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MICROELECTRONIC ENGINEERING

Basic Analog Electronic Circuits Using Operational Ampliiers

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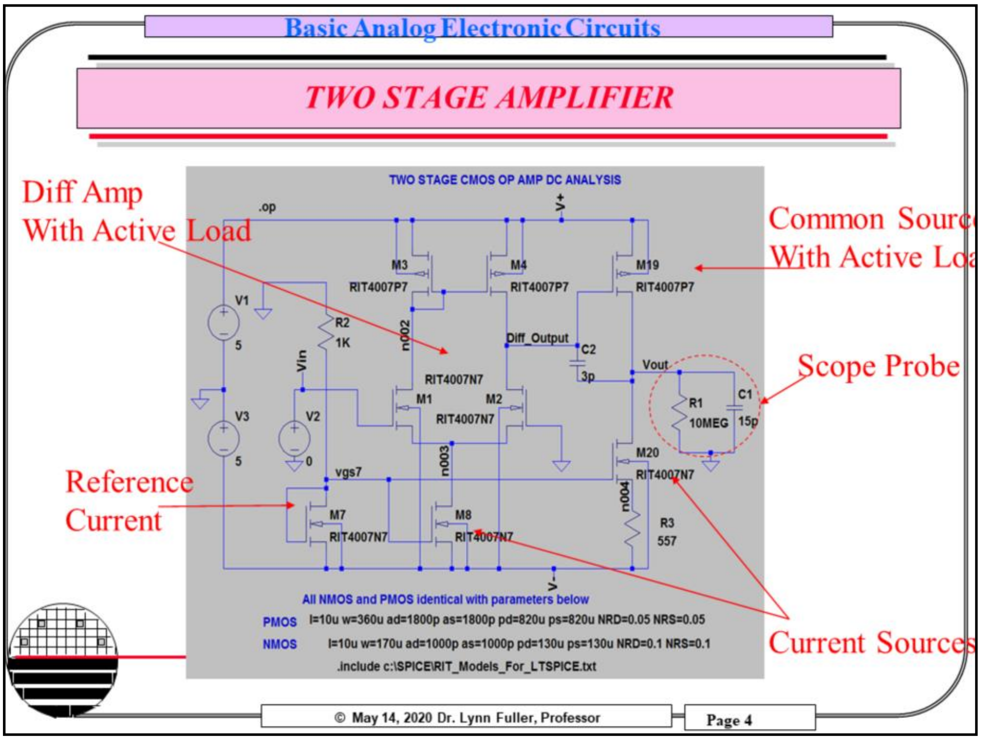
OUTLINE

Introduction
Op Amp
Comparator
Bistable Multivibrator
RC Oscillator
RC Integrator
Peak Detector
Switched Capacitor Amplifier
Capacitors
Design Examples
References
Homework

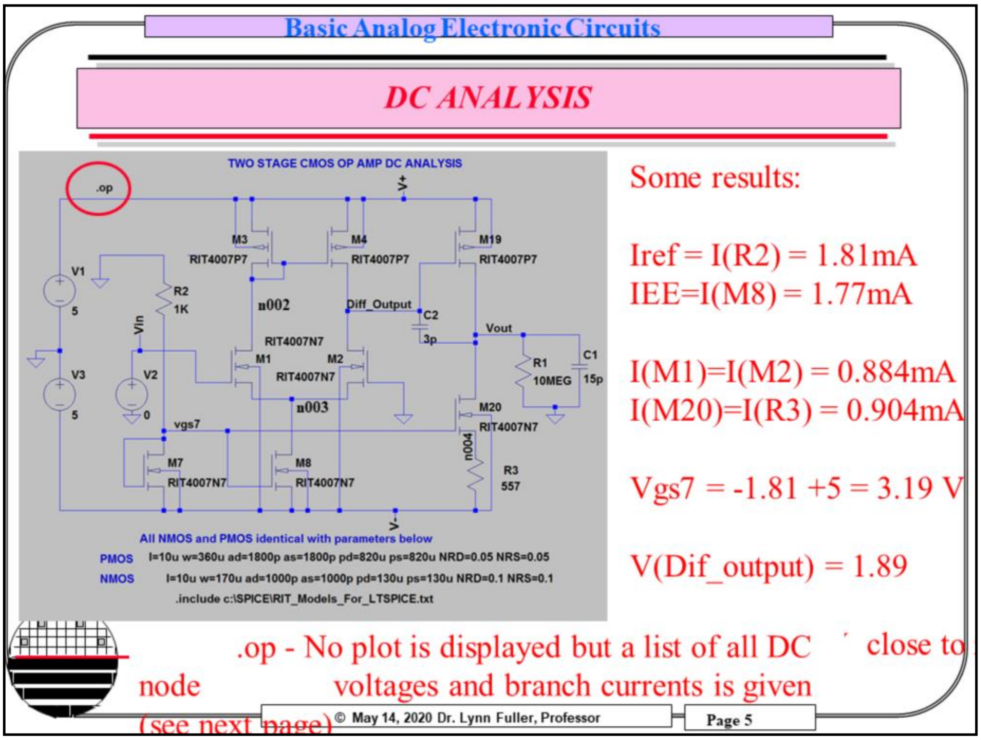
INTRODUCTION

Analog electronic circuits are different from digital circuits in that the signals are expected to have any value rather than two discrete values. Primitive analog components include the diode, mosfet, BJT, resistor, capacitor, etc,. Analog circuit building blocks include single stage amplifiers, differential amplifiers, constant current sources, voltage references, etc. Basic analog electronic ciruits include the operational amplifier, inverting amplifier, non-inverting amplifier, integrator, bistable multivibrator, peak detector, comparator, RC oscillator, etc. Mixed-mode analog integrated circuits include D-to-A, A-to-D, etc.

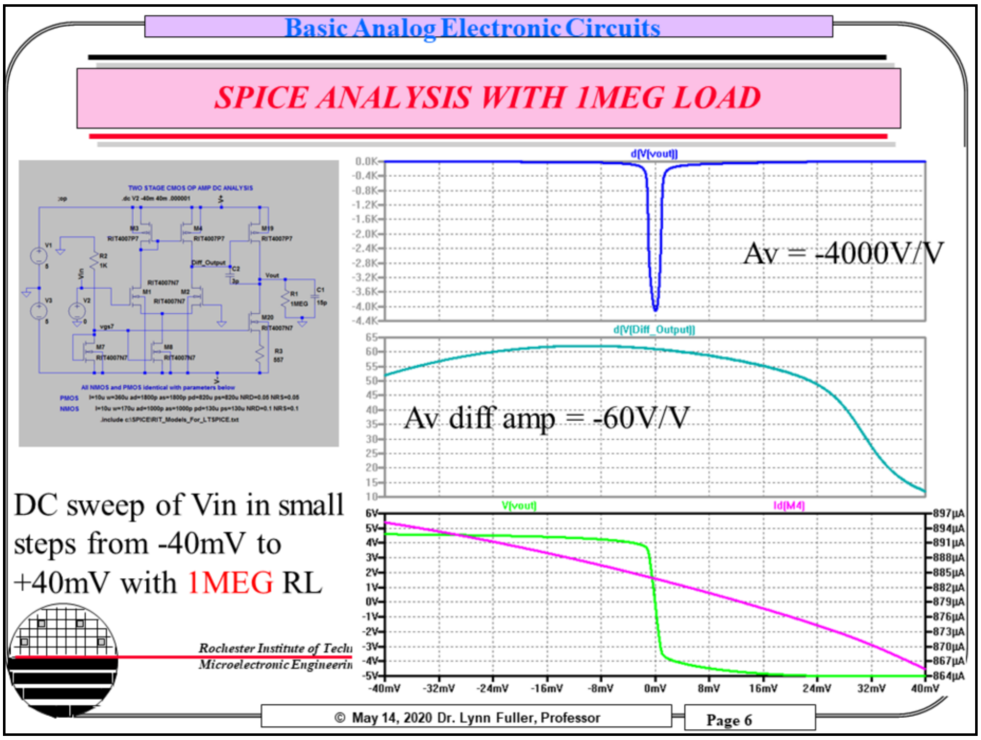
This document will introduce some Basic analog electronic circuits using operational amplifiers.



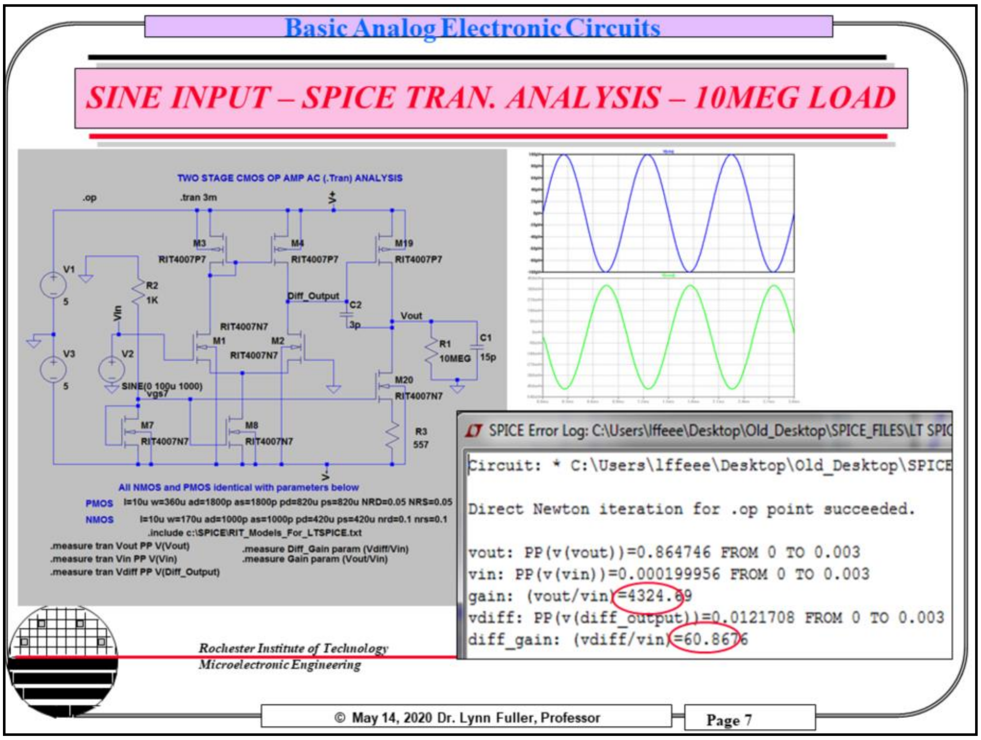
This is the CMOS op amp that we will build in lab. Look carefully at the schematic and identify the current sources, reference current, differential amplifier, active loads, common source 2nd stage with active load and scope probe. (note: MEG works in spice but M is milli and m is also milli) Note the current source for the 2nd stage is different than M8 in that R3 will make the current smaller.



