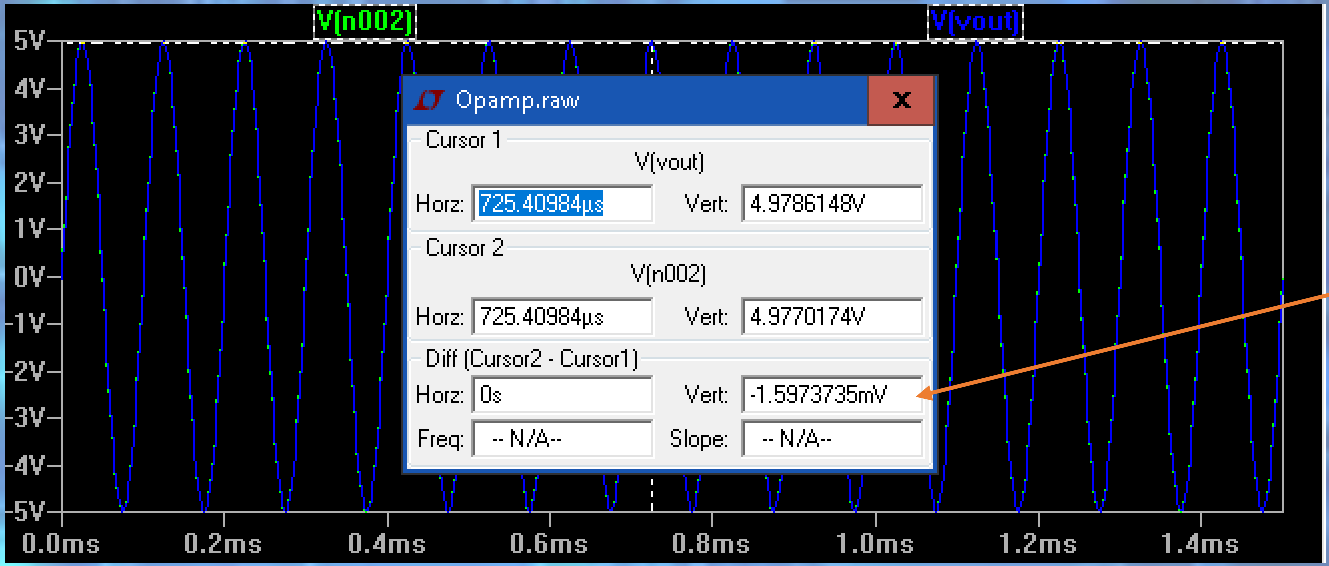


Don't have to swing to rail. Only swing to 3.3V

Stay away from the rails for more accuracy

Experiment 9: AC Voltage Follower or Buffer



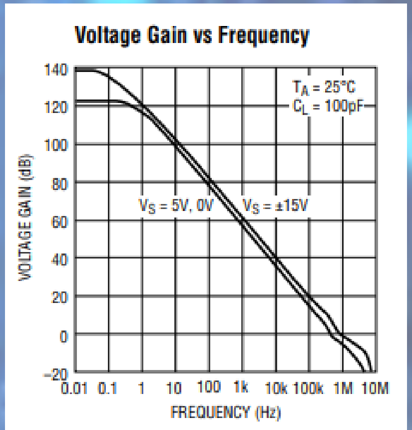


Don't have to swing to rail. Only swing to 5V

Difference larger for 5V than 3.3V. Slew Rate?

HOMEWORK:

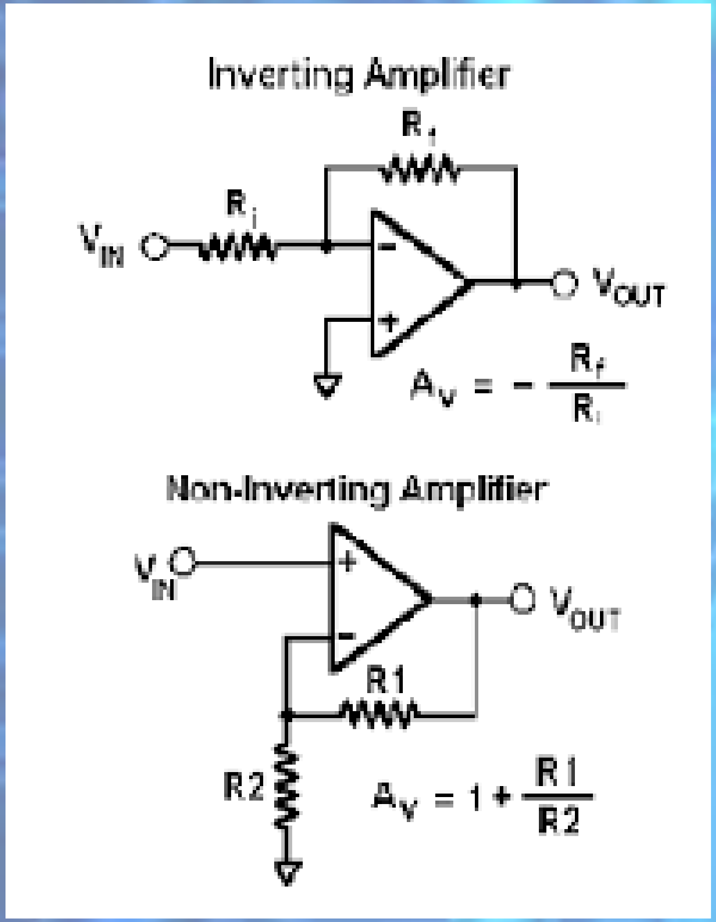
1. Create a voltage follower with a low frequency AC
2. Increase frequency and what happens to output when frequency is above 20 KHz?



$$\text{Slew rate} = 2\pi f V$$

Principal 3: Gain and Negative Feedback

1. **Feedback can be used to create gain for an inverting configuration or a non inverting configuration**

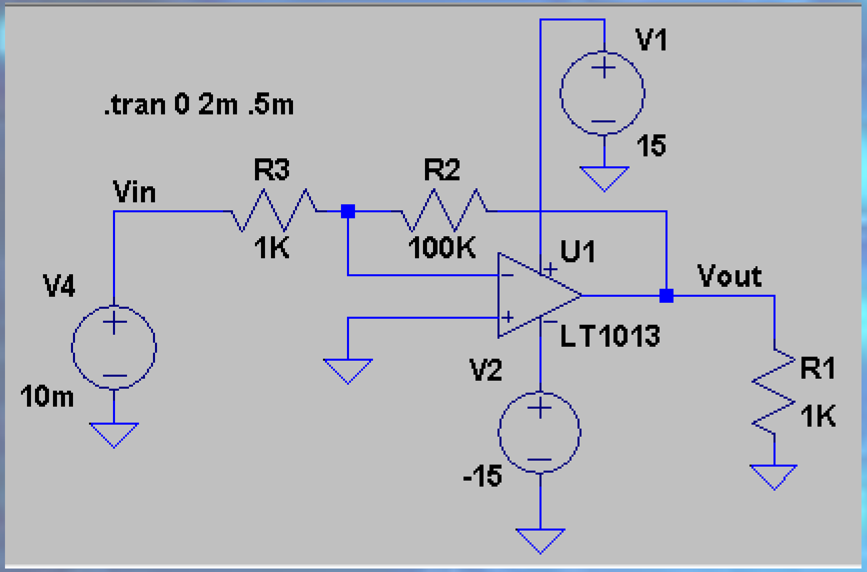


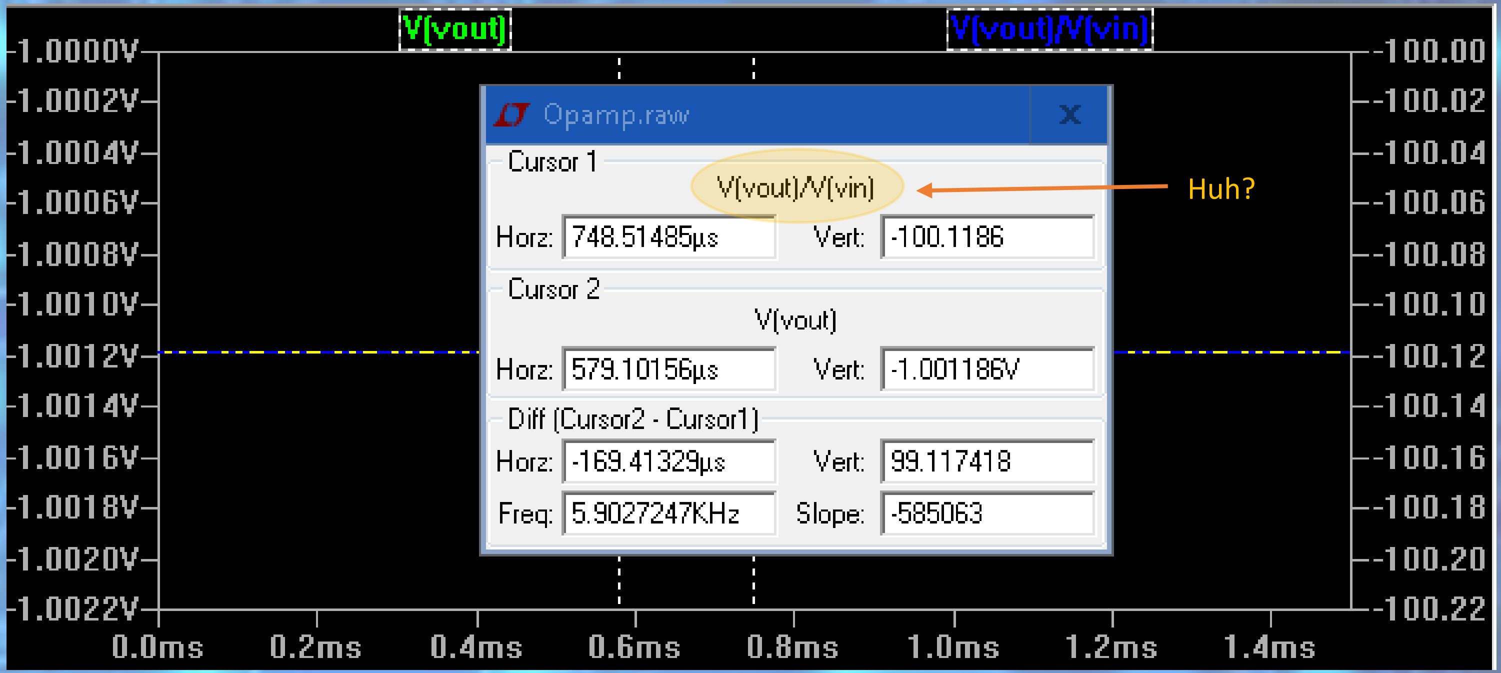
With feedback, the opamp alters output so that input offset is between (+) and (-) input are the same

Use a <u>voltage divider</u> to feedback a fraction of the output voltage

Cavet emptor: Opamp may have low noise. Resistors add noise (thermal). Choose them wisely

