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***Session 4 – Analog Integrated
Circuits and Components***

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Analog Integrated Circuits and Components

Introduction

- **Instructor : Bill Smith, KQ1S**
 - Amateur Extra
 - Licensed since 1983
- *The ARRL Handbook for Radio Communications, 98th Edition, 2021*
 - Sections 4.5.7 – 4.11.11

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Analog Integrated Circuits and Components

Course Overview

- **Transistors**
- **Op Amps**
- **Miscellaneous Analog ICs**
- **Timers**
- **Analog-Digital Interfacing**
- **Heat Management**

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Analog Amplifiers

- The most common type of *analog* circuit in use
- **Amplification** occurs when a small input signal controls a larger output signal
- The basic component of an amplifier is a **Transistor**
- Many designs today employ **Integrated Circuit (IC)** amplifiers
- One of the most common IC amplifiers is the **Operational Amplifier (OP Amp)**

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Amplifier Terminology

- **Input Impedance** – The equivalent ac impedance that one observes looking *into* the *input* of a circuit or device
- **Output Impedance** – The equivalent ac impedance that one observes looking *into* the *output* of a circuit or device
- **Gain (Voltage, Current, Power)** – The **ratio** of *output* voltage, current, or power to *input* voltage, current, or power – $V, C, P_{\text{Out}} / V, C, P_{\text{In}} = \text{Gain}$
- **Buffer** – An amplifier used to provide isolation between two circuits
- **Isolation** – Lack of effect of one circuit from changes in another circuit

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Semiconductor Amplifier Models

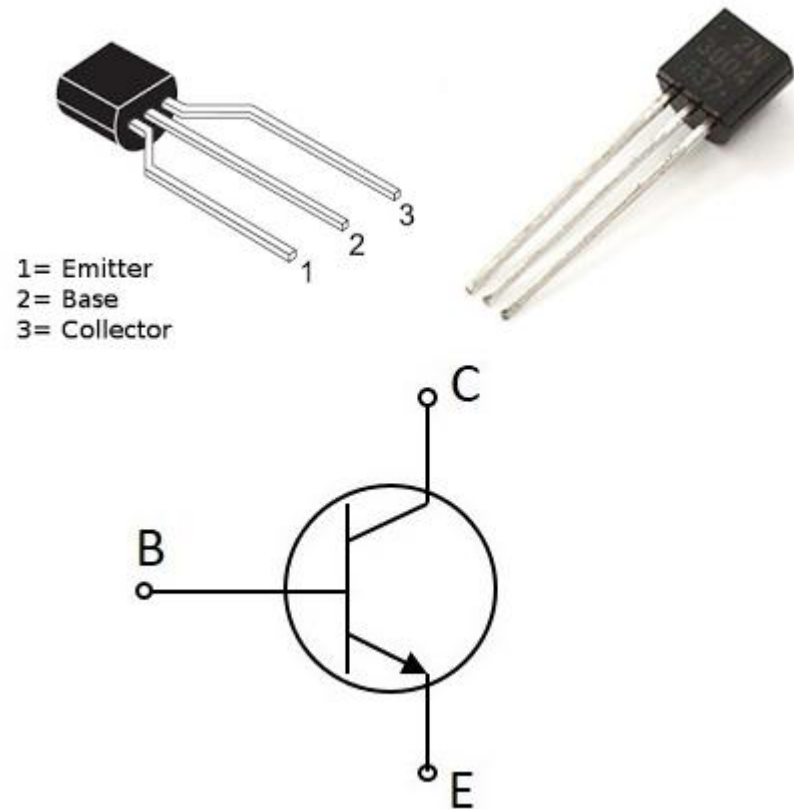
- **Model** – Semiconductor ***equivalent circuit*** design comprised of voltage and current sources, resistors, capacitors, and inductors
- Various models for specific purposes:
 - **Small-signal Model** – Used when voltage and current interact in a near linear fashion
 - **Large-signal Model** – Used when the device will be operated at saturation or cut-off
 - **Low-frequency Model** – Used in DC, audio, and very low RF frequency applications
 - **High-frequency Model** – Used for high frequency, high gain, or phase shift applications

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Transistor Amplifiers - Bipolar Junction Transistor (BJT)