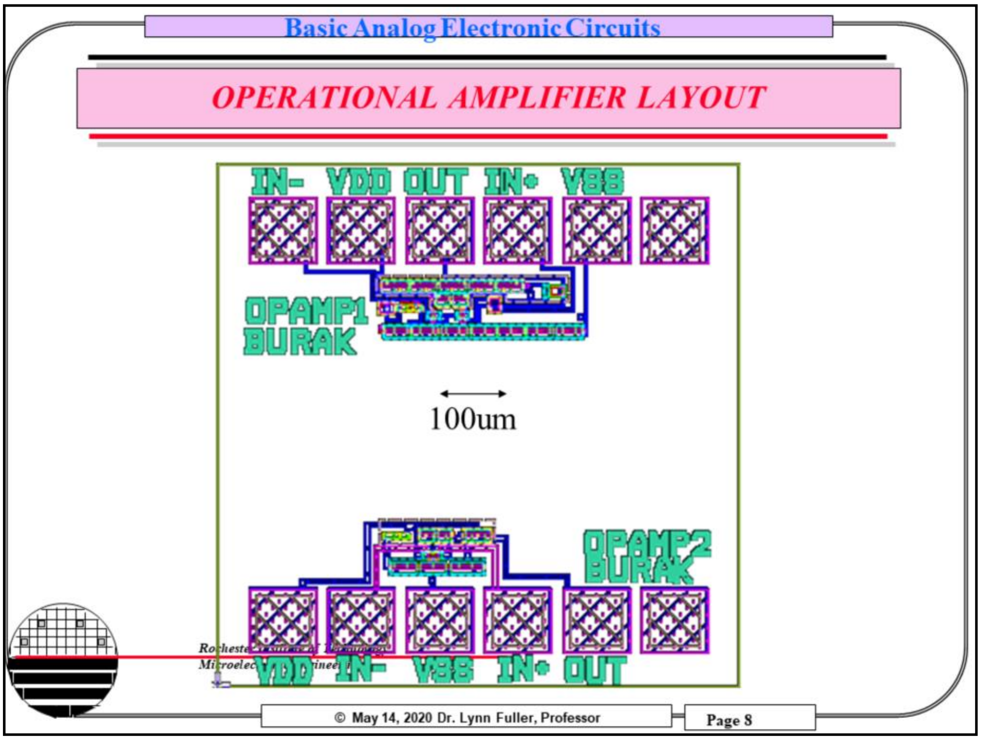
Start with the DC analysis. In LTSPICE the .op command does the DC analysis and lists all the node voltages and branch currents in a table after running the simulation. Some of the results in the table are given here. The reference current I(R2) is 1.81 mA and is matched with the current source IM8=IEE=1.77mA. IEE splits in half for the diff amp transistors giving 0.884 mA each. The current in the 2nd stage is 0.9mA. The DC output offset voltage is 40mV which is close to zero as desired.



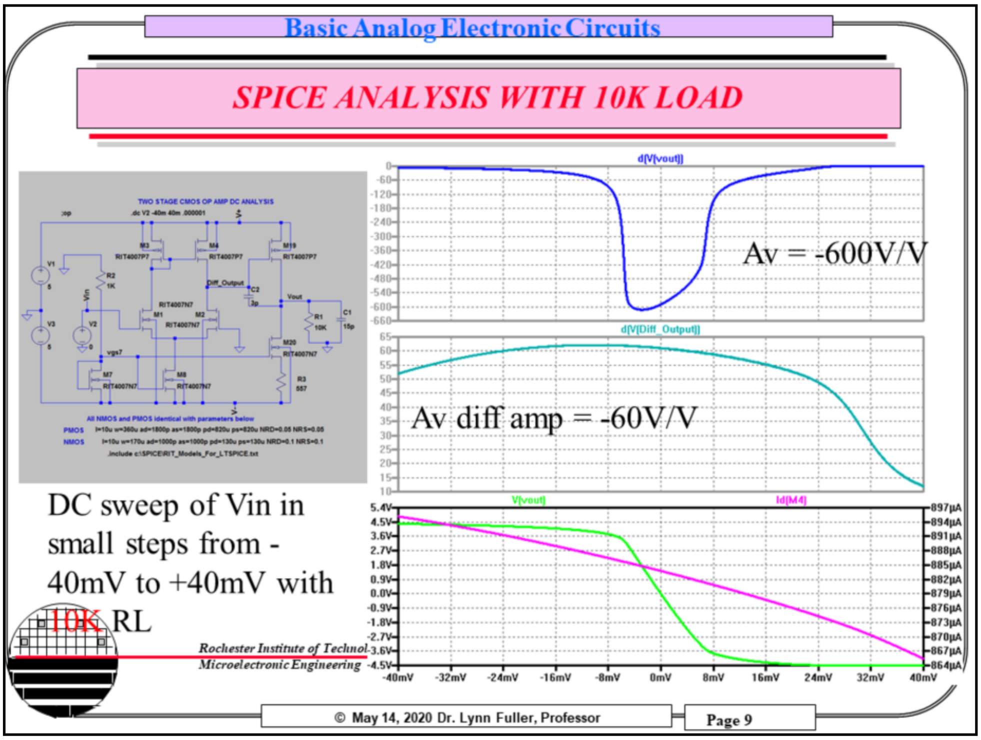
One way to get the voltage gain (the other is to input sine wave) is to do a DC sweep near zero volts. In this example we sweep from -40mV to +40mV is small steps. The output voltage is shown in green. The derivative of the green plot is shown in dark blue in the top plot plane and is the overall voltage gain. The derivative of the differential amp stage output voltage is the gain of the diff amp shown in the middle plot plane. The maximum overall gain is ~4000V/V and for the diff amp is ~60V/V



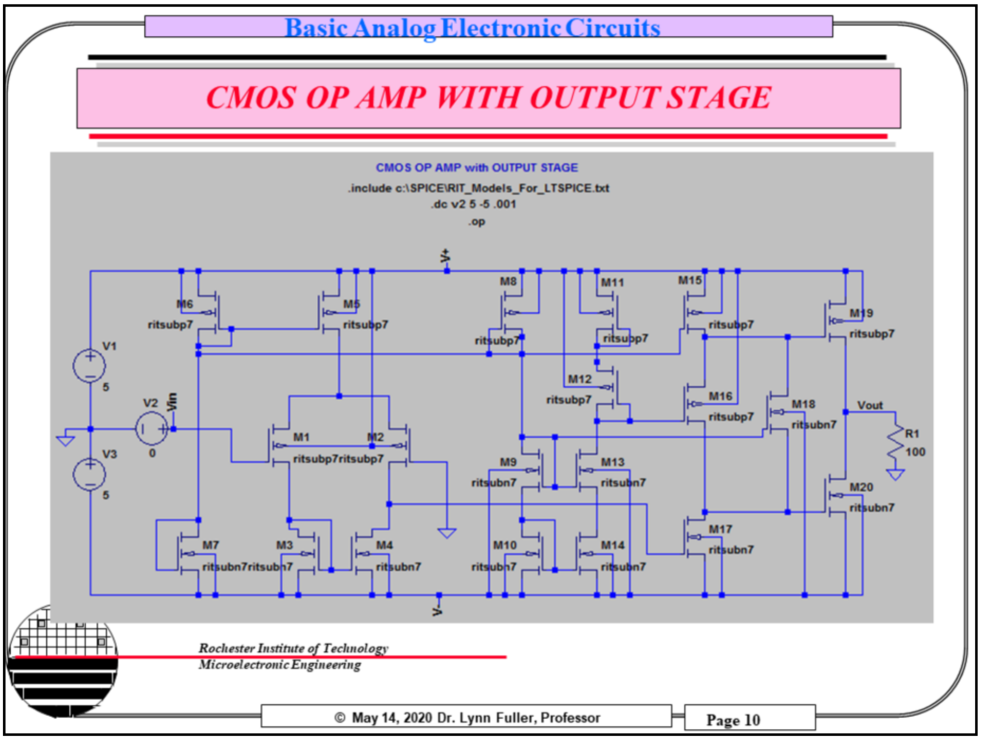
Similar results are found for sinusoidal input.



This shows two versions of the layout of the op amp shown on the previous few pages. The upper design is based on L=2um. The lower design is a L=1um design. They should both work but the larger one always works when made by RIT students.



With a 10K load the voltage gain drops from ~4000V/V to ~600V/V. Obviously this amplifier has little ability to output current to loads less than 1MEG ohm.

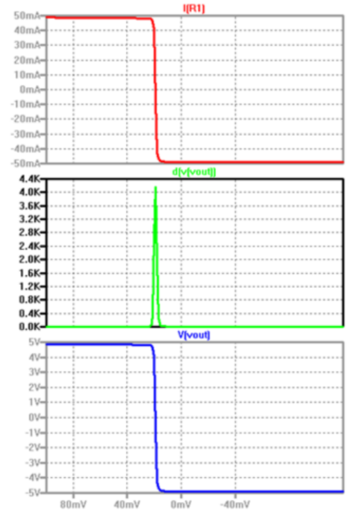


LTSPICE for CMOS op amp with output stage to drive loads of 100 ohms.

CMOS OP AMP WITH OUTPUT STAGE

Note: R1 is the load resistor = 100 ohms
The voltage gain is still 4000 V/V and the current is +/- 50mA

Not possible with the two stage Op Amp



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A few extra transistors allows the op amp to drive 100 ohm loads.

OPERATIONAL AMPLIFERS

The 741 Op Amp is a general purpose bipolar integrated circuit that has input bias current of 80nA, and input voltage of +/- 15 volts @ supply maximum of +/- 18 volts. The output voltage can not go all the way to the + and - supply voltage. At a minimum supply of +/- 5 volts the output voltage can go ~6 volts p-p.

The newer Op Amps have rail-rail output swing and supply voltages as low as +/- 1.5 volts. The MOSFET input bias currents are ~ 1pA. The NJU7031 is an example of this type of Op Amp.

Please read.

LOW VOLTAGE, RAIL-TO-RAIL OP AMP

JRC **NJU7031/32/34**

LOW VOLTAGE C-MOS OPERATIONAL AMPLIFIER

■ GENERAL DESCRIPTION

The NJU7031/32/34 are single, dual and quad single supply, low offset, output full swing C-MOS Operational Amplifiers.

The wide operating voltage 3V to 16V, High slew rate 3.5V/µs and output full swing are suitable for fast signal processing amplifiers. Additionally, low input bias current 1pA, and single supply operation offer amplification of the very small signal around the ground level.

The NJU7031 has external offset null function.

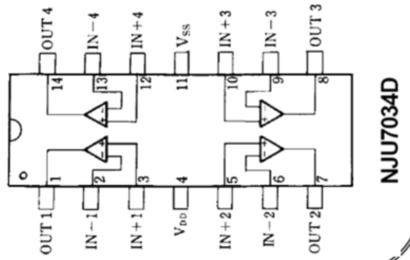
■ FEATURES

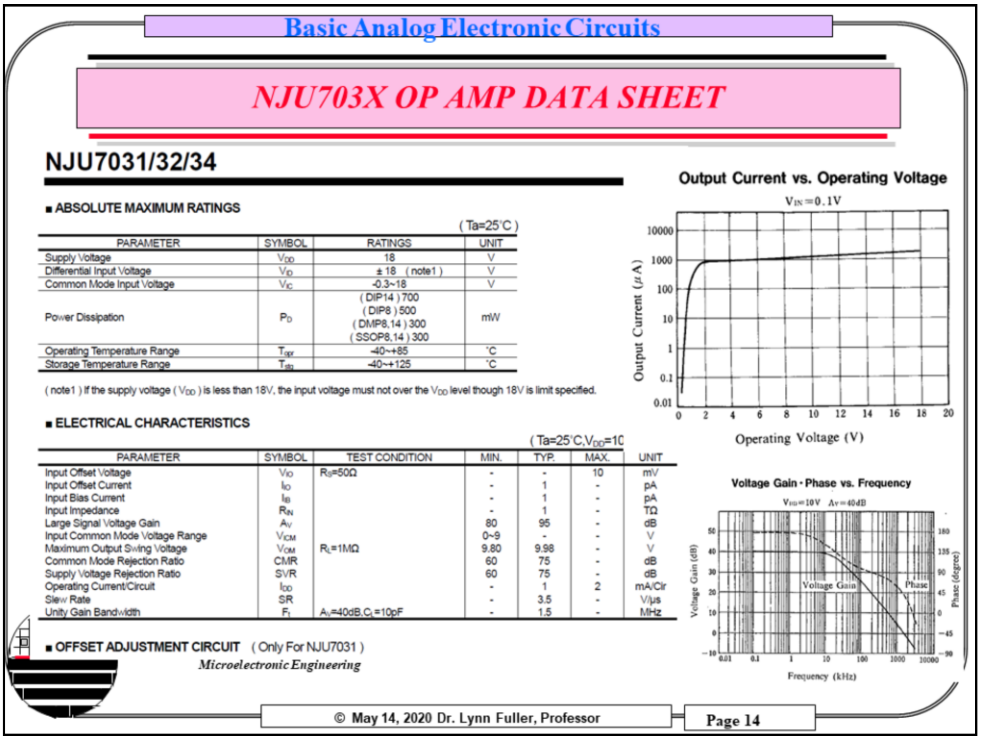
- High Slew Rate 3.5V/µs
- Wide Operating Voltage +3V to +16V
- Output Voltage with full Swing V_{OM}=9.98V typ. (@V_{DD}=10V)
- Input Common Mode Voltage Range V_{ICM}=0V to 9V (@V_{DD}=10V)
- Low Bias Current I_B=1pA typ.
- Input Common Mode Voltage range includes ground.
- External Offset Null Adjustment (Only NJU7031)
- C-MOS Technology
- Package Outline NJU7031 (single) DIP8, DMP8, SSOP8
  NJU7032 (dual) DIP8, DMP8
  NJU7034 (quad) DIP14, DMP14, SSOP14

■ PACKAGE OUTLINE

1. 3 to 16 Volt operation
2. Rail to Rail input and output voltages
3. Low Input bias ~ 1pA
4. Output Current ~1mA
5. Unity Gain Bandwidth 1.5 MHz
6. Power Dissipation 1mA at 3 V = 3000uW

New Japan Radio Co.,Ltd





Basic Analog Electronic Circuits

NJU703X OP AMP DATA SHEET

NJU7031/32/34

■ ABSOLUTE MAXIMUM RATINGS

(Ta=25°C)

PARAMETER	SYMBOL	RATINGS	UNIT
Supply Voltage	V_{DD}	18	V
Differential Input Voltage	V_{ID}	± 18 (note1)	V
Common Mode Input Voltage	V_{IC}	-0.3~18	V
Power Dissipation	P_D	(DIP14) 700 (DIP8) 500 (DMP8,14) 300 (SSOP8,14) 300	mW
Operating Temperature Range	T_{opr}	-40~+85	°C
Storage Temperature Range	T_{stg}	-40~+125	°C

(note1) If the supply voltage (V_{DD}) is less than 18V, the input voltage must not over the V_{DD} level though 18V is limit specified.