Experiment 10: Inverting Amplifier



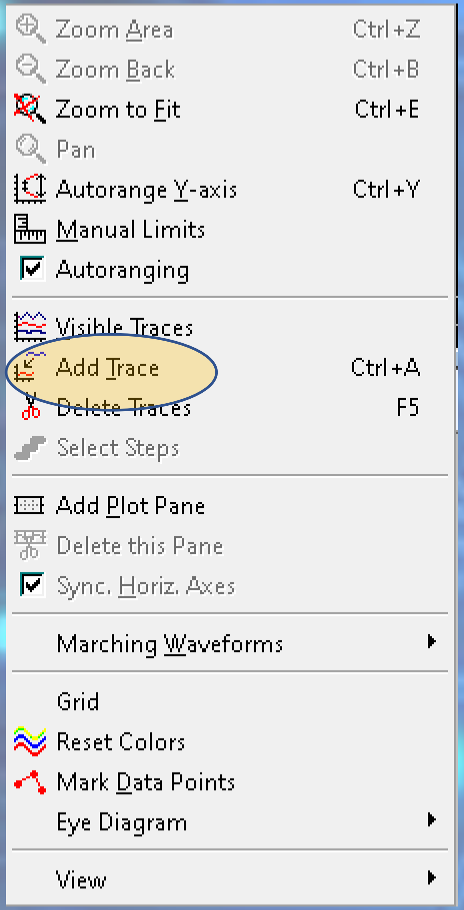


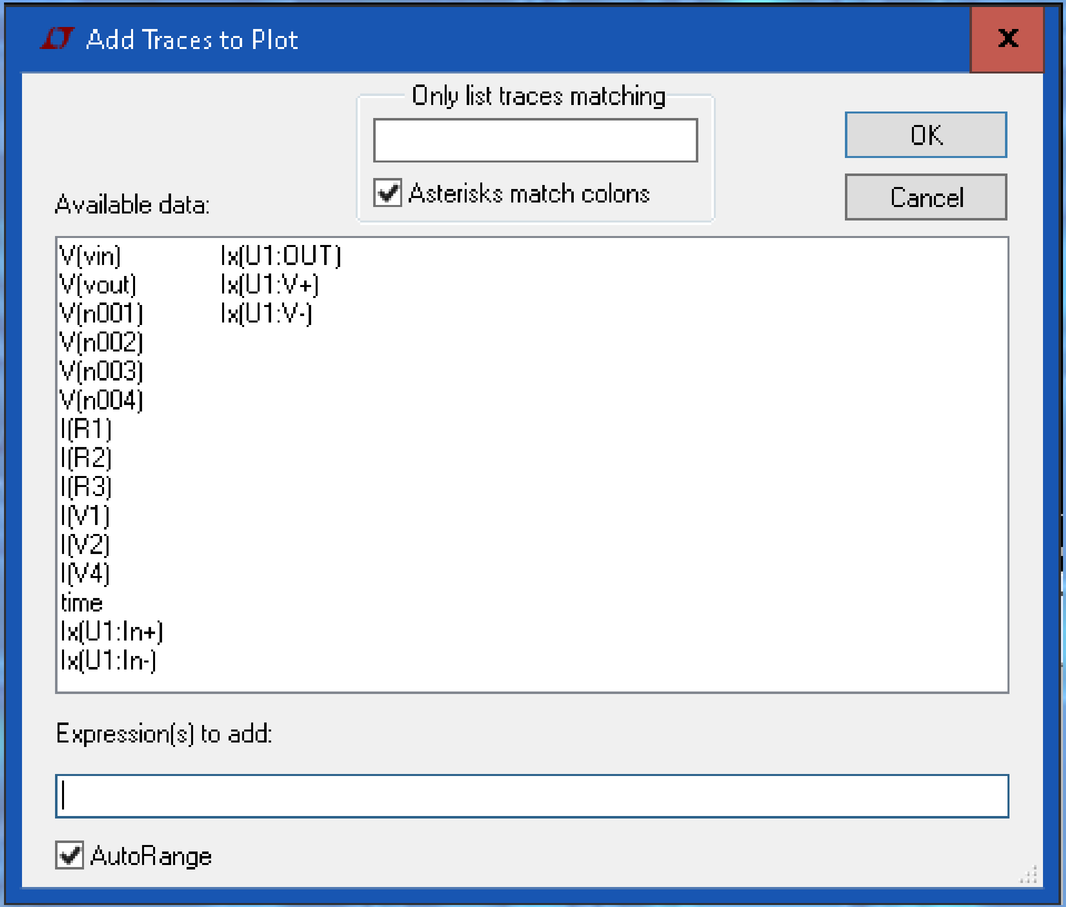
- Inverting Gain = -R2/R1 = -100K/1K = 100
- For 10mV input, output should be -10mVx100 = -1V

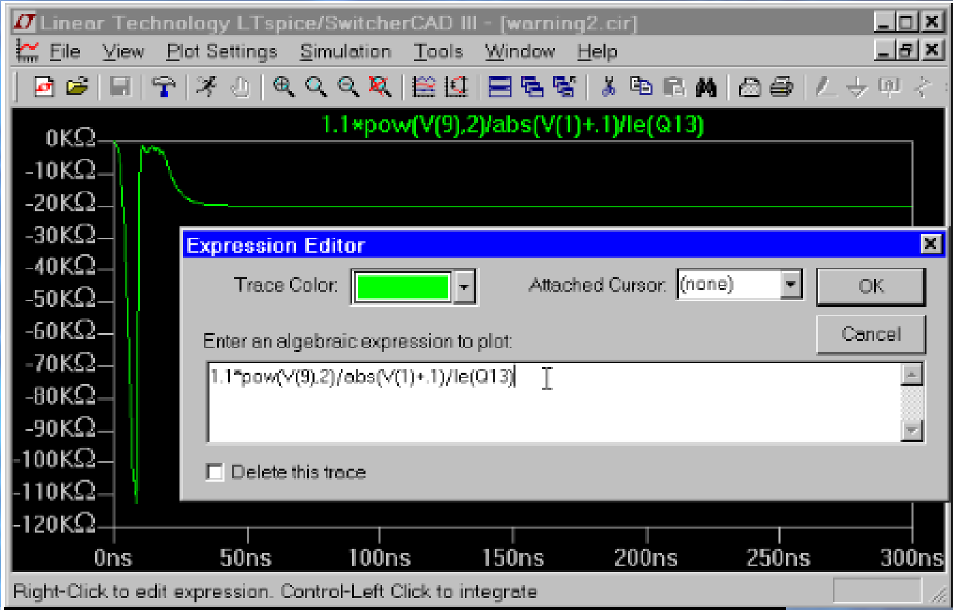
HOMEWORK:

1. Change input voltage. At what point does the voltage clip (i.e., hit the negative rail)
2. Change R2 and R3. What is the max gain you can get.
3. Introduce a small AC signal and see if gain is the same as DC gain

LTSPICE MINUTE: TRACE CALCULATION



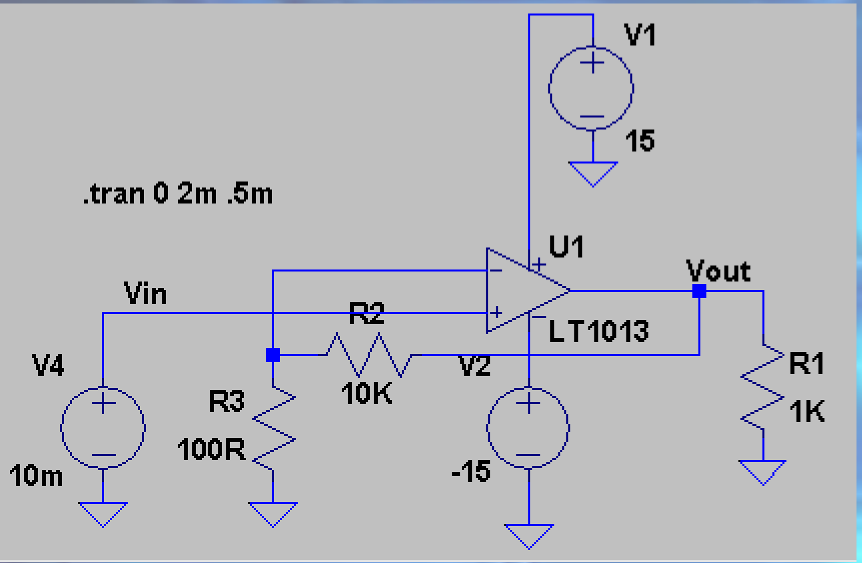


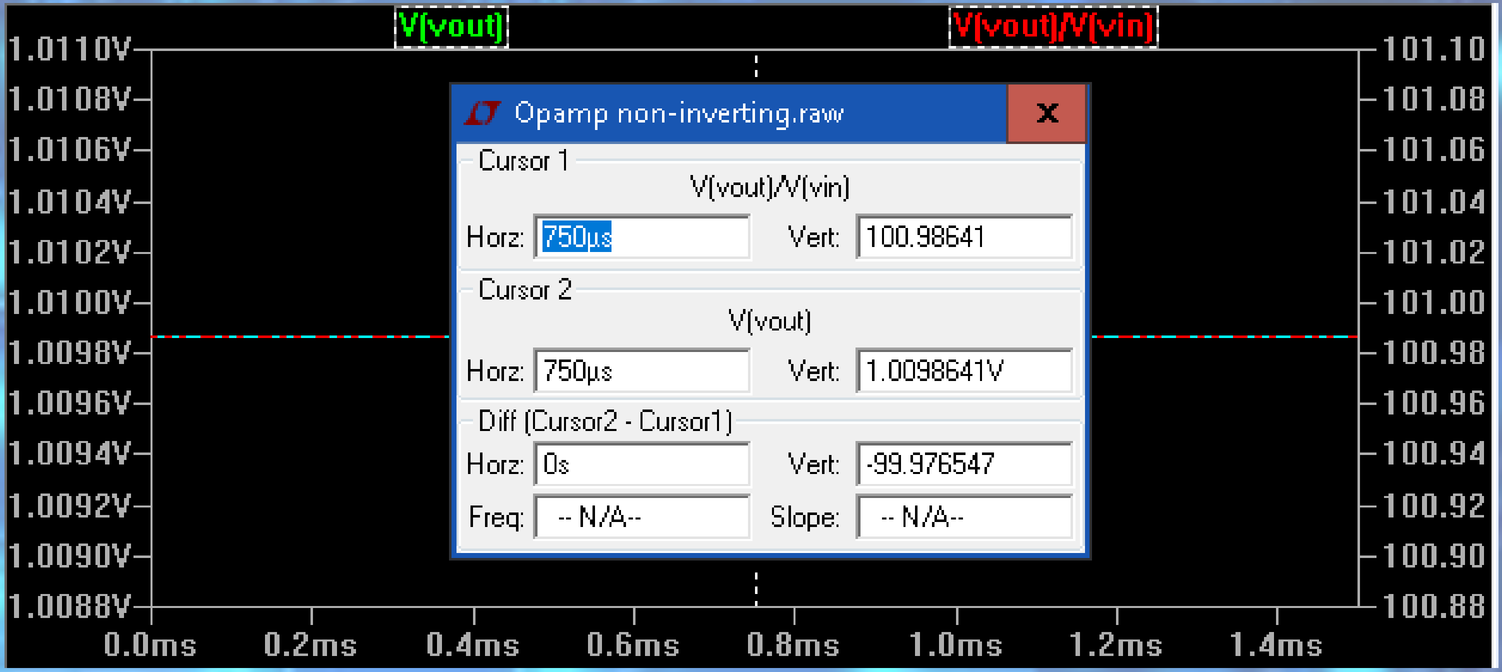


Operand	Description
&	Convert the expressions to either side to Boolean, then AND.
|	Convert the expressions to either side to Boolean, then OR.
^	Convert the expressions to either side to Boolean, then XOR.
>	TRUE if expression on the left is greater than the expression on the right, otherwise FALSE.