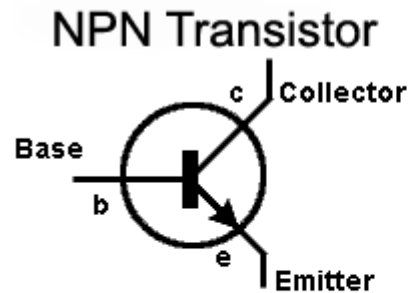
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Bipolar Junction Transistor (BJT)

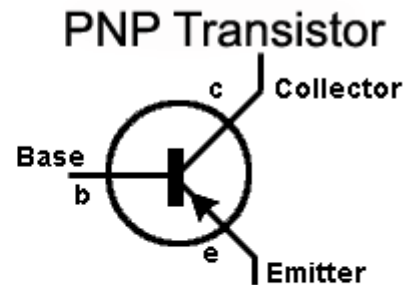
- Two Types – **NPN** and **PNP**
 - **NPN** – N-type substrate with P-type channel infused
 - **PNP** – P-type substrate with N-type channel infused

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Bipolar Junction Transistor (BJT)



N Never
P Points
N iN



P Points
N iN
P Permanently

(Current flow is generally in the direction of the emitter arrow)

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Bipolar Junction Transistor (BJT) Amplifiers

- Three Common BJT Amplifier Configurations
 - Common-Emitter (Most common amplifier configuration)
 - Common-Collector (Often referred to as an ***Emitter Follower***)
 - Common-Base
- BJT amplifiers are mainly ***current-controlled*** devices
- “Common” = The part of the transistor used by both the input and output

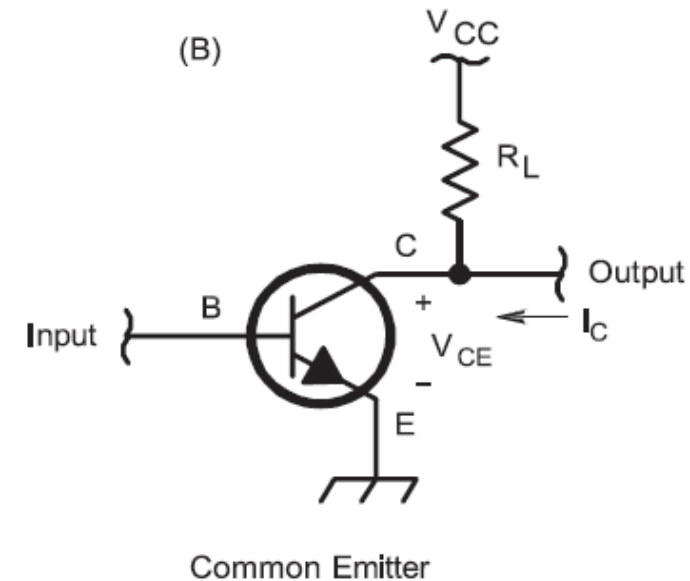
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Common-Emitter Amplifier

- Most common *small-signal* amplifier
- Used when a **modest voltage gain** and a **low to medium input impedance** is required
- A positive increase in input amplitude *increases* base current and *reduces* collector current
- The output signal is *inverted* relative to its input signal



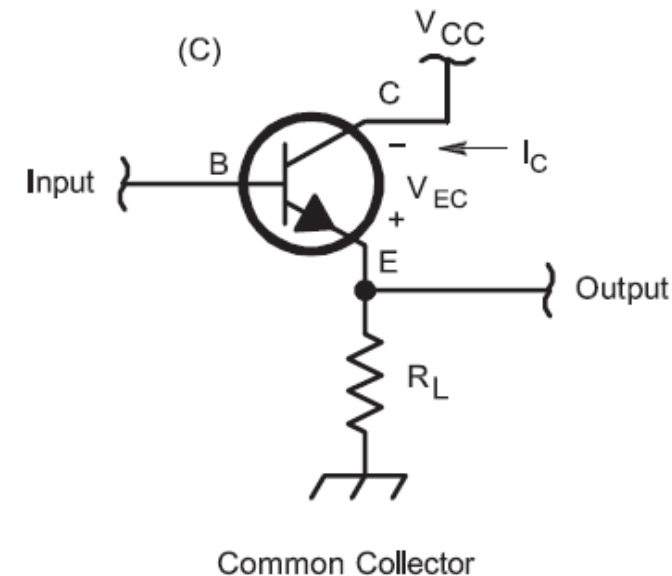
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Common-Collector (Emitter-Follower) Amplifier