■ ELECTRICAL CHARACTERISTICS

(Ta=25°C,V_{DD}=10

PARAMETER	SYMBOL	TEST CONDITION	MIN.	TYP.	MAX.	UNIT
Input Offset Voltage	V_{IO}	R_S=50Ω	-	-	10	mV
Input Offset Current	I_{IO}		-	1	-	pA
Input Bias Current	I_B		-	1	-	pA
Input Impedance	R_{IN}		-	1	-	TΩ
Large Signal Voltage Gain	A_V		80	95	-	dB
Input Common Mode Voltage Range	V_{ICM}		0~9	-	-	V
Maximum Output Swing Voltage	V_{OM}	R_L=1MΩ	9.80	9.98	-	V
Common Mode Rejection Ratio	CMR		60	75	-	dB
Supply Voltage Rejection Ratio	SVR		60	75	-	dB
Operating Current/Circuit	I_{DD}		-	1	2	mA/Cir
Slew Rate	SR		-	3.5	-	V/µs
Unity Gain Bandwidth	F_T	A_V=40dB,C_L=10pF	-	1.5	-	MHz

■ OFFSET ADJUSTMENT CIRCUIT (Only For NJU7031)

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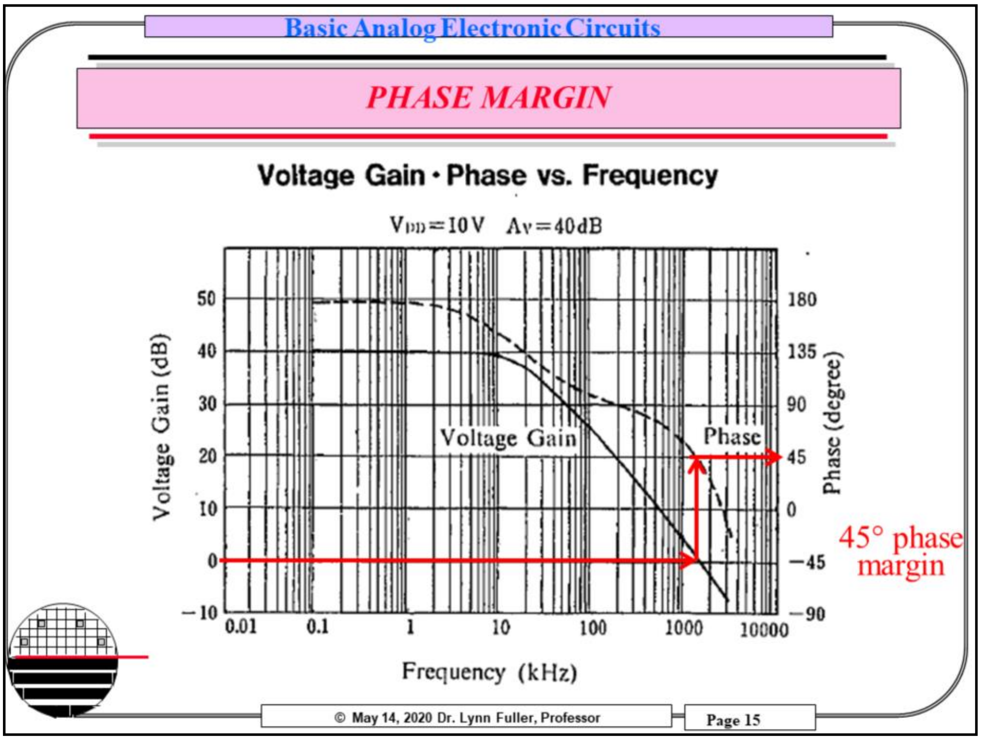
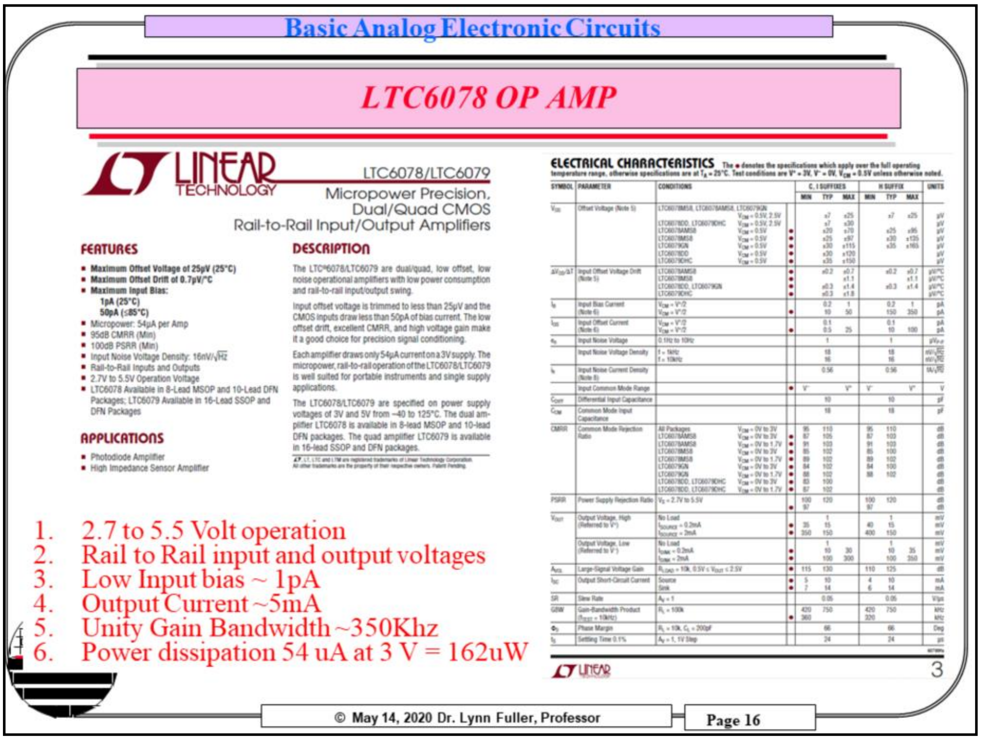
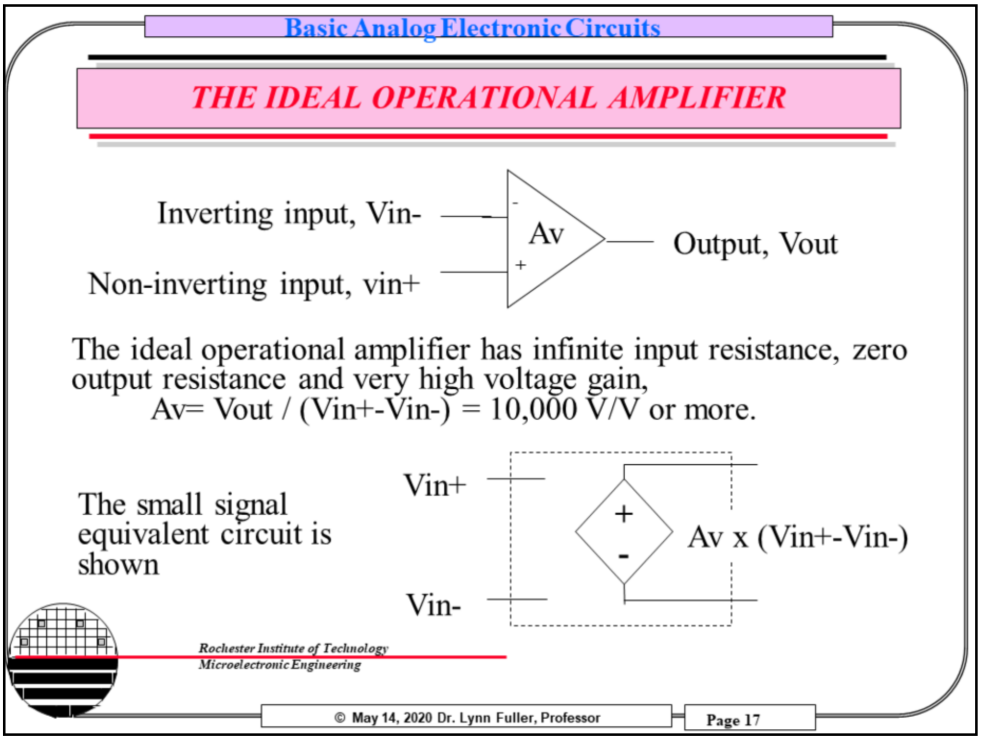
More from the data sheet.



This is a plot of the voltage gain and phase vs Frequency for an inverting amplifier configuration with, Rf and Rin, to give a low frequency gain to 40 dB or 100 V/V.

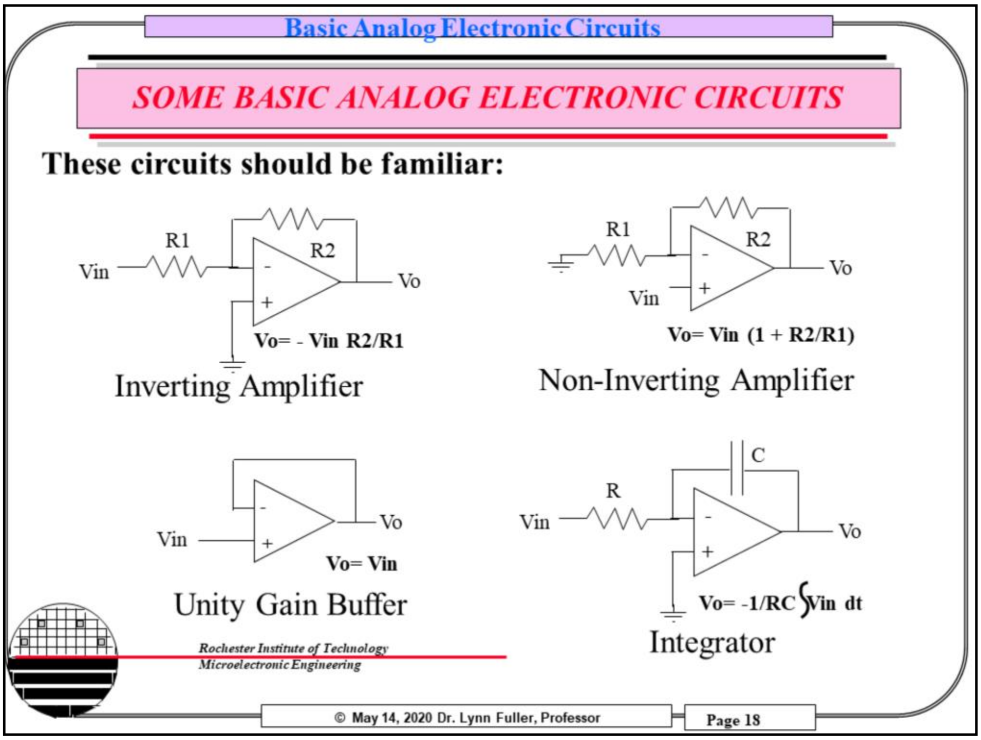


This is a low voltage op amp from Linear Technology that can output up to 5mA.