Function Name	Description
abs(x)	Absolute value of x
acos(x)	Arc cosine of x
arccos(x)	Synonym for acos()
acosh(x)	Arc hyperbolic cosine
asin(x)	Arc sine
arcsin(x)	Synonym for sin()
asinh(x)	Arc hyperbolic sine
atan(x)	Arc tangent of x

Experiment 11: Non-Inverting Amplifier





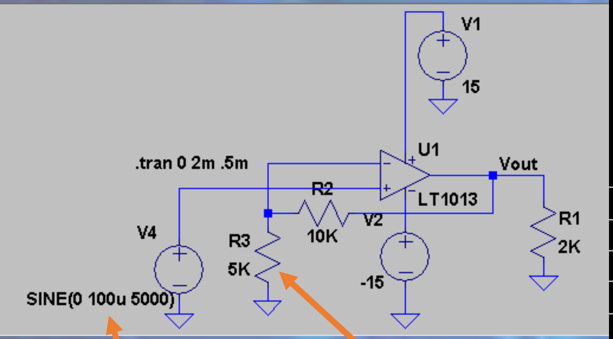
- Non-Inverting Gain = 1+ R2/R1 = 1+ 10K/100 = 101
- For 10mV input, output should be 10mx101 = +1.01V

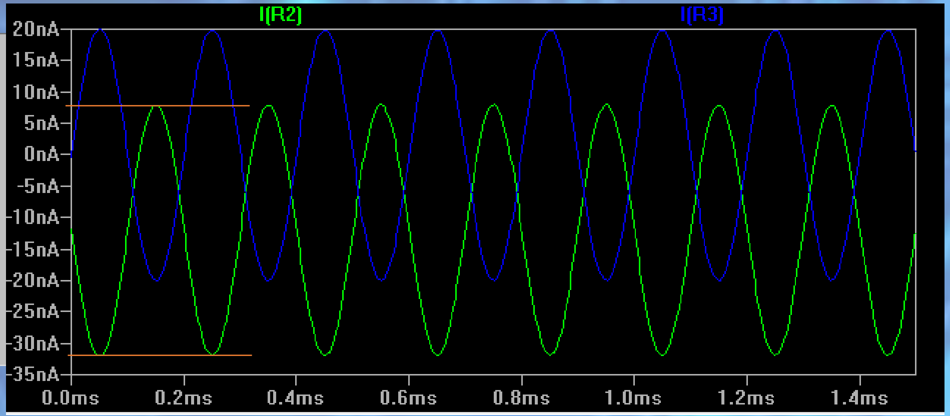
HOMEWORK:

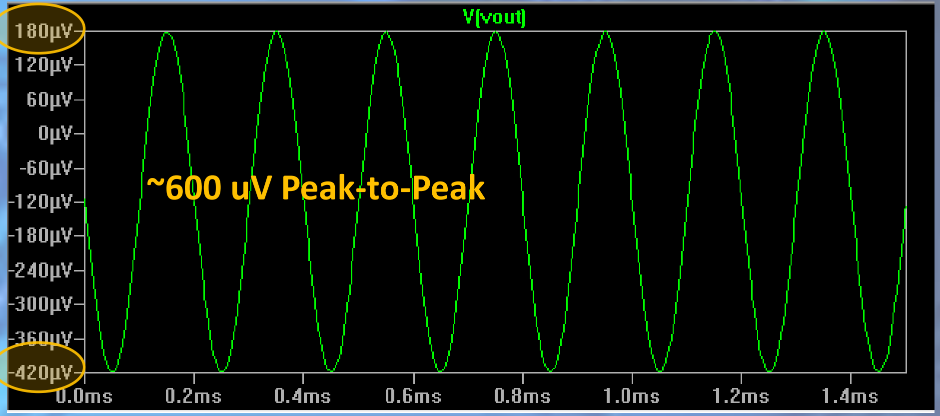
1. Same as inverting amplifier

Finding 4: Current Sink

Will f**** you up!