- Generally referred to as an ***Emitter-Follower*** amplifier
 - Emitter voltage follows input voltage
 - Exhibits ***unity voltage gain***
- Used as a buffer amplifier to couple low impedance loads or protect sensitive circuits
- Used when a **high input/low output impedance** is required



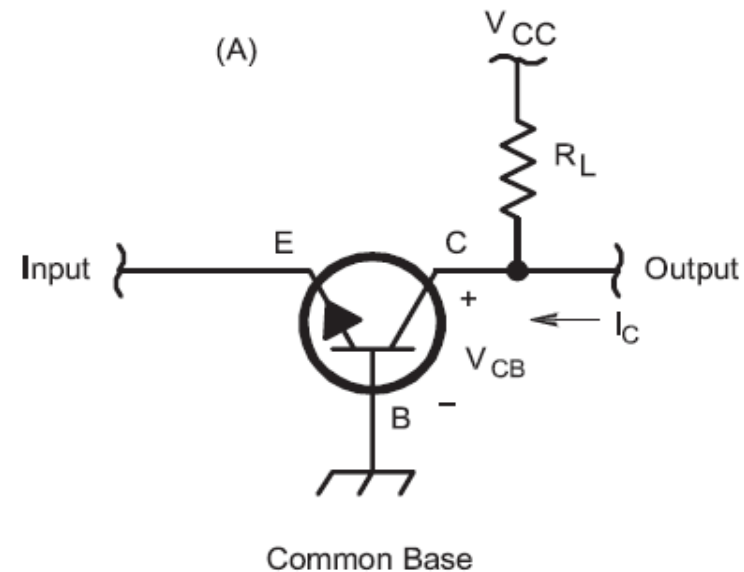
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Common-Base Amplifier

- Exhibits ***unity current gain***
- Used when a **low input/high output impedance** is required
- Useful for Ham radio pre-amplifiers
- A positive increase in input amplitude ***reduces*** base current – V_{BE} is lowered; V_C is raised



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Bipolar Junction Transistor (BJT) Comparison

NPN-Type	PNP-Type
If the base is at a lower voltage than emitter , <i>current flows emitter-collector</i>	If the base is at a higher voltage than the emitter , <i>current flows collector-emitter</i>
A small amount of current also flows emitter to base	A small amount of current also flows base to emitter
Emitter and collector not interchangeable	Emitter and collector not interchangeable
Voltage at base controls amount of current flow thru transistor (E-to-C)	Voltage at base controls amount of current flow thru transistor (C-to-E)
Current flows in direction of the arrow	Current flows in direction of the arrow

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Analog Amplifier Operating Classes

<u>Class</u>	<u>Characteristic</u>
A	100% duty cycle
B	50% duty cycle
C	<50% duty cycle
AB	50% to 100% duty cycle
AB-1, AB-2	50% to 100% duty cycle

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Transistor Amplifiers – Field-Effect Transistor (FET)

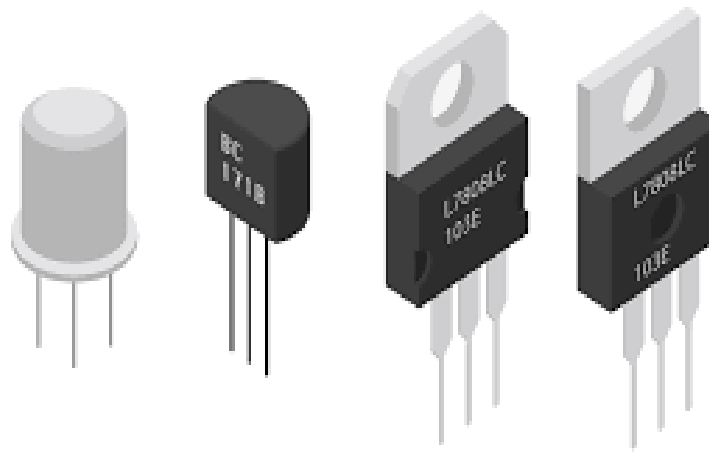
- Widely used in radio and other RF applications today
 - **JFET** – Junction Field Effect Transistor
 - **MOSFET** - Metal-oxide-semiconductor Field Effect Transistor