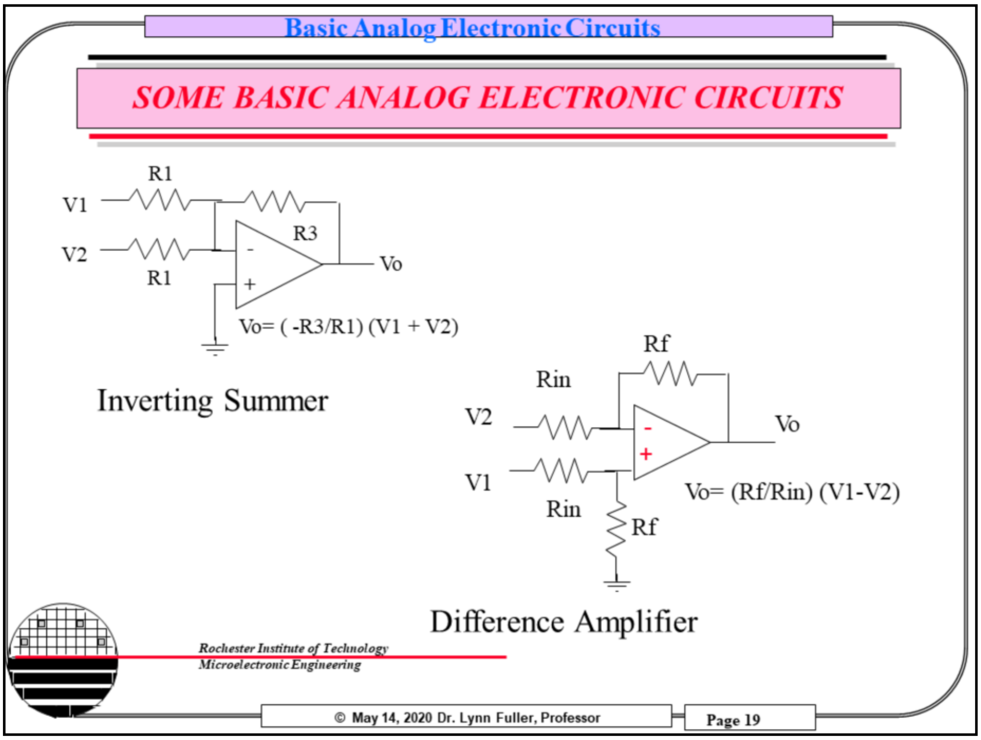


These properties imply in zero current into either of the differential inputs because the input resistance is infinite.

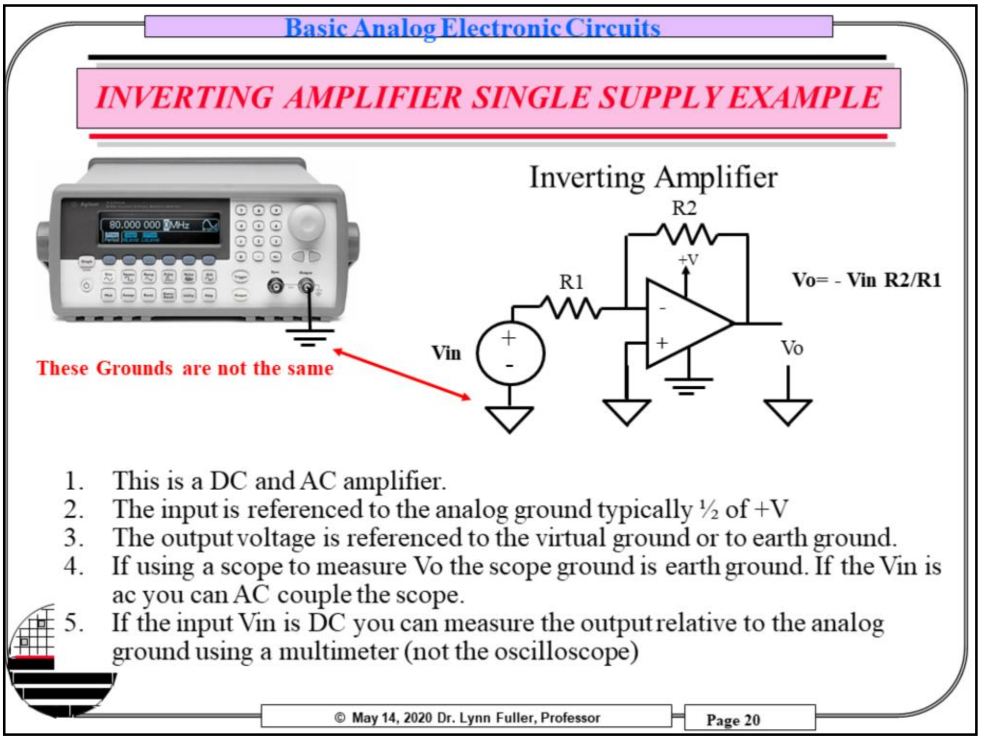
And very small voltage difference between the two inputs, (we say Vin+ and Vin- are at virtually the same voltage). This is because if the output voltage is finite the input is output divided by the very high gain, resulting in a very small voltage difference input.



These basic op amp circuits should be familiar. Lets apply ideal op amp fundamentals to the Inverting amplifier. Vin+ and Vin- are virtually at the same voltage, virtual ground and ground. The current in R1 is Vin/R1. With infinite input resistance the current in R1 has to go through R2 creating a voltage at Vo of – I x R2 which is equal to Vo. Combining these two equations we have Vo/Vin = - R2/R1 the inverting amplifier gain. You can apply these same concepts to derive the output equations for each of these circuits. Note the feedback connection always goes from Vo back to the inverting input.



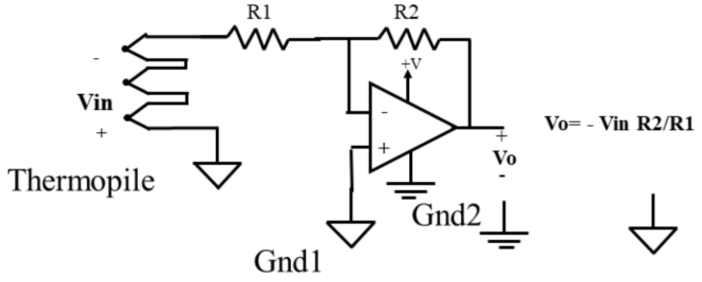
Two more basic op amp circuits. You can use the concepts of the ideal op amp with other circuit analysis techniques to derive the equation for the output voltage. The concept of superposition for linear circuits can help with these two circuits. That is find Vout due to V1with V2 equal to zero and add the result to Vout due to V2 with V1 equal to zero.



Most op amp circuits use dual power supplies so that the input and output voltages are referenced to ground. However, it is sometimes useful to use a single supply instead of two. In the single supply case the input and outputs should be referenced to a voltage near ½ of the single supply value. This requires careful consideration of grounds and analog signal grounds which are not the same for single supply op amp circuits.

INVERTING AMPLIFIER SINGLE SUPPLY EXAMPLE

Single Supply DC Inverting Amplifier



Gnd1 is analog ground ~1/2 of supply voltage. Vout can be taken relative to Gnd1 or Gnd2 however there is a +V/2 DC added to Vo if relative to Gnd2.

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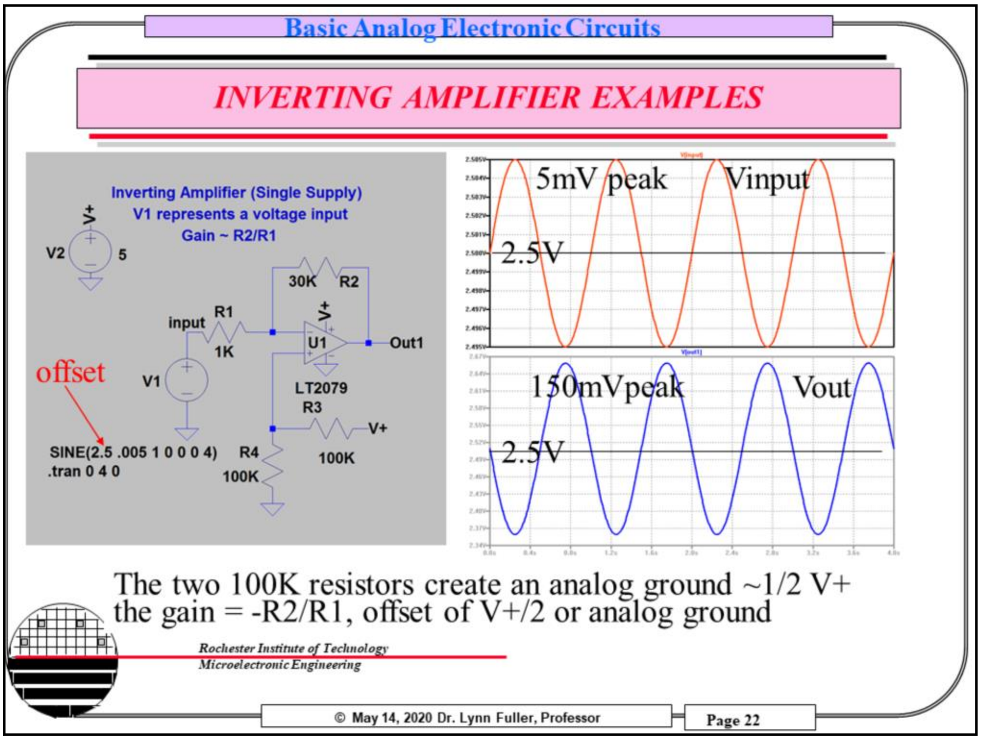
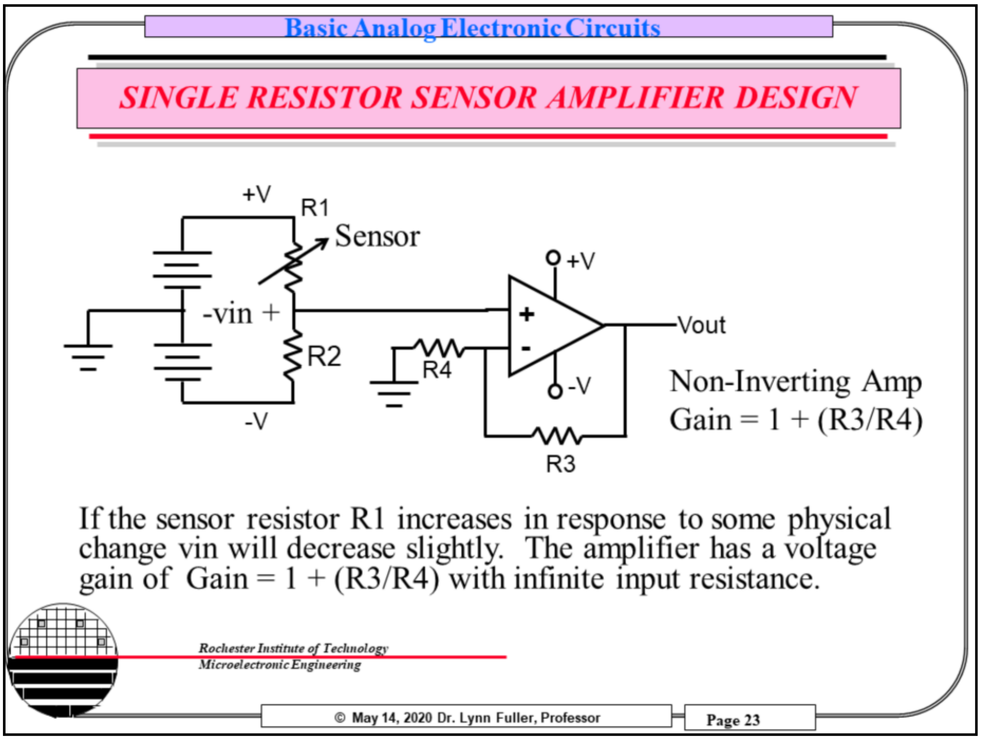
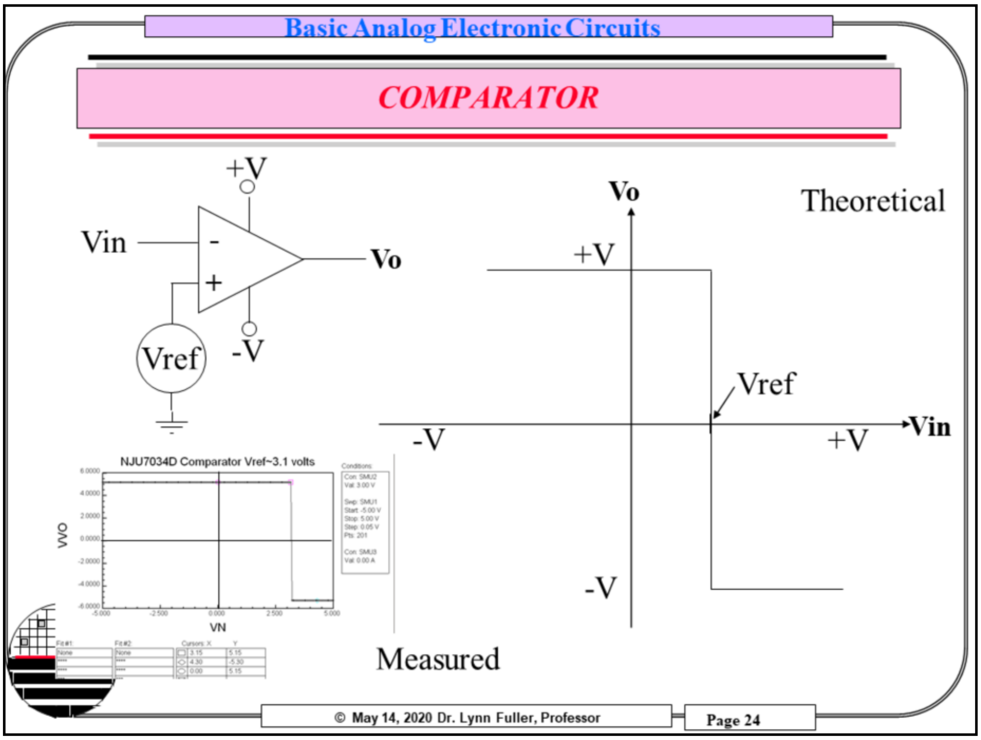
This is an example of a single supply op amp inverting amplifier for a small DC input voltage from a thermopile, Vin. If you had a analog ground at a voltage at ½ way between the +V and ground the output voltage would be ½ way between +V and ground for no Vin. With Vin not zero Vout will be –Vin (R2/R1) plus V+/2 volts.