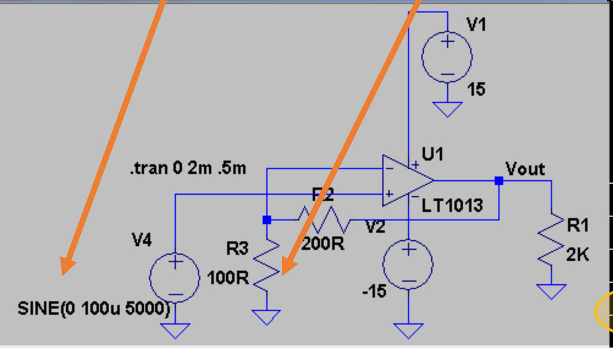


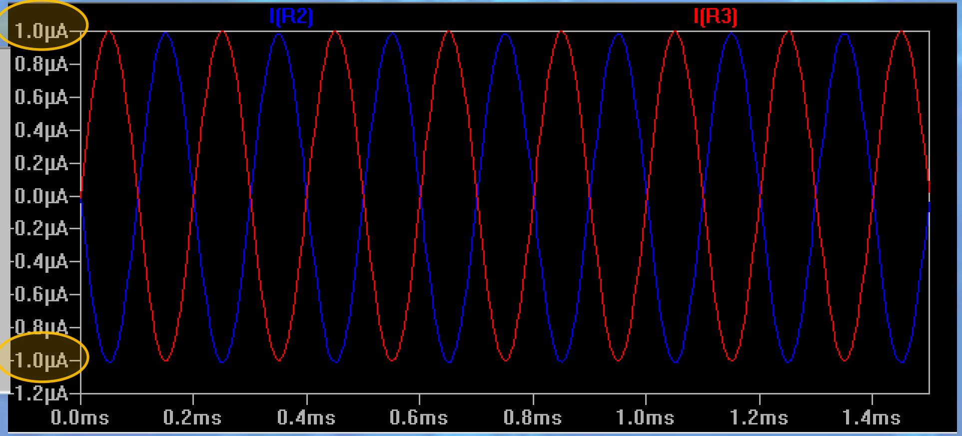


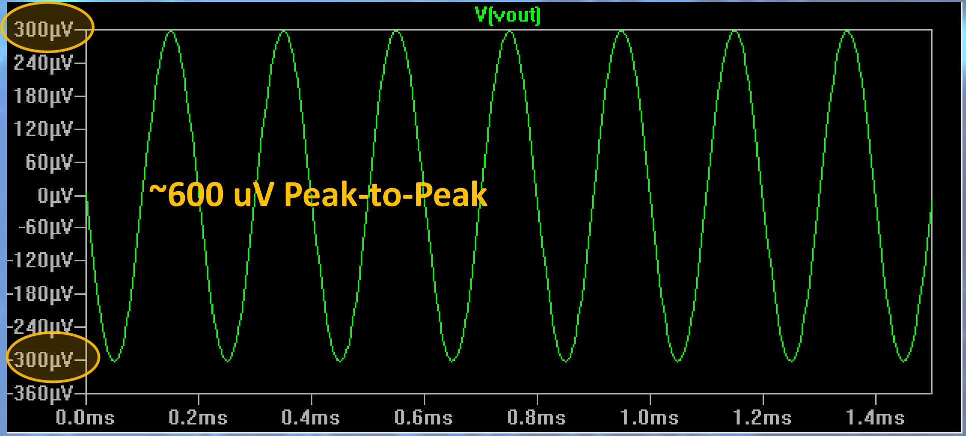


Resistor needs to be low enough to sink current for Non-Inverting Opamp

Small Signal

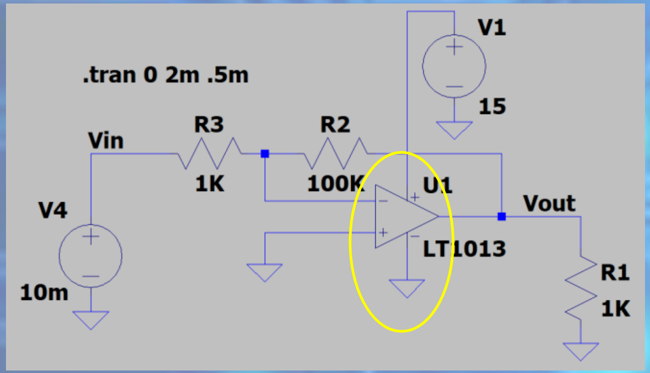




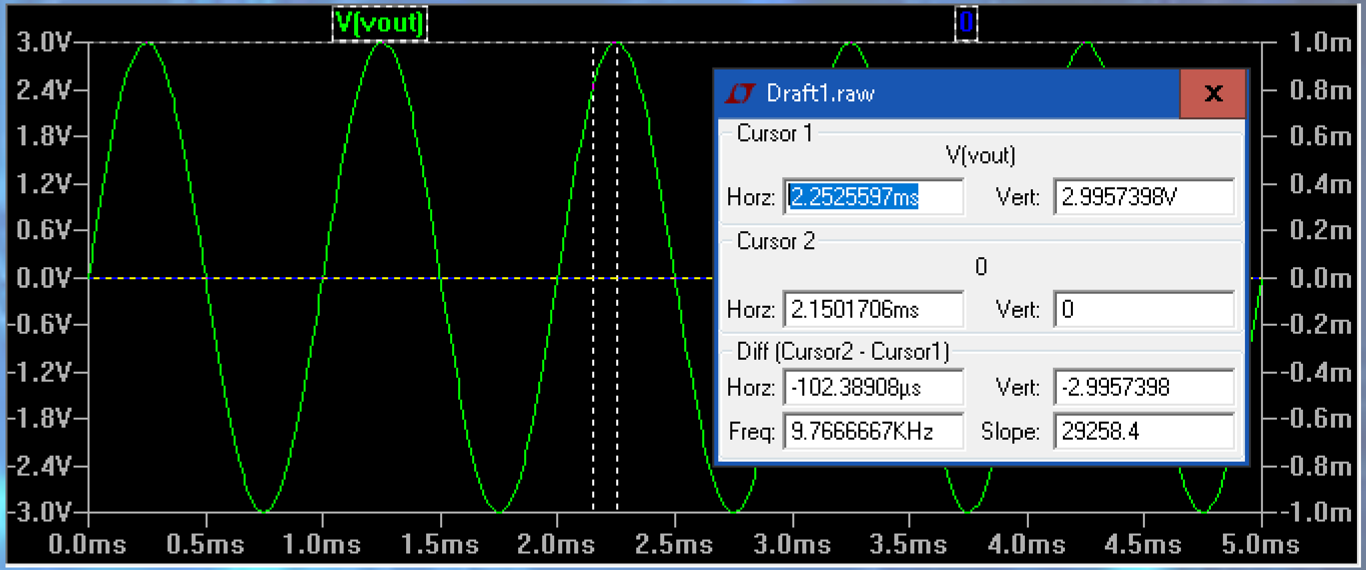


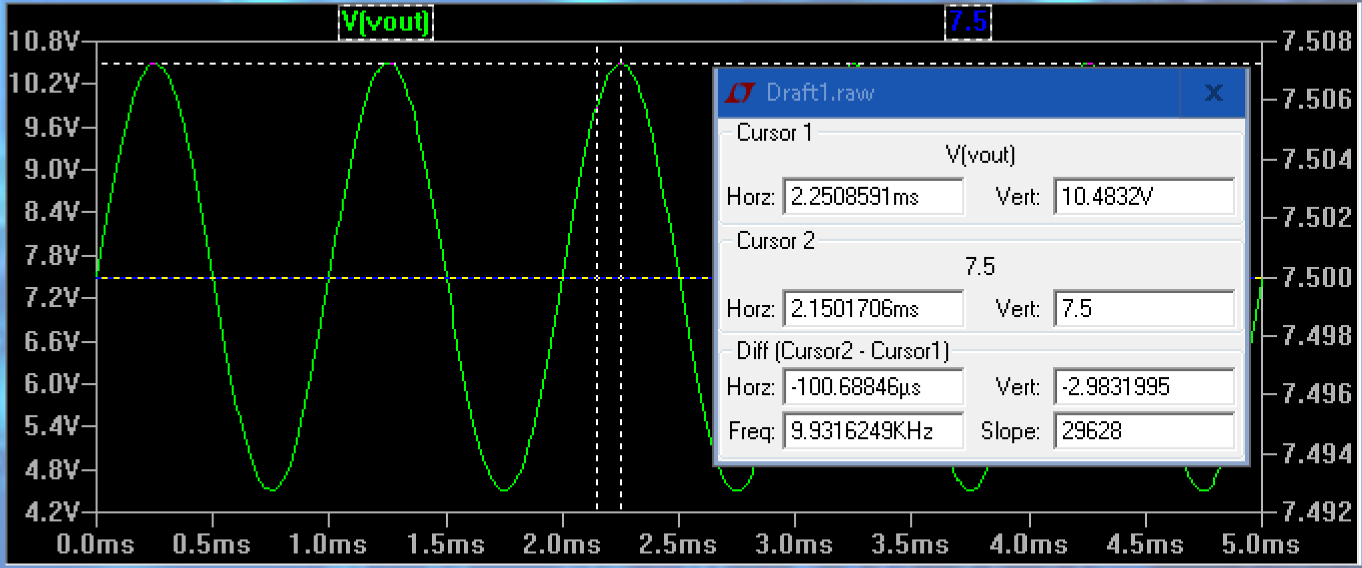
Single Supply

1. **Opamps swing between Positive Rail and Negative Rail**
2. **For +Rail and –Rail, swing is around 0**
3. **Negative rails allows voltages to swing below 0**



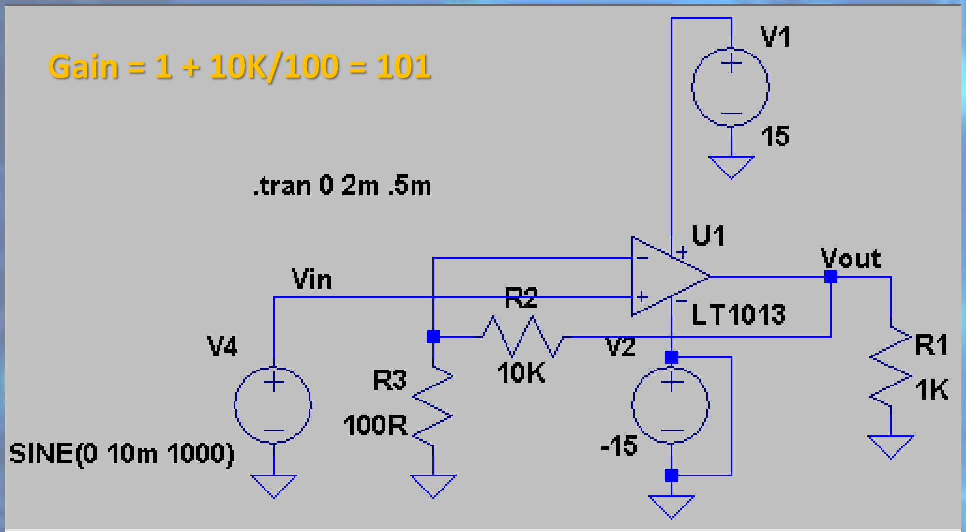
1. **For single supply swing needs to be between +Rail and Gnd**
2. **Need to add ½ supply offset to input**

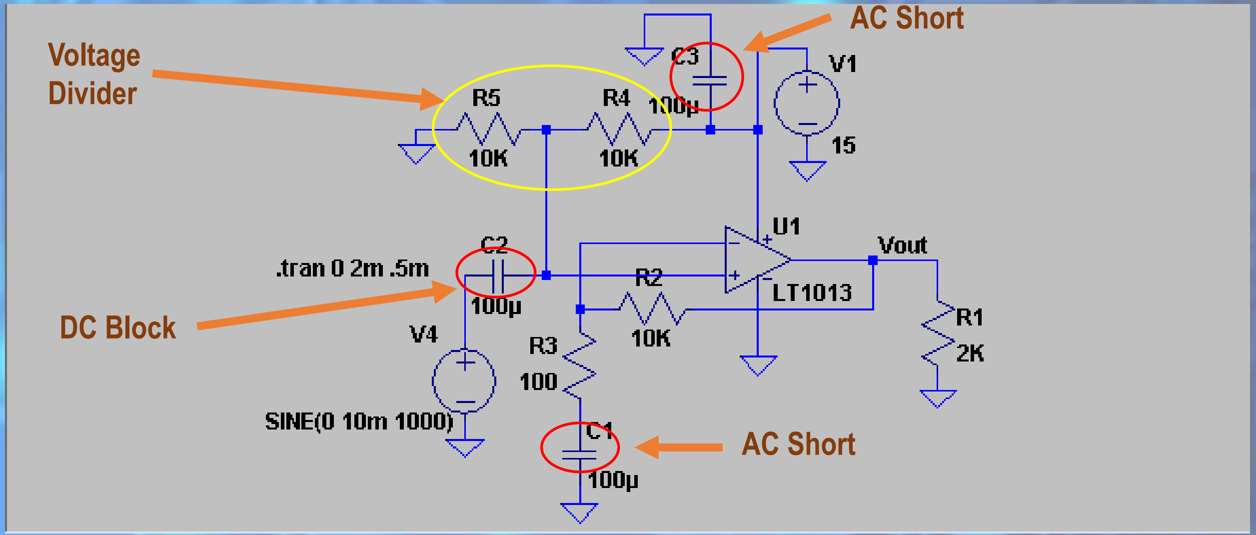


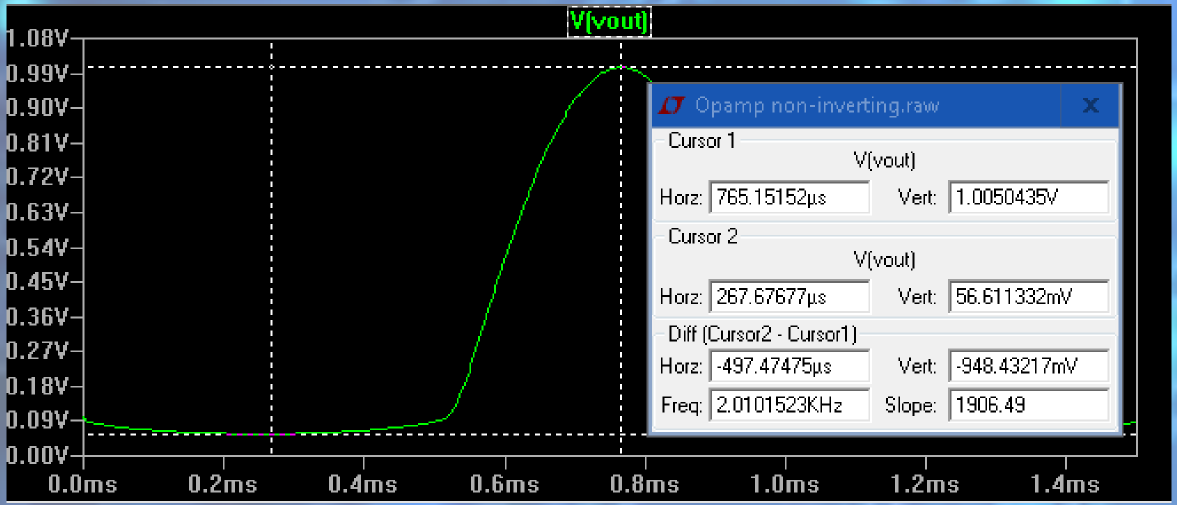


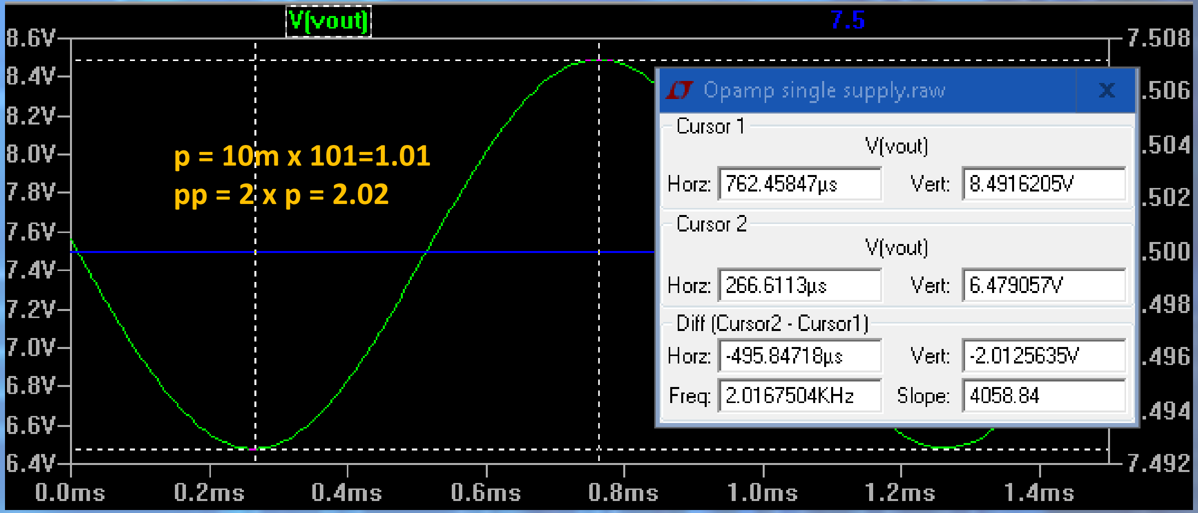
Experiment 12: Single Supply

What happens if –Rail is 0 (ground)? What happens to the swing?