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Field-Effect Transistor (FET)



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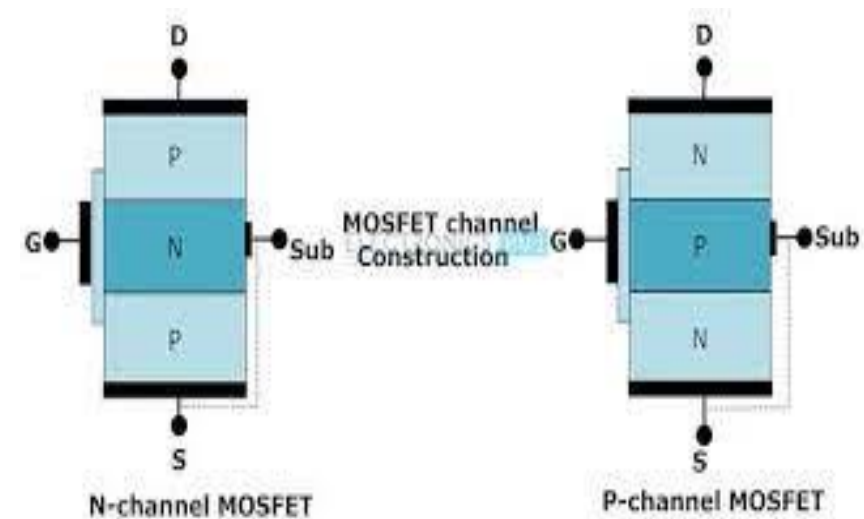
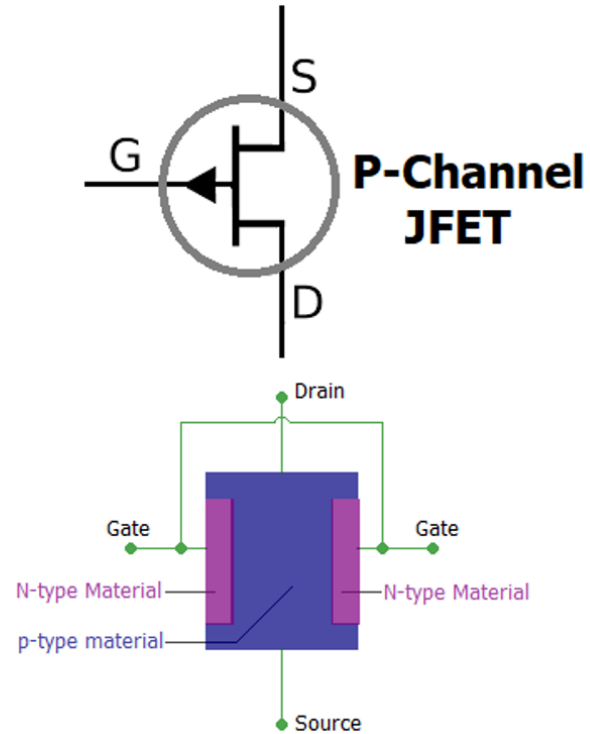
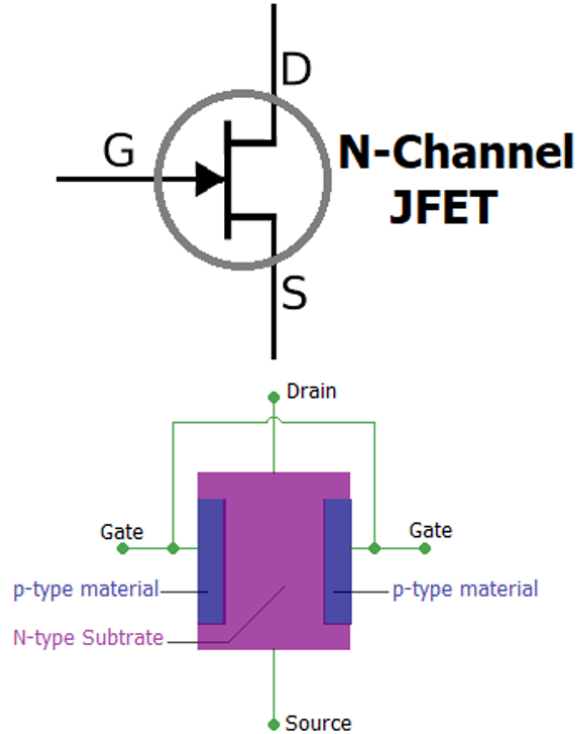
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Field-Effect Transistor (FET)