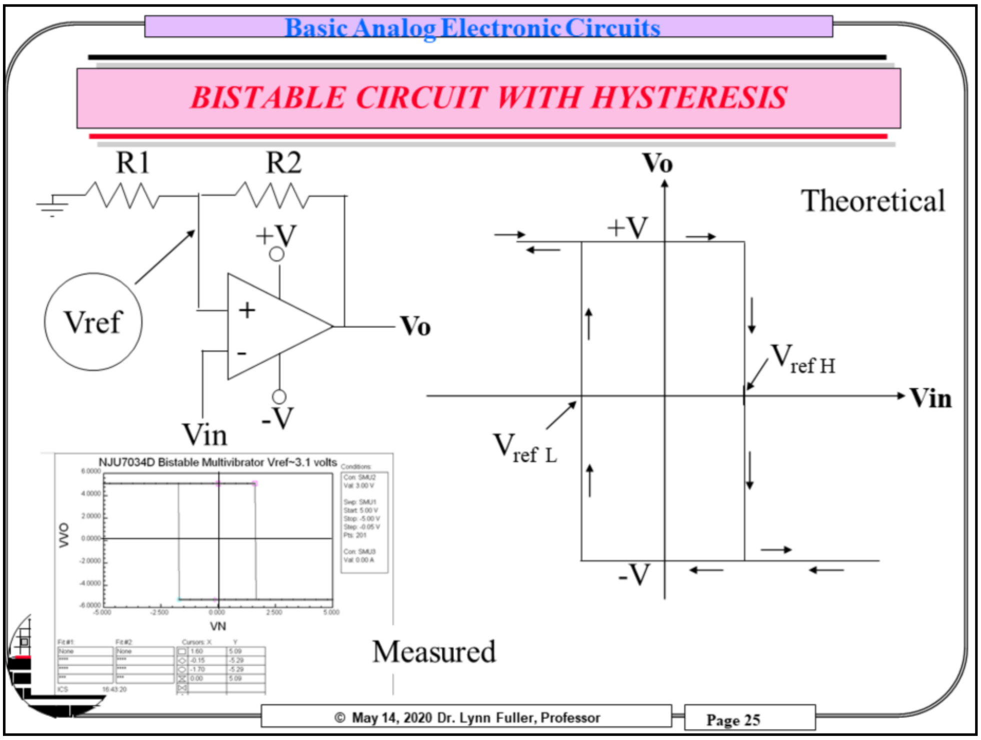
This shows a single supply amplifier for a sinusoidal input with a DC offset equal to the analog ground. In this case V+ divided by two. The output voltage is a sinusoid on a DC offset of V+/2. That is 5/2 = 2.5volts.



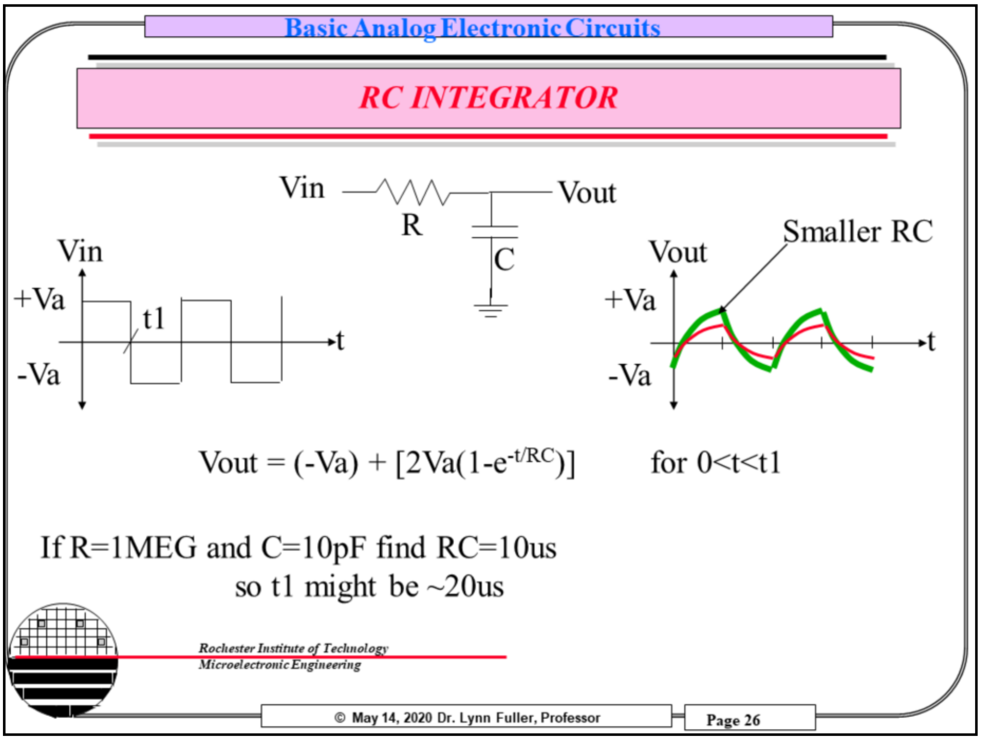
Single resistors can be used to sense temperature, light, strain and are used in pressure sensors, accelerometers and other applications. With a dual supply op amp a small change in resistance can be converted to a change in voltage with a circuit such as the dual supply op amp circuit shown above. Initially R1 and R2 are identical and vin is zero. If the sensor resistor R1 increases in response to some physical change vin will decrease slightly. The amplifier has a gain of Gain = 1 + (R3/R4) with infinite input resistance. Vout will be a DC voltage relative to ground or zero volts.



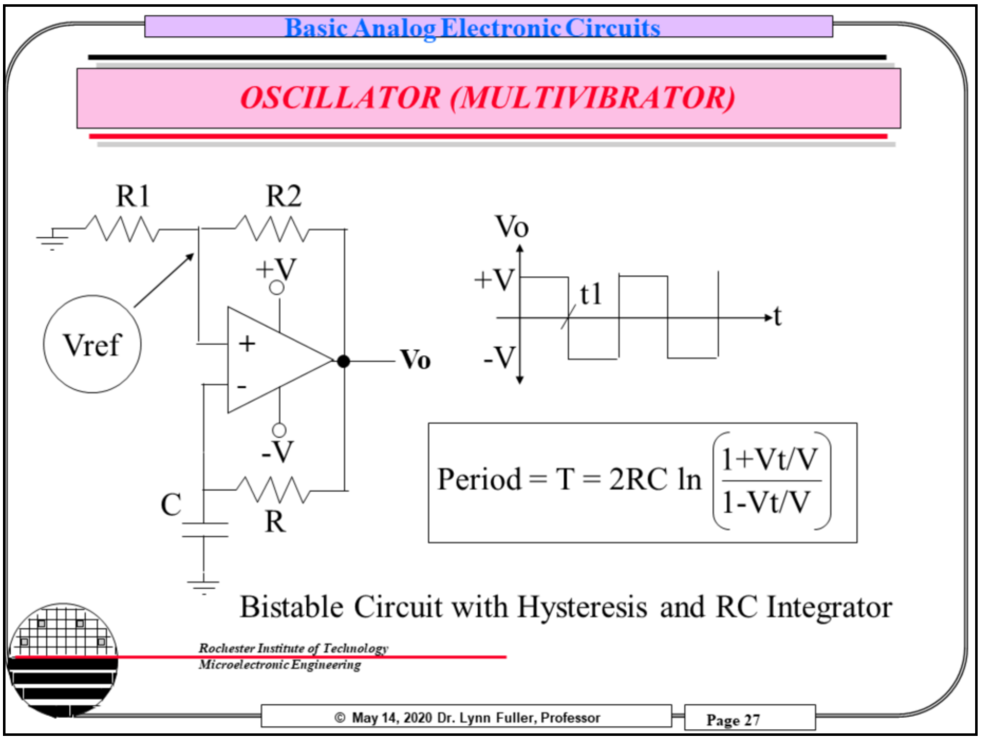
This is an example of the non linear operation of an op amp because there is no feedback from output to the inverting input. Because of the high gain of the op amp any small difference in Vin compared to Vref will be amplified by the huge gain of the op amp. So the output will be either +V or –V depending on if Vin is less than or greater than Vref. The vout vs vin plot is shown for Vin swept from –V to +V. The Vout will be +V when Vin is less than Vref and –V when Vin is greater than Vref.