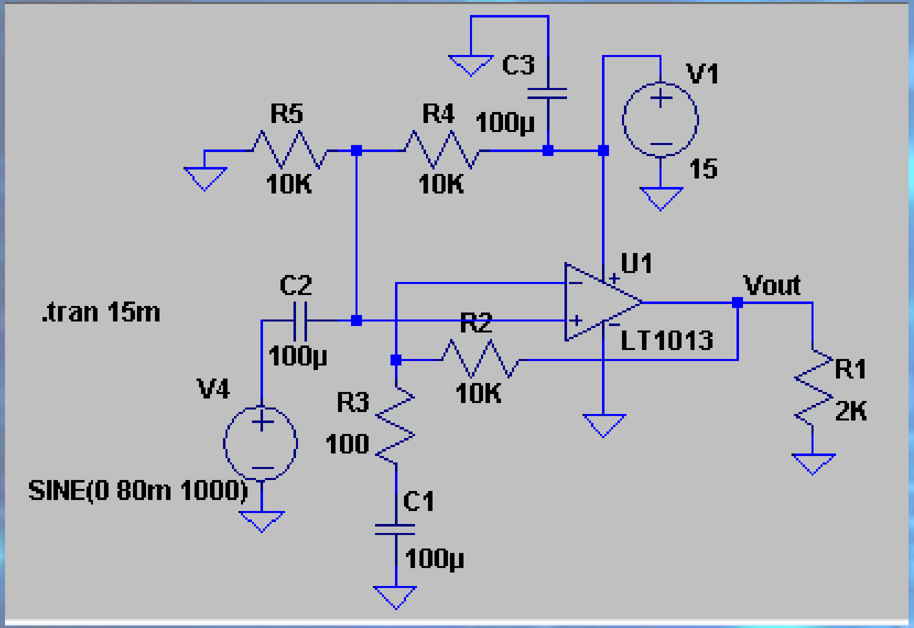


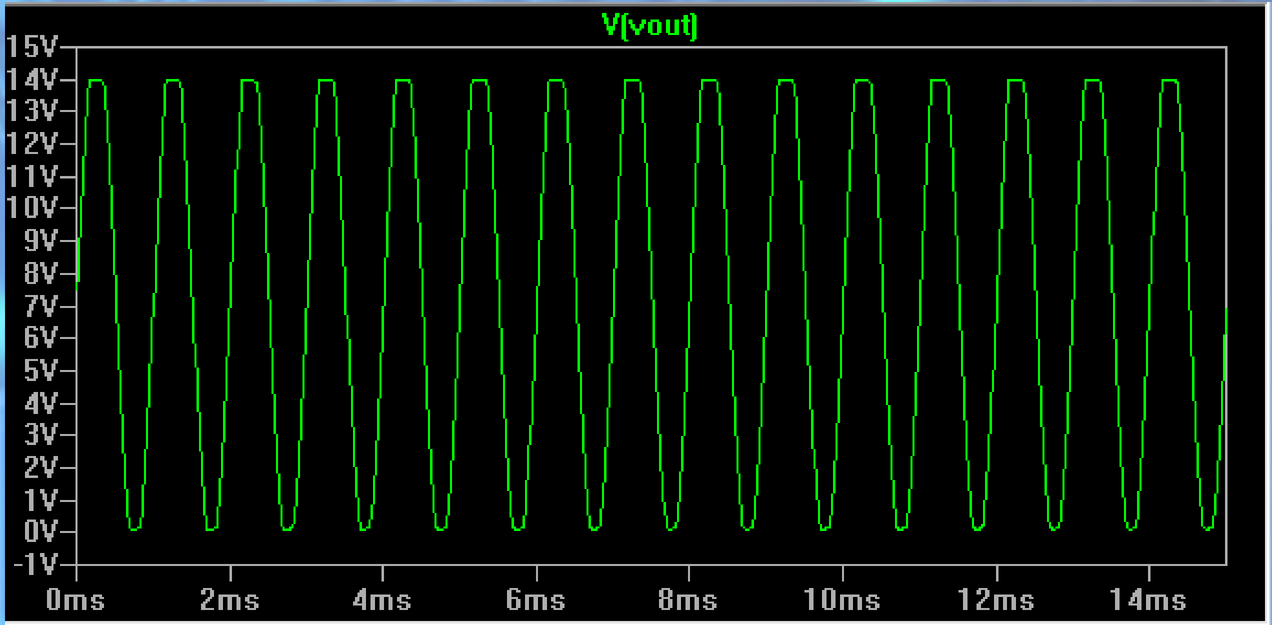




Experiment 13: Distortion

What happens If gain is too high?





1. **Gain is 100x. Input is 80mV, Output is 8V.**
2. **Voltage swing is from 7.5V->0 and 7.5V -> 14**
3. **Not enough room to accommodate necessary swing so it clips at Rails**

OPAMP LIMITATIONS

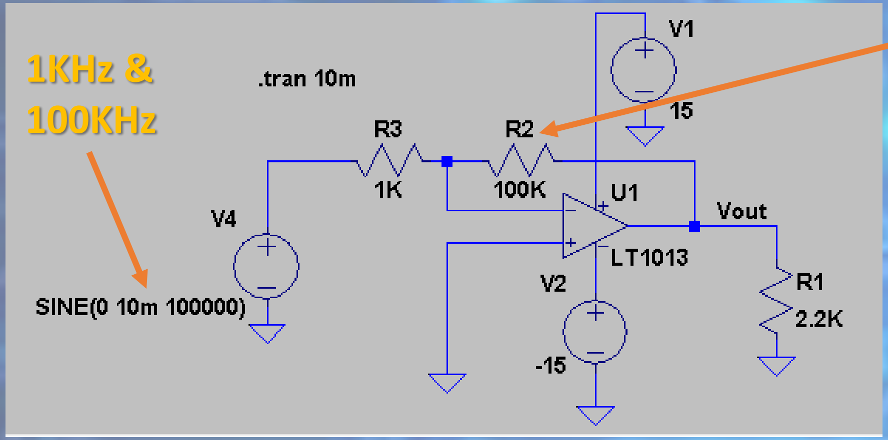
1. **Frequency Limitation – Gain Bandwidth Product**

2. **Frequency & Output Voltage Limitation - Slew Rate**

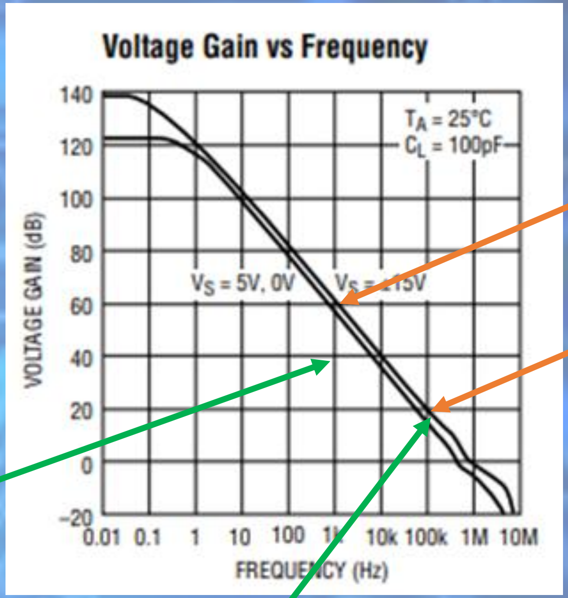
3. **Noise**

Experiment 14: Gain Bandwidth Product

Opamps gain vary with Frequency

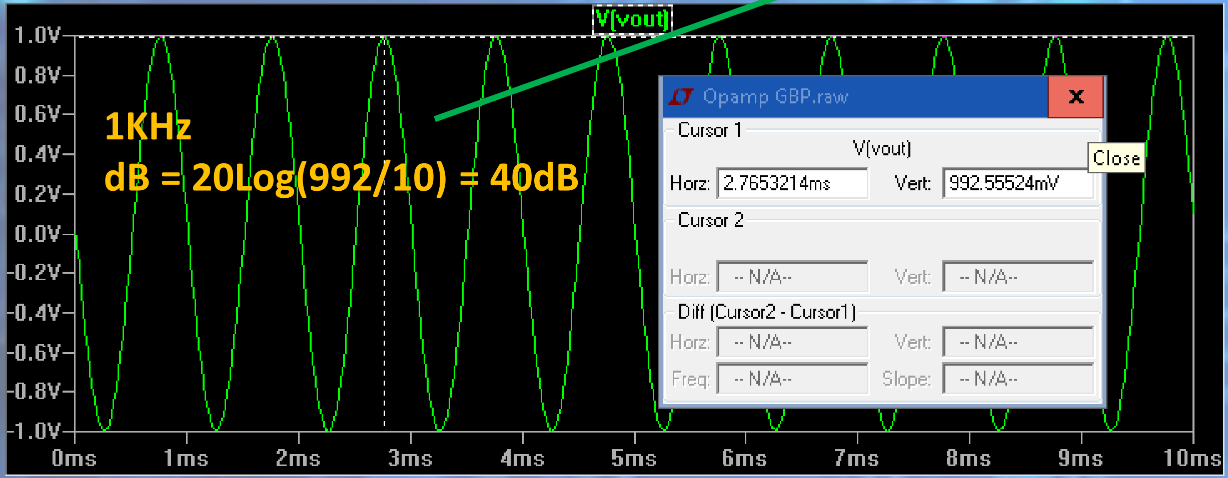


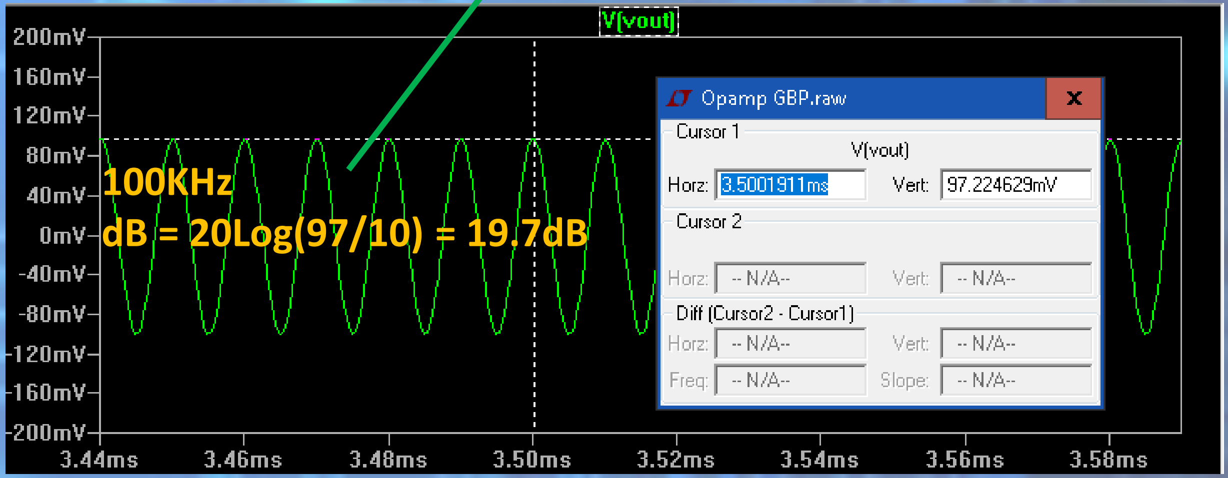
Gain = 20Log(100/10) = 40dB



60dB @ 1KHz

20dB @ 100KHz



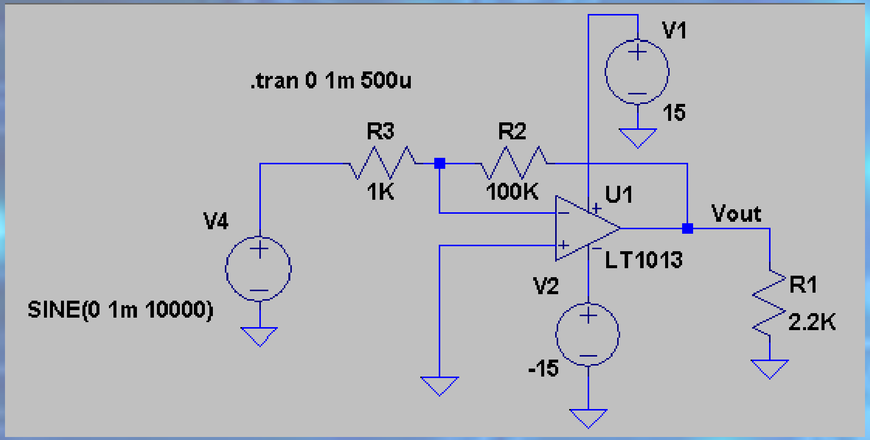


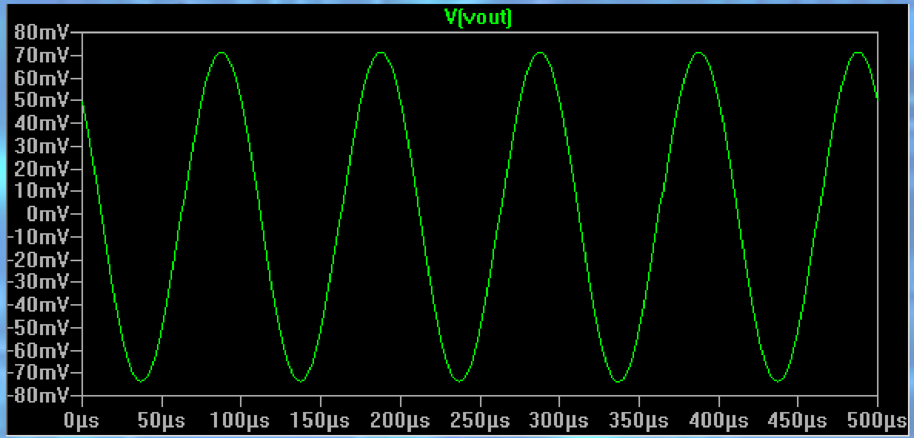
Experiment 15: Slew Rate **Will f**** you up!**

The output of an operational amplifier can only change by a certain amount in a given time. This limit is called the slew rate of the op-amp, and although slew rate is not always mentioned, it can be a critical factor in ensuring that an amplifier is able to provide an output that is a faithful representation of the input..