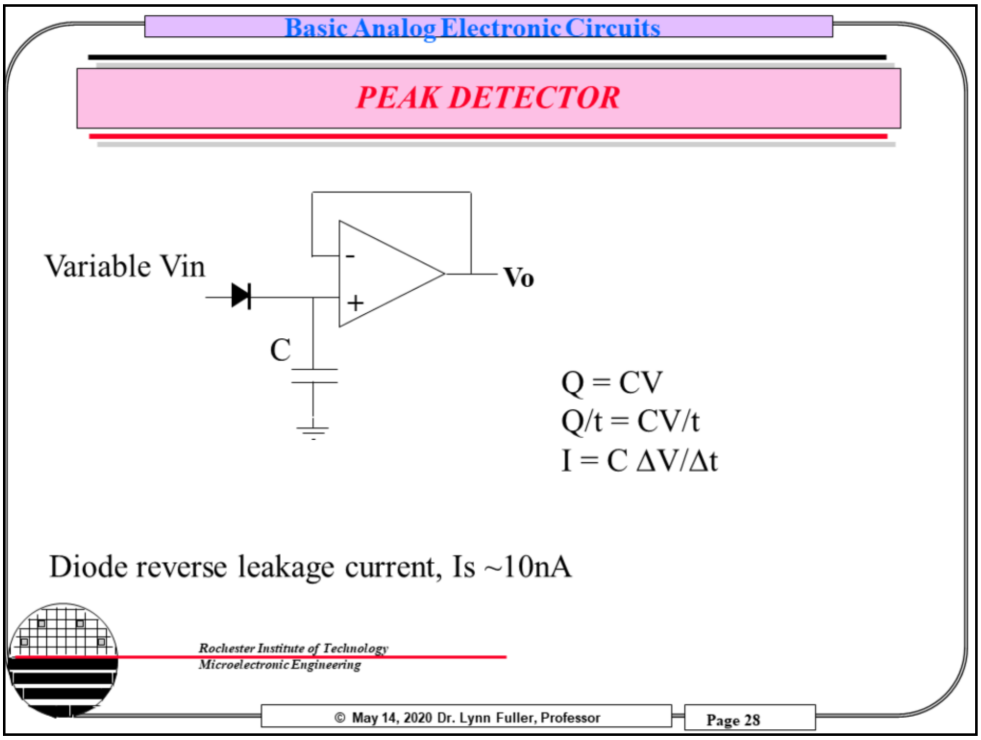
If the reference voltage Vref comes from Vout and a voltage divider R1/(R1+R2) then the reference voltage will have two different values one when Vout is high and a different value when Vout is low. If R1 is equal to R2 for example the reference voltage will be either +V/2 or –V/2. This will create hysteresis in the Vo vs Vin plot depending on which direction the Vin is being swept. If Vin is swept from low to high, Vout will start high, +V, (because the reference voltage is connected to the non-inverting input) and Vout will switch to low –V when the input gets to V/2. When sweeping in the negative direction the reference will be –V/2 and switching Vout to high when Vin reaches –V/2.



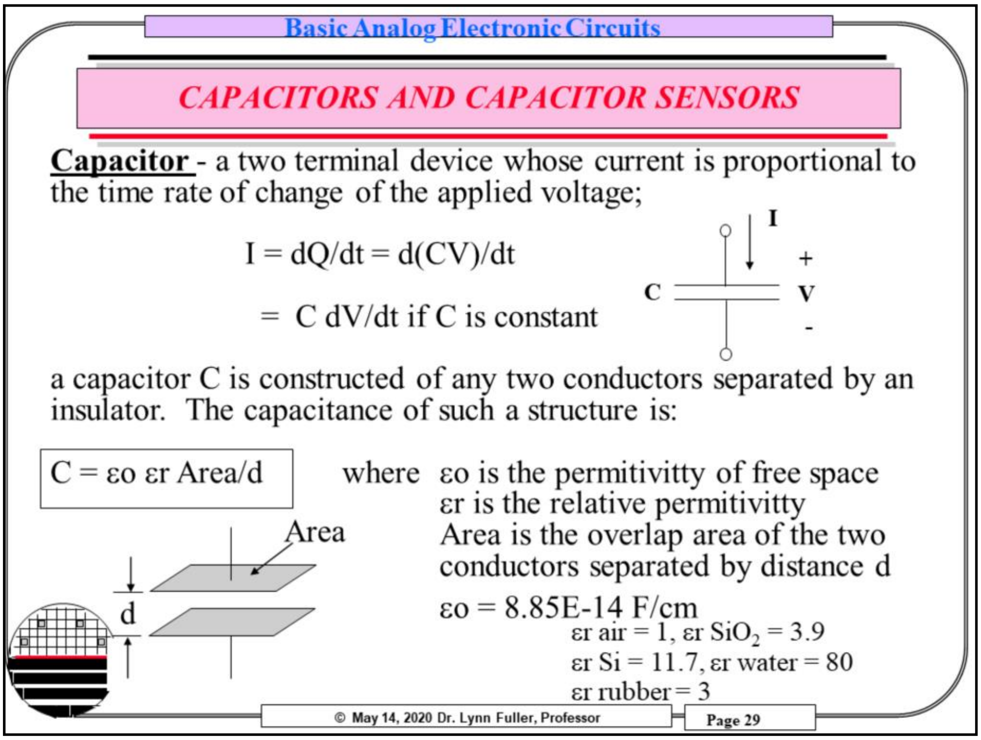
Instead of sweeping the input lets use a RC circuit to charge a capacitor to what ever the output voltage is at. If the output voltage is high the capacitor will try to charge up to high. If the RC circuit is used with the comparator circuit discussed on the previous page the output voltage will switch to low when the capacitor voltage reaches Vref making the output low and the capacitor will try to discharge to low but before I gets to –V it reaches the Vref Low and the output switches to high….. Thus continually oscillating high and low depending on the RC time constant.



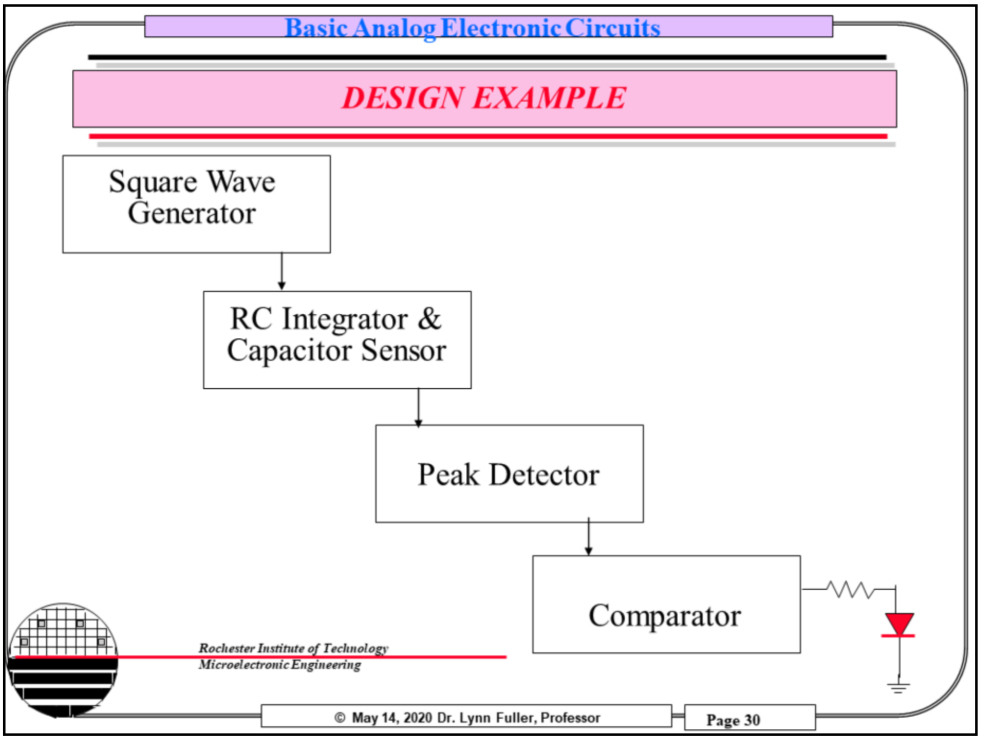
The voltage across the capacitor charges from –Vref towards +V with time constant RC at +Vref it triggers and changes to charge toward –V with time constant RC and continues to oscillate.



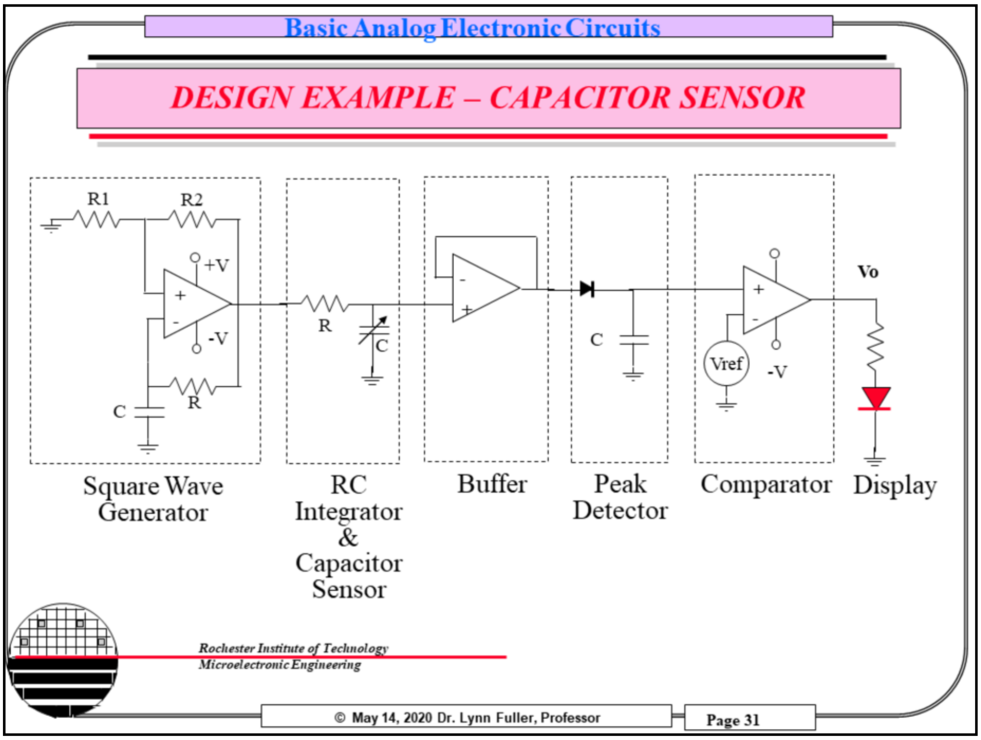
A changing input voltage will charge up the capacitor C to the peak of Vin. The capacitor will slowly discharge backwards through the diode with a constant current equal to the reverse leakage current, Is. The equation shown can be used to calculate the change in voltage on a capacitor when it is being discharged with a constant current. For example if Is=10nA and C=1uF the voltage across the capacitor can decrease at 10 millivolt per second. Adjusting the value of C changes how quickly Vout can respond to changes in Vin.



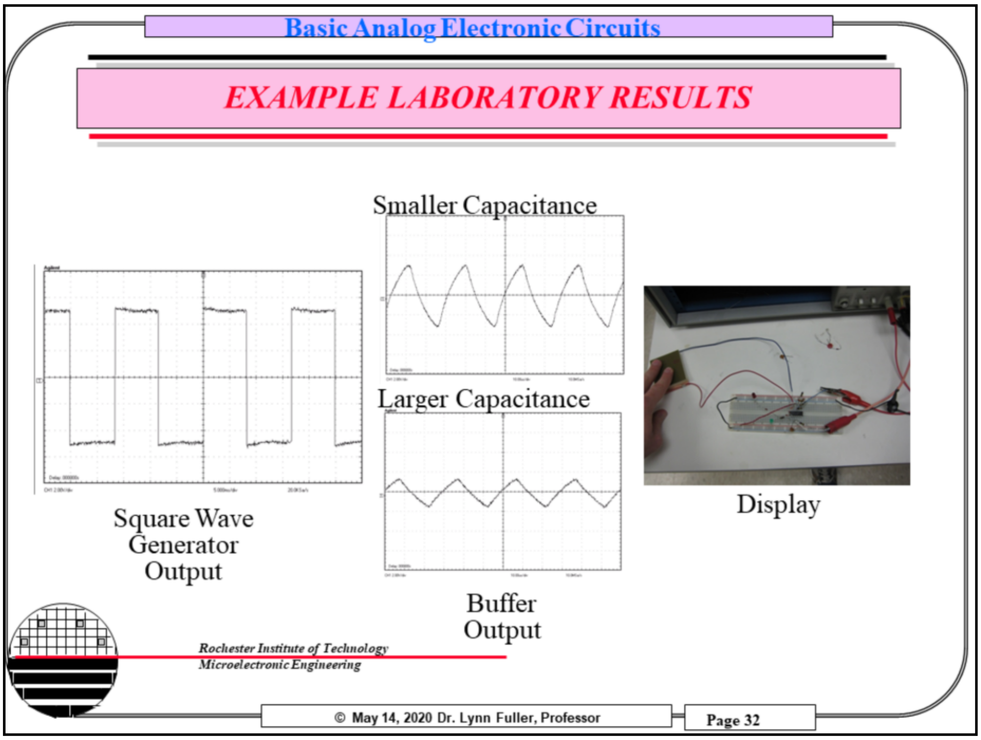
The equations at the top show the relationship for voltage and current in a capacitor. The equation in the box can be used to calculate the capacitance for two parallel plates. Other conductor configurations have different equations for capacitance.