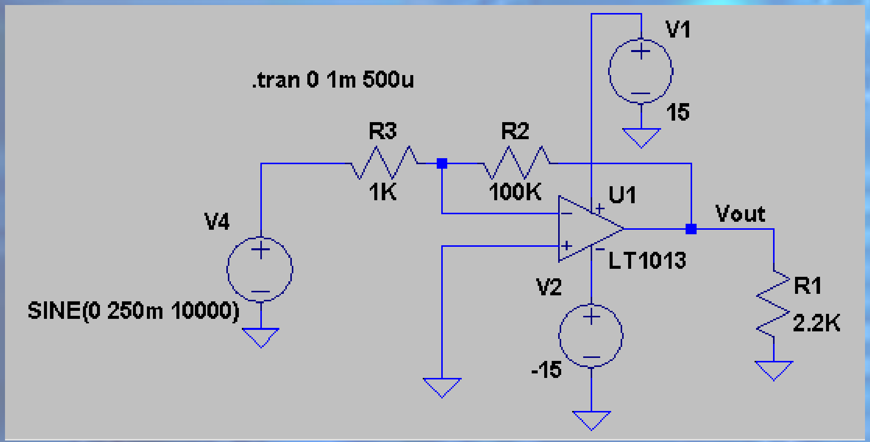
$$\text{Slew rate} = 2\pi f V$$

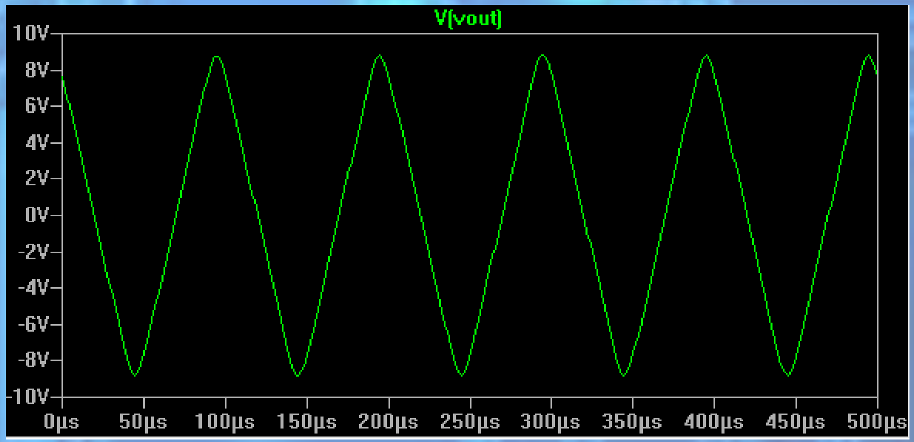
Slew Rate		0.2 0.4	0.2 0.4	V/µs





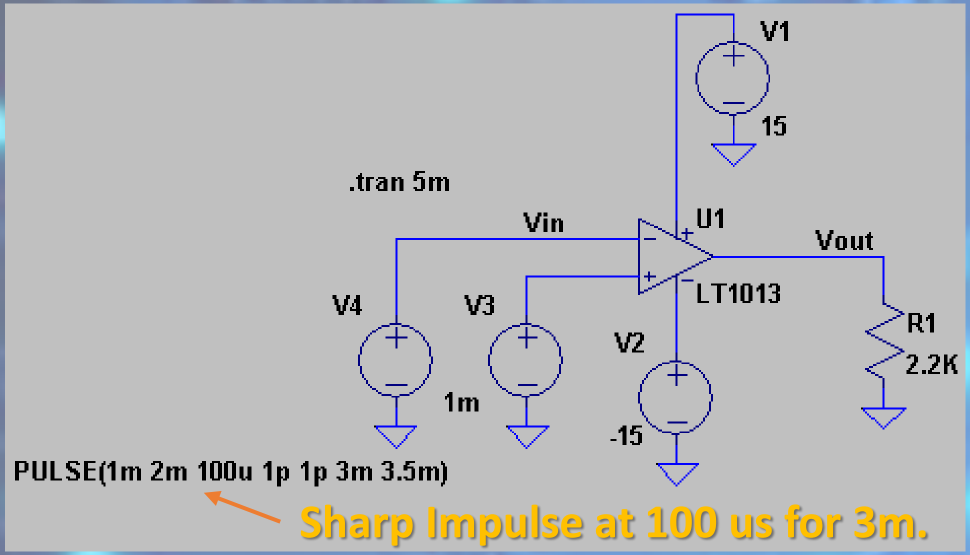
10 KHz

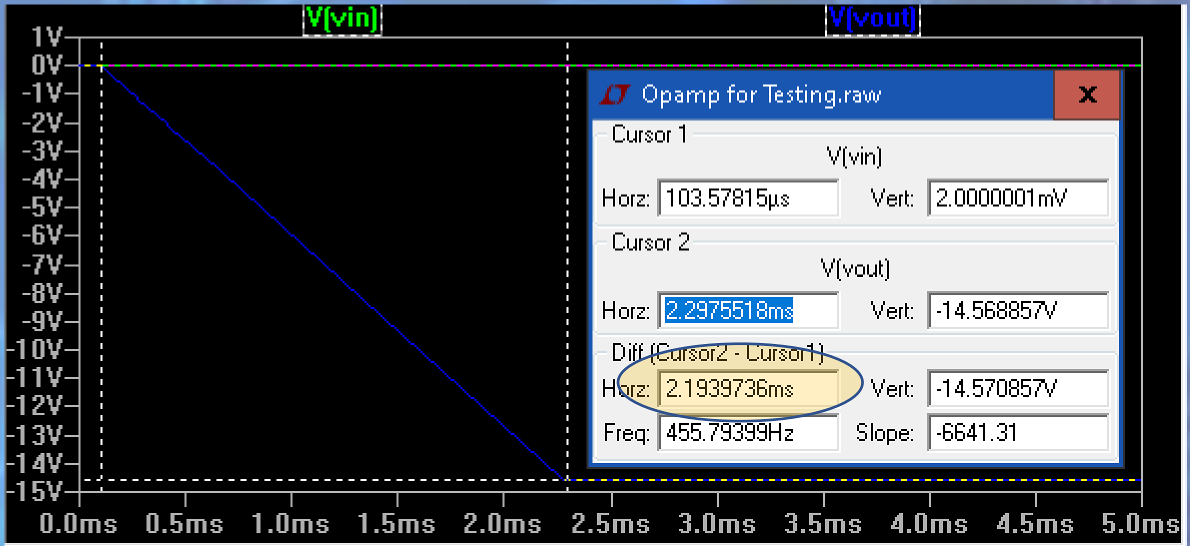


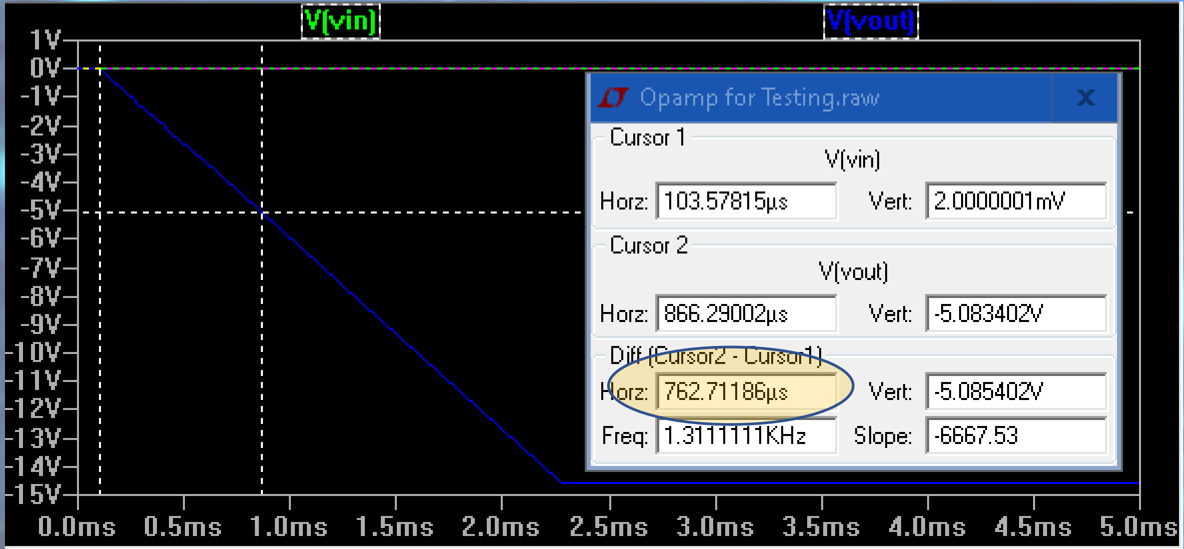


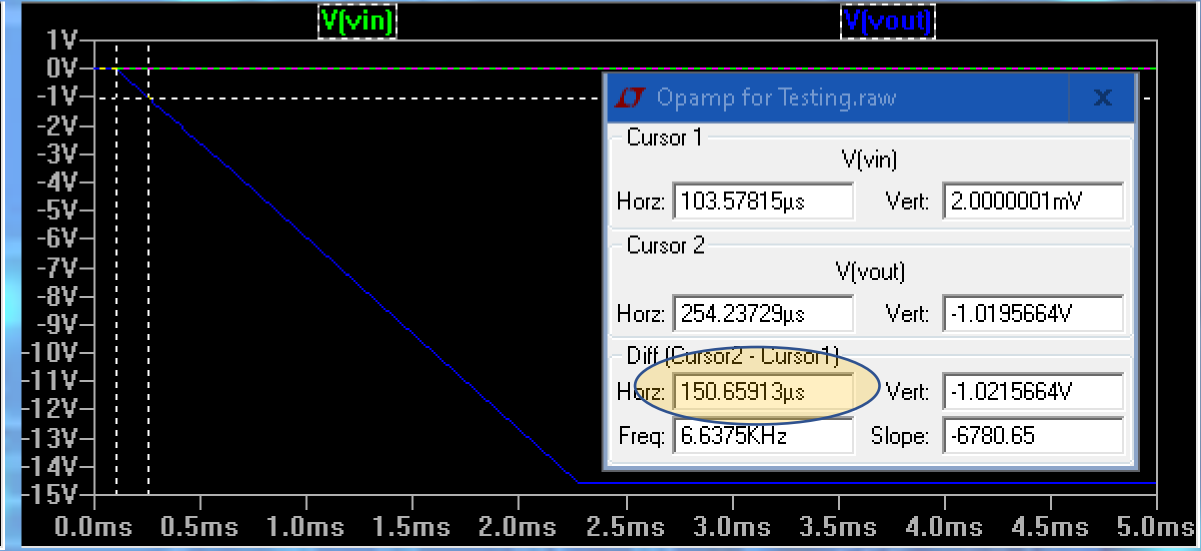
20 KHz

Experiment 16: SR Simplification









Homework: Add feedback to this circuit and measure time

Finding 4: Slew Rate Calculation

$$\text{Slew rate} = 2\pi f V$$

Slew Rate		0.2 0.4	0.2 0.4	V/µs

Slew Rate = 0.3 V/us = 300,000 V/s

1. **For 13 Volts,**
   F = SR/(2*PI*V) = 300,000 / (2 * 3.14 * 13) = 3.675 KHz

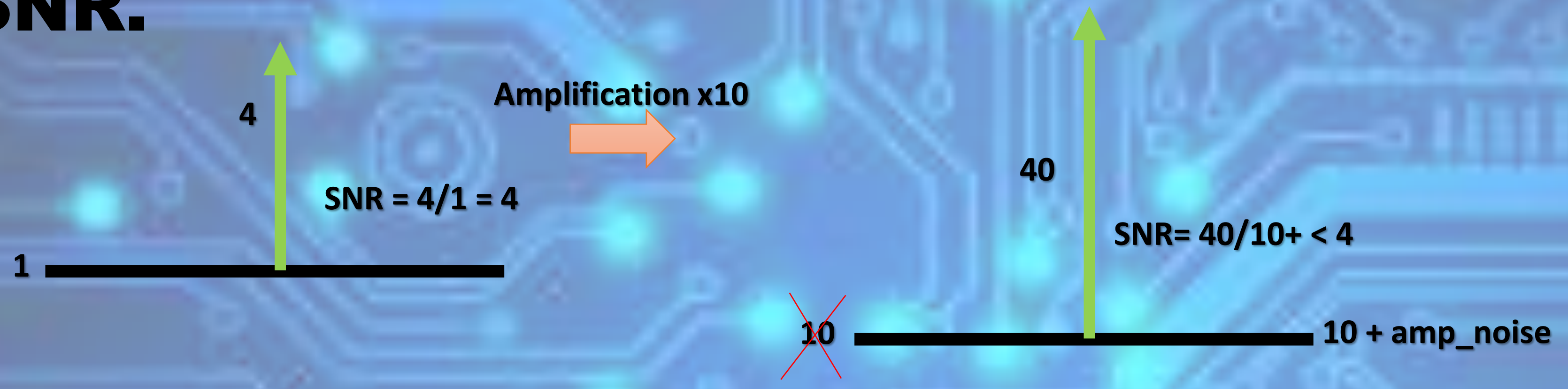
2. **For 1 Volt, F = 47.771 KHz**

3. **For 5 Volts, F = 9.554 KHz**

Homework: Create test circuit with gain and see how the output is impacted after these frequencies and voltages.
**Don't forget gain bandwidth product

Principal 4: Opamp Noise

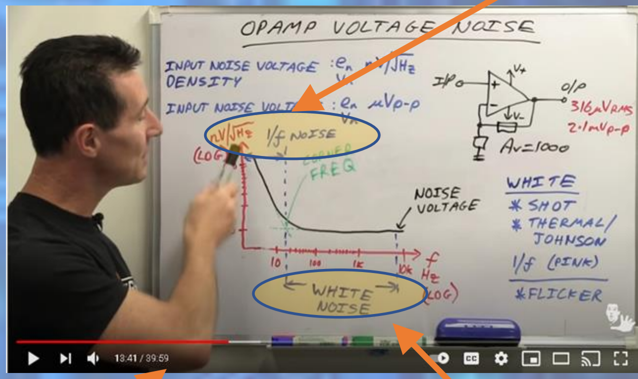
1. **All amplifiers introduce noise into a circuit that reduces SNR.**



1. Opamp
2. Feedback Network

2. **Opamps introduce "White" Noise and "Pink" Noise. Noise is subject to gain with voltage and current noise added to input.**
3. **Feedback network introduces White Noise from resistors – Usually Largest**

Low F - PINK

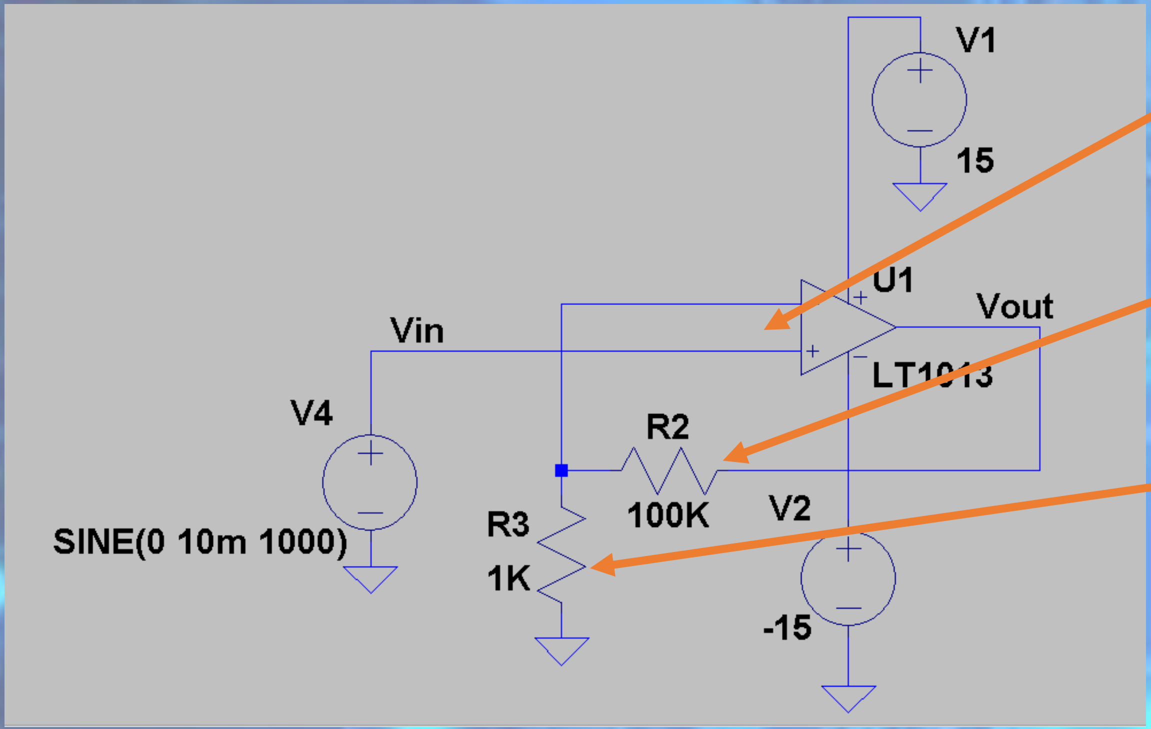


e_n	Input Noise Voltage	0.1Hz to 10Hz	0.55	0.55	μV_{P-P}
e_n	Input Noise Voltage Density	f_0 = 10Hz f_0 = 1000Hz	24 22	24 22	$nV/\sqrt{Hz}$ $nV/\sqrt{Hz}$
i_n	Input Noise Current Density	f_0 = 10Hz	0.07	0.07	$pA/\sqrt{Hz}$

Higher F - White

Spectral Noise Density

Modeling Noise in Opamps



Current Noise and Voltage Noise

Resistor Voltage Noise

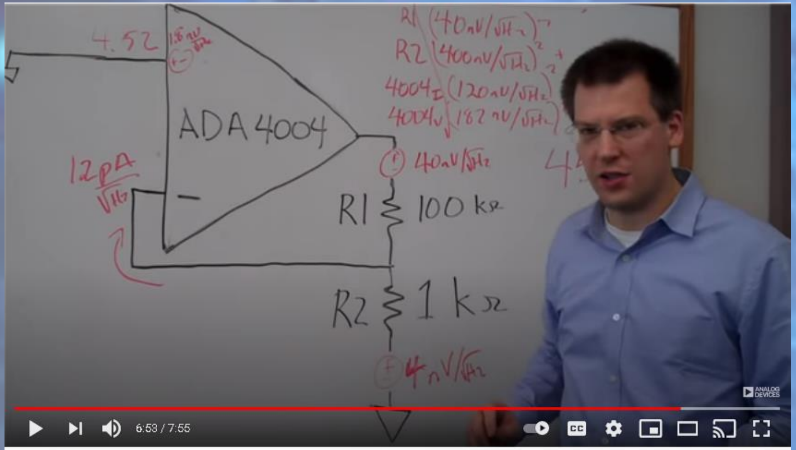
Resistor Voltage Noise

$$E = \sqrt{4 \cdot R \cdot k \cdot T \cdot \ \Delta F}$$

Where *E* is the RMS noise signal in volts, *R* is the resistance in ohms, *k* is Boltzmann's constant, *T* is the temperature in Kelvin and *dF* is the bandwidth in Hz. The equation shows that the noise level can be decreased by reducing the resistance, the temperature or the bandwidth. Knowing Boltzmann's constant, the formula is

Resistor noise is about 4nV/rHz for 1K Resistor at room temp

Experiment 17: Calculate Opamp Noise

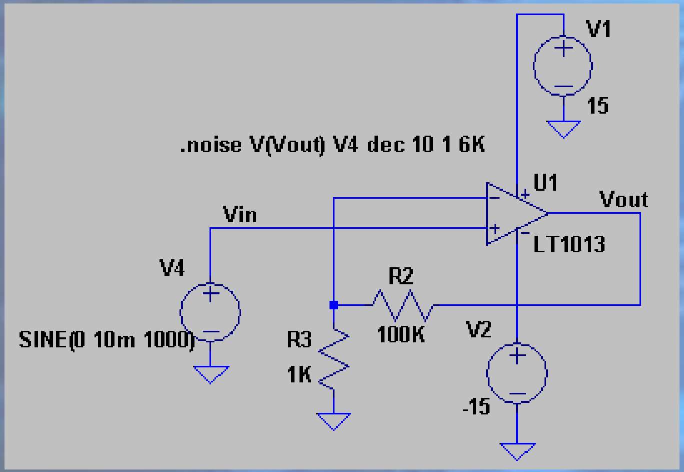


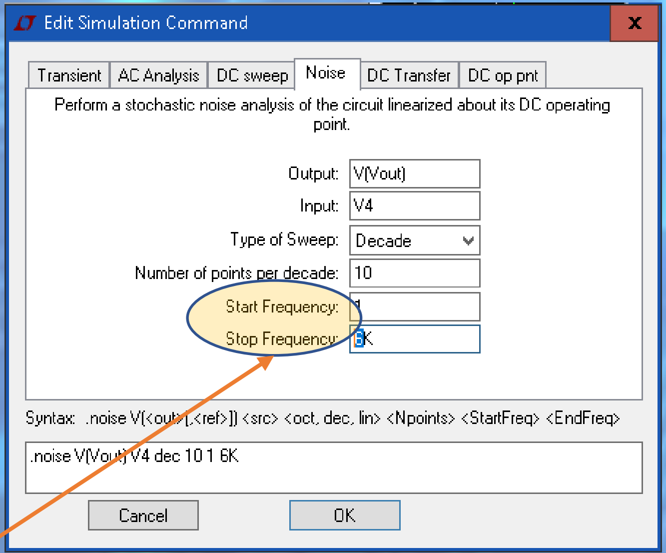
Noise of a Non-inverting Operational Amplifier Circuit