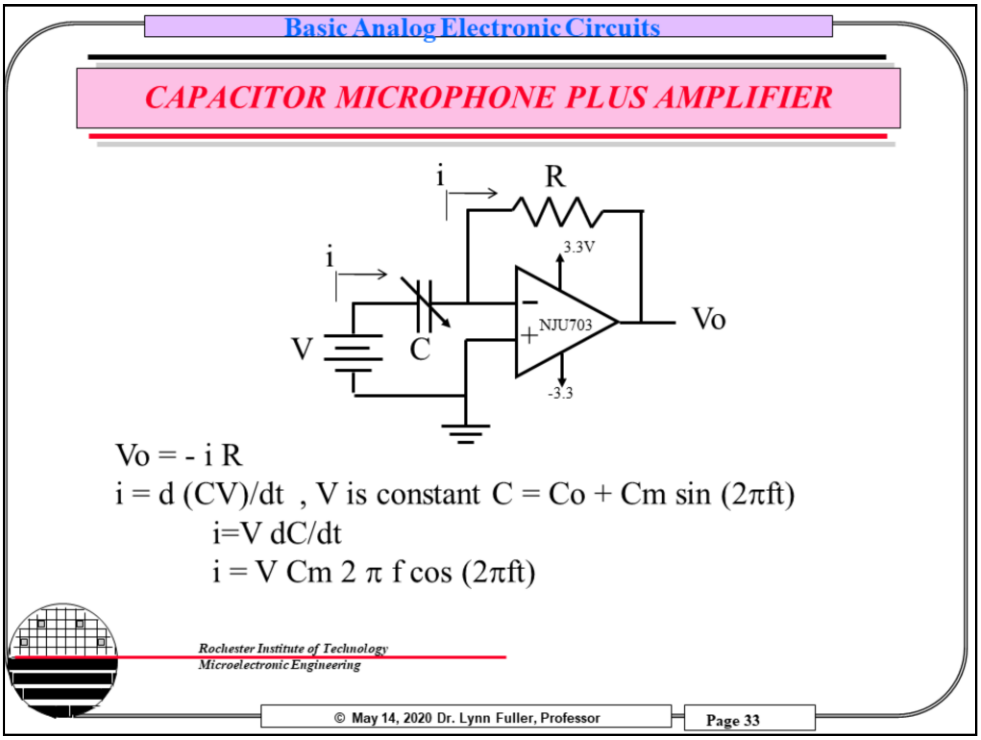
This shows an approach for an analog circuit design that will indicate when a capacitor sensor has reached some value. For example a capacitor used to measure a liquid level and when full turn on an LED indicator. Each block in the design approach above is converted into a circuit schematic on the next page.



This shows the op amps and other components used to realize the capacitor sensor design.



The circuit design from the previous page was used with a capacitor force sensor. Two parallel plates with foam between the plates. Pressure can push the plates closer increasing the capacitance. The buffer output shows that the waveform peak is related to the capacitance value. A bread board for this circuit was built and the signals were obtained using an oscilloscope. Note: this type of circuit can detect slowly changing capacitance values or even different steady capacitance values.



Microphones have a capacitor sensor that changes with sound pressures. The capacitor is a thin flexible diaphragm parallel plate structure. A small microphone, like the one in your smart phone, might have a capacitance of several pF with changes in capacitance of a few hundred fF in response to sound pressure waves. The capacitance changes will be at audio frequencies, say 1KHz to 10KHz range. The capacitance is shown as C0 + Cm sin (2πft) where Co might be 10pF and Cm might be 100fF and the frequency might be 5KHz. The calculation for Vo is shown in this slide. Do the math and find the amplitude of the output voltage for R of 1MEG. This circuit converts changing capacitance to changing voltage.

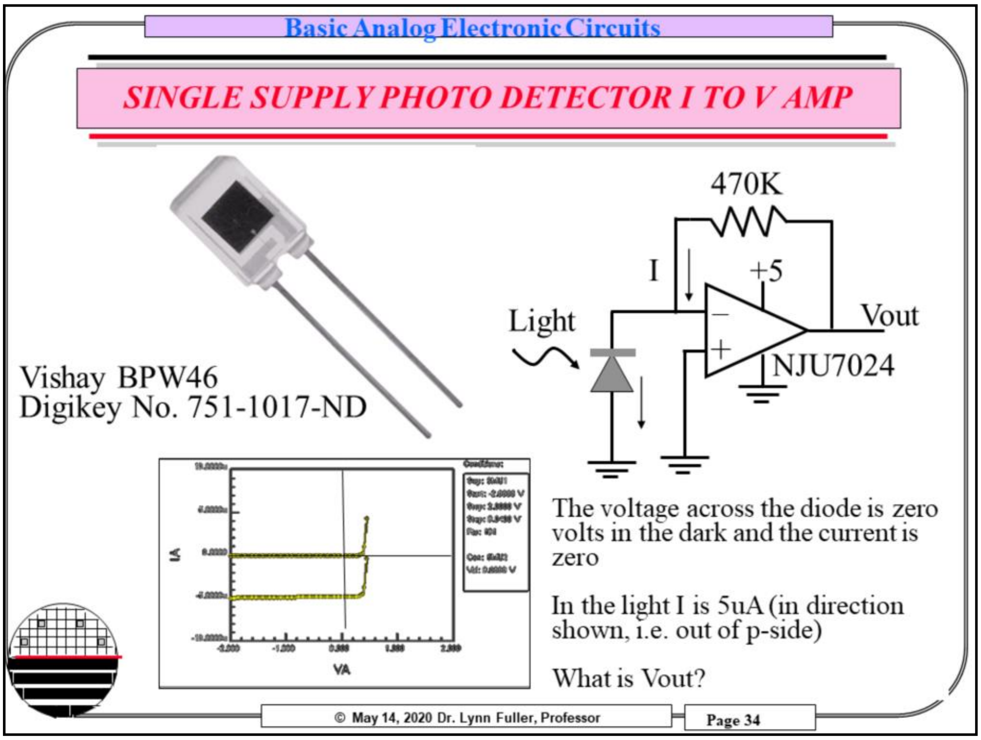
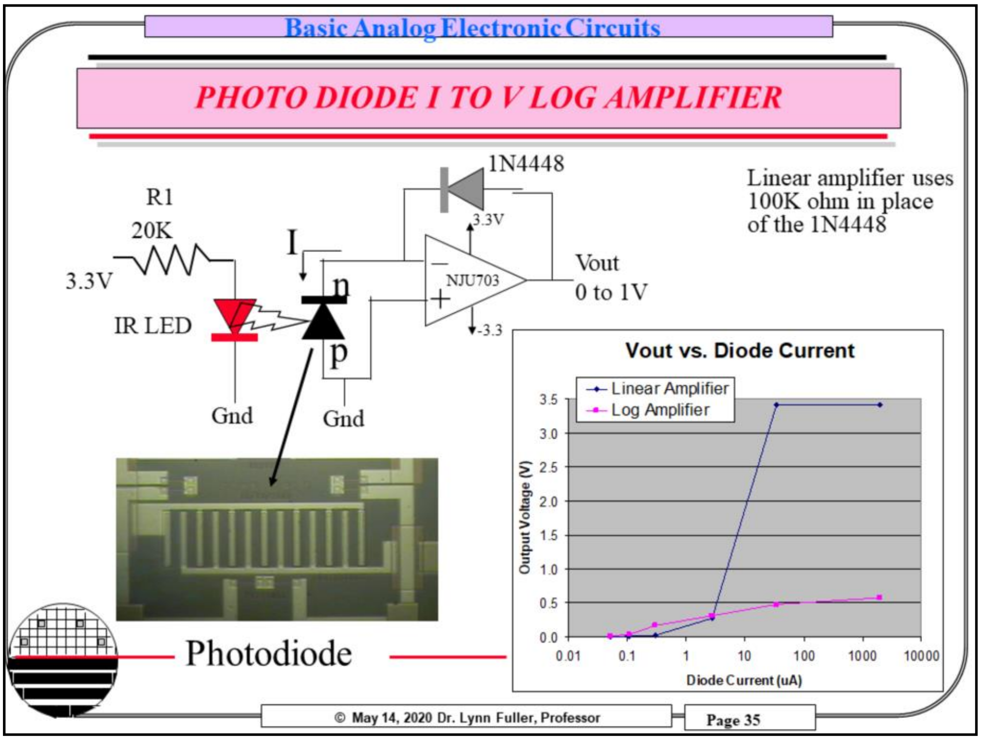
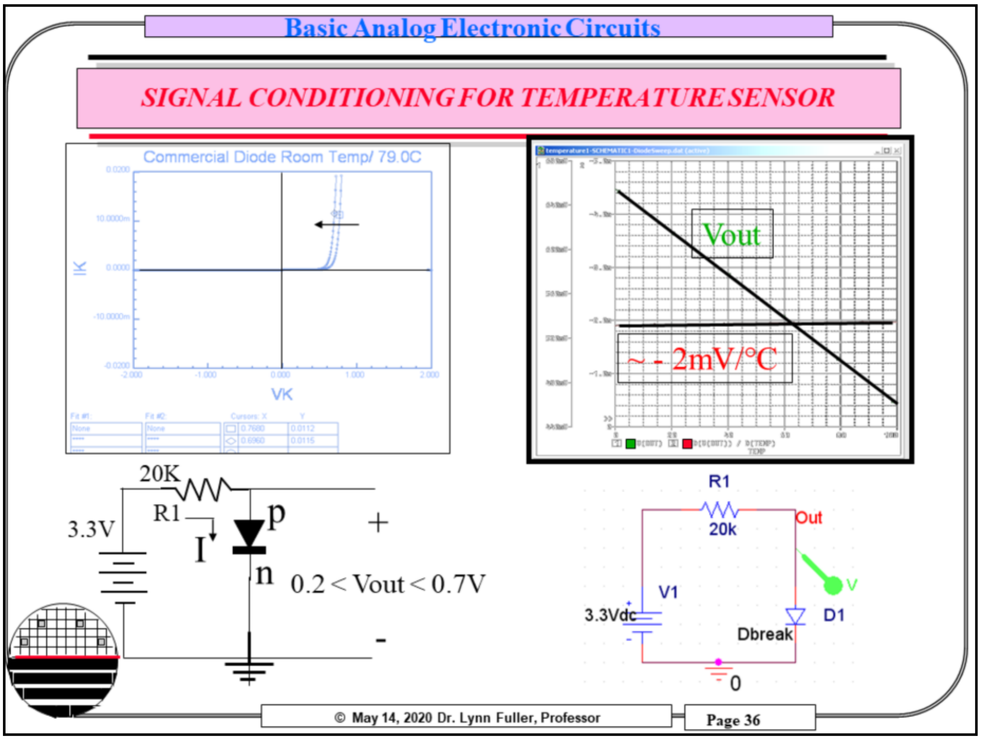