At the output: Spectral Noise Density:

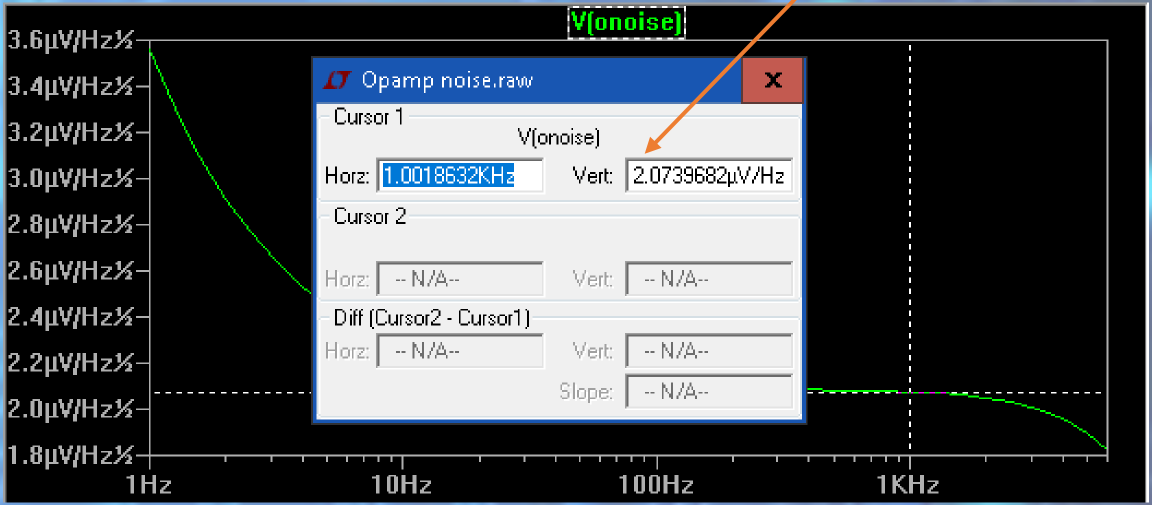
1. **Noise from resistors:**
   - **R1: 40nV/rHz**
   - **R2: 400nV/rHz**
2. **LT1013 Opamp current noise**
   - **7nV/rHz**
3. **LT1013 Opamp voltage noise**
   - **2200nV/rHz**

Sum of Squares: 2236 nV/rHz (2.2uV/rHz)

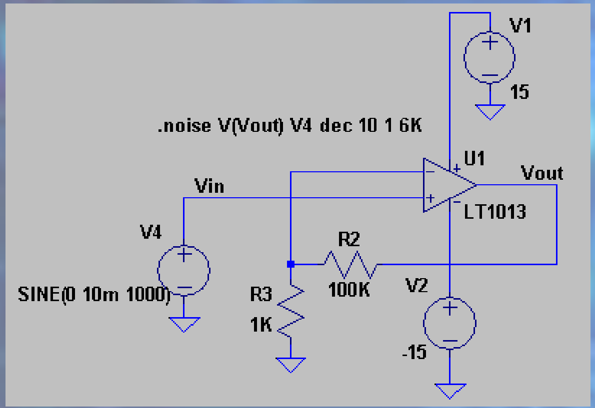


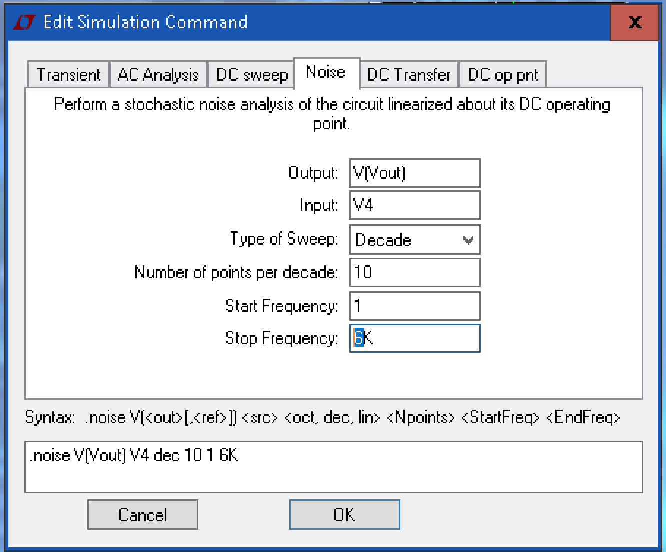


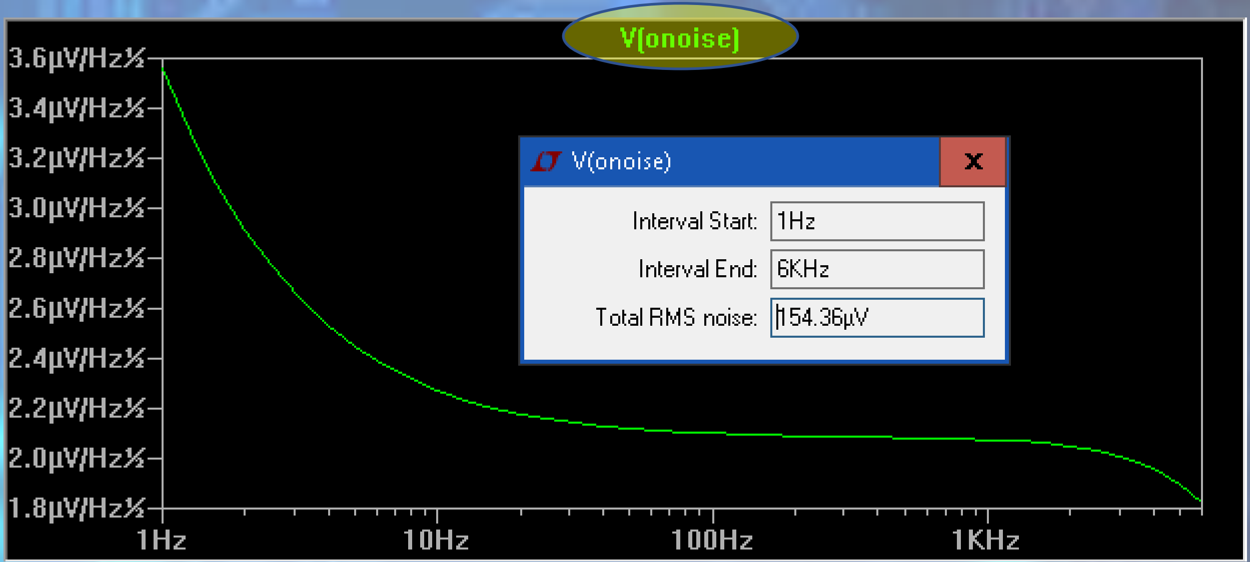
Bandwidth



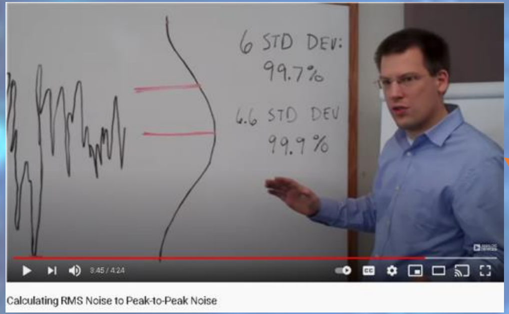
Experiment 18: Noise in Audio Range

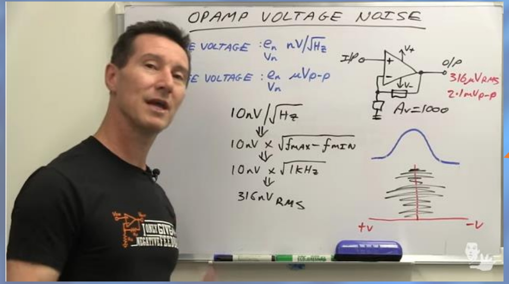






Point to Trace Name and Press CTL-Click



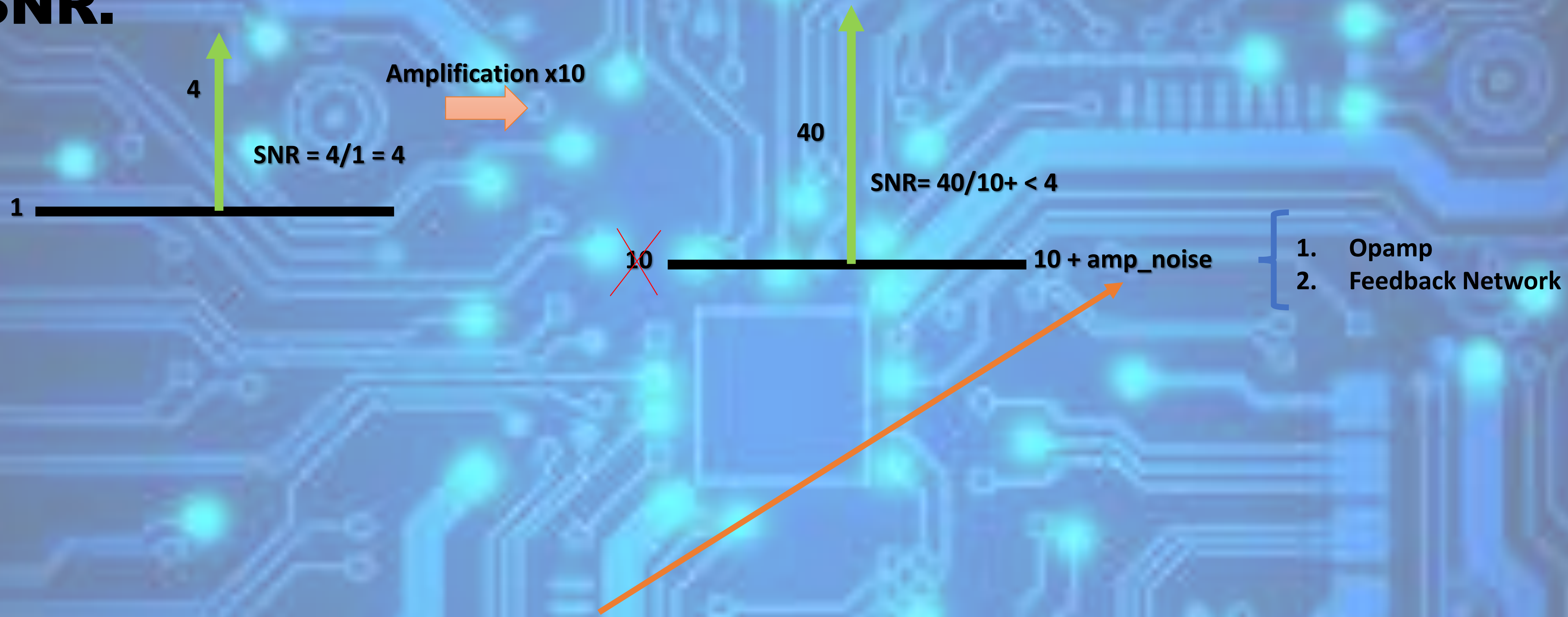


Dumb it down: Multiply RMS noise by 6.6 to get peak-peak voltage

Peak-Peak Noise: 6.6x154uV = 1.02 mVpp

NOISE WRAP UP

1. **All amplifiers introduce noise into a circuit that reduces SNR.**



We now know how much noise opamp will add!!

FIN