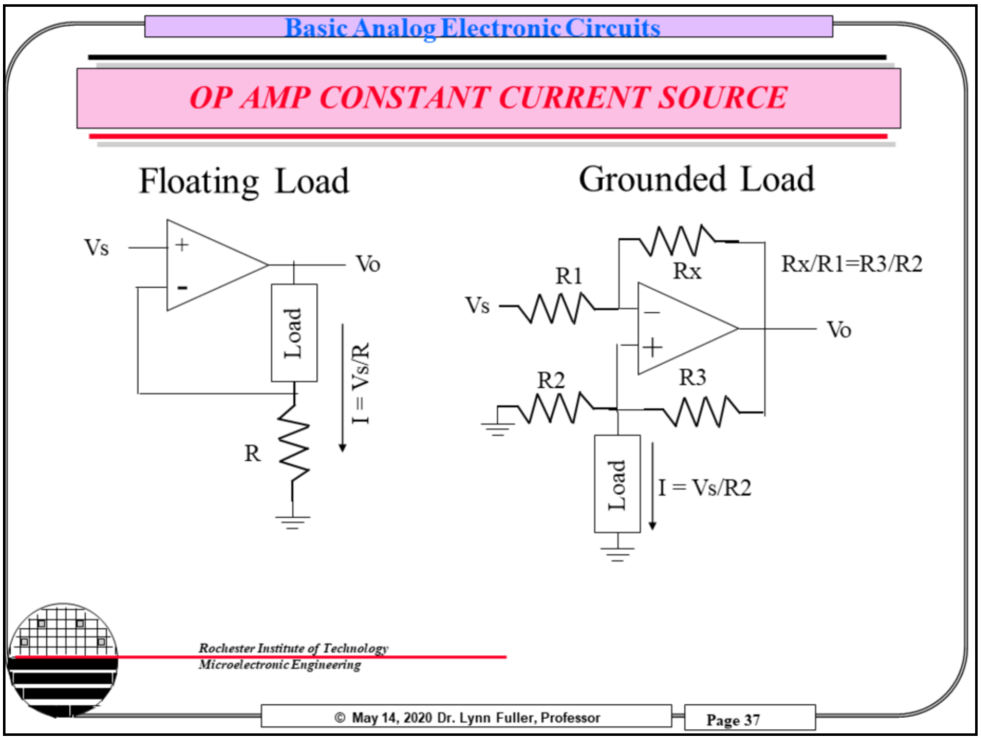
Photo diodes output current that is proportional to light intensity. The voltage changes a little but not much, always around .5 to .7 volts. This circuit is a current to voltage converter not a voltage amplifier. Light will cause current to flow out of the p-side of the diode. That current flows through the feedback resistor creating the output voltage relative to ground, virtual ground.



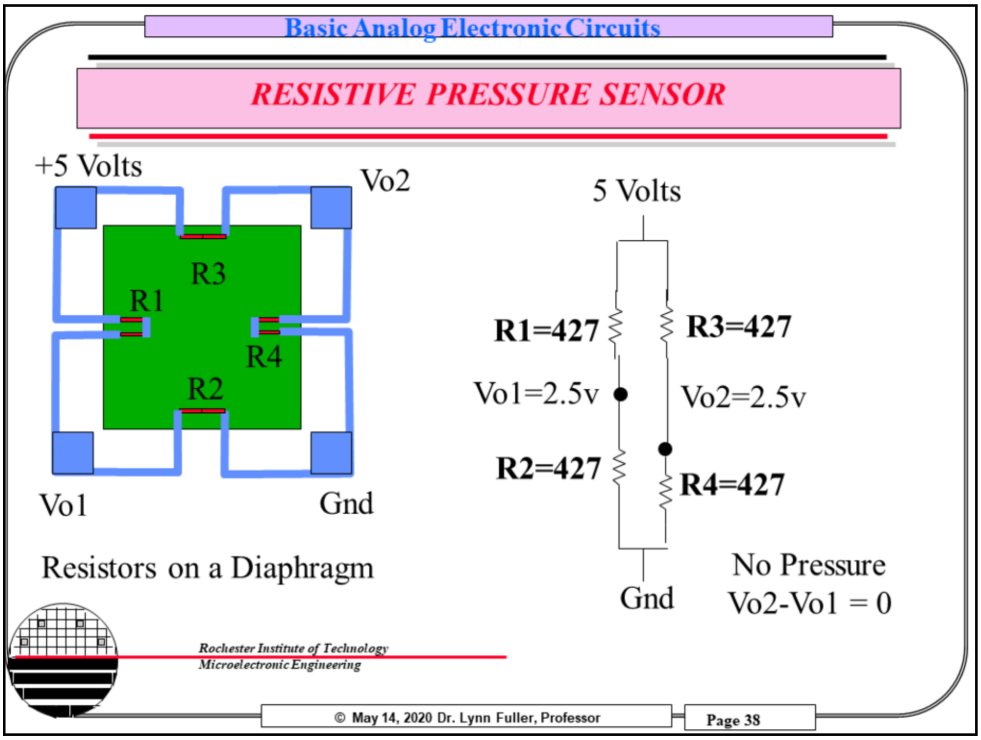
Light intensity changes many orders of magnitude from dark to very bright. A non linear current to voltage converter is shown here where the feedback resistor is replaced with a diode. The plot shows the difference between a linear amplifier, R in feedback, and logarithmic amplifier, diode in feedback, for photo diode currents over many orders of magnitude. This could be useful to set the exposure time for a camera based on the brightness.



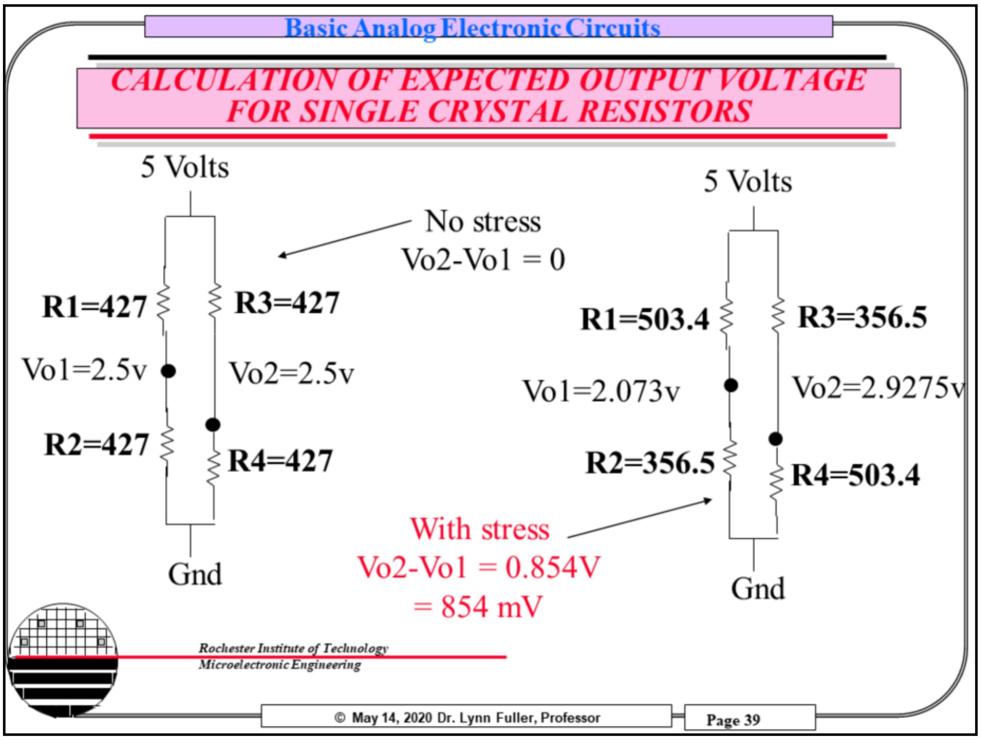
The forward voltage drop across a forward biased diode changes by ~ -2mV/°C. This circuit forward biases a diode operating at approximately (3.3 -0)/20K = 0.13 mA The plot of Vout has a slope of ~-2mV/°C which is fairly constant over the temperature range shown on the x-axis of zero to 100 °C, The I-V curve shifts to the left at higher temperatures.



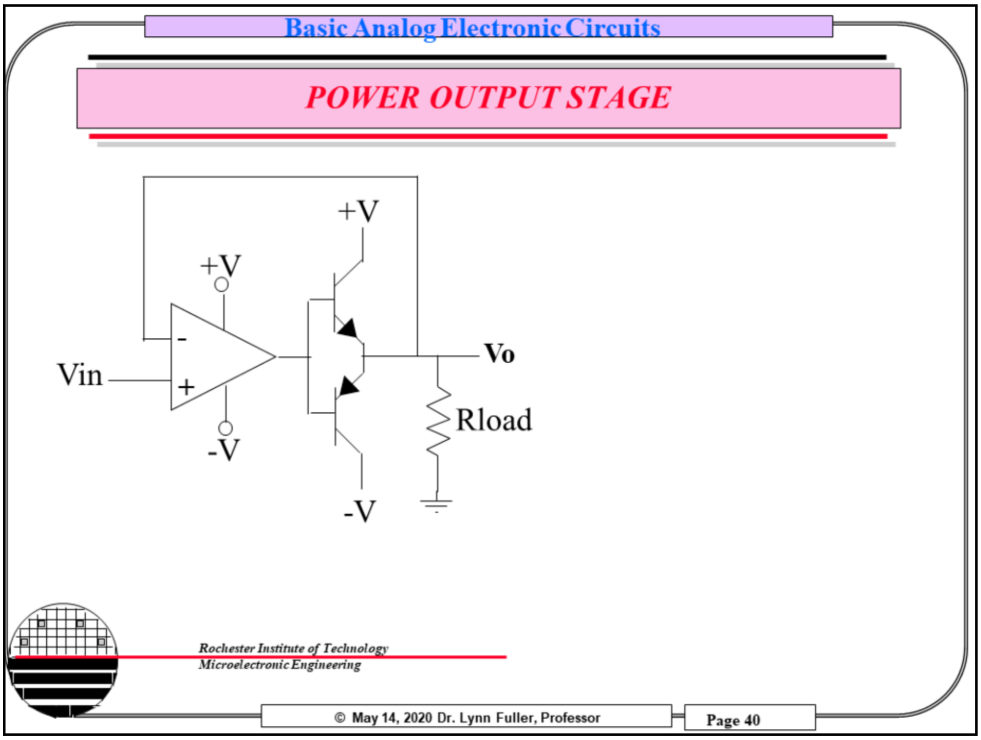
These two circuits provide a constant current to the load. The current value is set by the voltage Vs.



This figure shows four resistors on a diaphragm use for sensing pressure. With no pressure all the resistors are equal in value. When pressure is applied a stress occurs making R1 and R4 longer and making R3 and R2 wider. The resistors change a little with pressure. How much they change depends on the how the resistors are made. In general the could by resistors in single crystal silicon or thin film resistors on top of the diaphragm. P-type resistors in single crystal silicon with a specific crystal orientation would result in R1 and R4 increasing in resistance while R3 and R2 decrease in resistance. See the next page.



This is a possible comparison of resistor values with no pressure applied on the left and with a specific amount of pressure applied on the right. Vo2 increases and Vo1 decreases. The pressure sensors in your smart phone work like this.



Op amps have limited output current. I you want a little more output current you can use power transistors as shown to boost the current available to the load. This is a unity gain configuration with infinite input resistance and voltage gain of 1 V/V

REFERENCES

1. Switched Capacitor Circuits, Phillip E. Allen and Edgar Sanchez-Sinencio, Van Nostrand Reinhold Publishers, 1984.

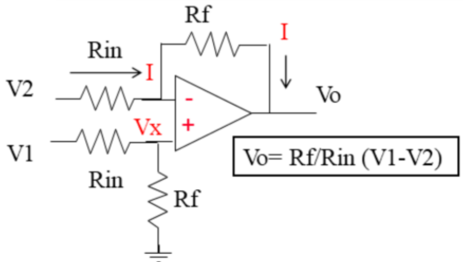
2. "Active Filter Design Using Operational Transconductance Amplifiers: A Tutorial," Randall L. Geiger and Edgar Sanchez-Sinencio, IEEE Circuits and Devices Magazine, March 1985, pg. 20-32.

3. Microelectronic Circuits, 5th Edition, Sedra and Smith

HOMEWORK – BASIC ANALOG CIRCUITS

1. Design a bistable multivibrator with Vth of +/- 7.5 volts and frequency of 5 Khz.
2. Design a temperature sensor circuit that will shut down a heater if the temperature exceeds 90°C
3 Design a peak detector that will respond to changes in input in less than one second.
4. Derive the voltage gain equation for the difference amplifier.

DERIVE GAIN EQUATION FOR DIFFERENCE AMP



Difference Amplifier

$$I = (V2 - Vx)/Rin$$

$$Vx = V1 \frac{Rf}{Rf + Rin}$$

$$Vo = -I\,Rf + Vx$$