- Two Types – **N-channel** and **P-channel**
 - ***N-channel*** – N-type substrate with P-type channel infused
 - ***P-channel*** – P-type substrate with N-type channel infused

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Field-Effect Transistor (FET)

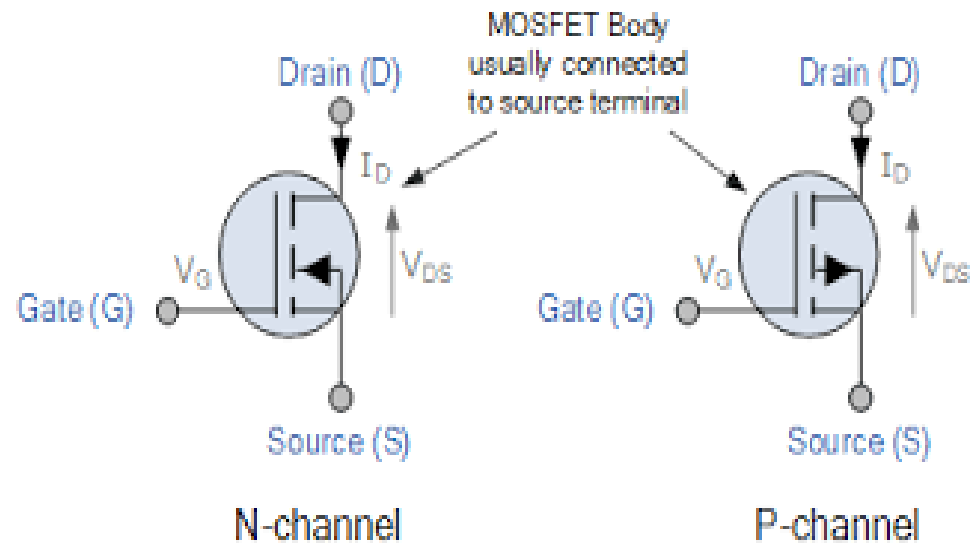


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Field-Effect Transistor (FET)



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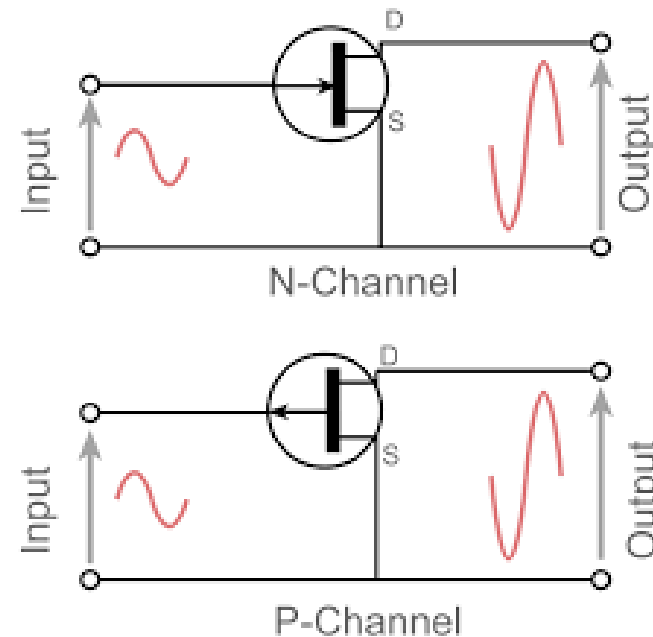
Field-Effect Transistor (FET) Amplifiers

- Three Common FET Amplifier Configurations
 - Common-Source (*Corresponds to the common-emitter*)
 - Common-Drain (Referred to as a **Source-Follower**; *Corresponds to the emitter-follower*)
 - Common-Gate (*Corresponds to the common-base*)
- FET amplifiers are strictly **voltage-controlled** devices
- “Common” = The part of the transistor used by both the input and output

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Common-Source Amplifier

- Can be used as a variable resistance – Usually operates in **saturation region**
- The Drain-Source channel can be treated as a current source
- A positive increase in input amplitude **reduces** output voltage
- The output signal is **inverted** relative to its input signal (similar to CE)



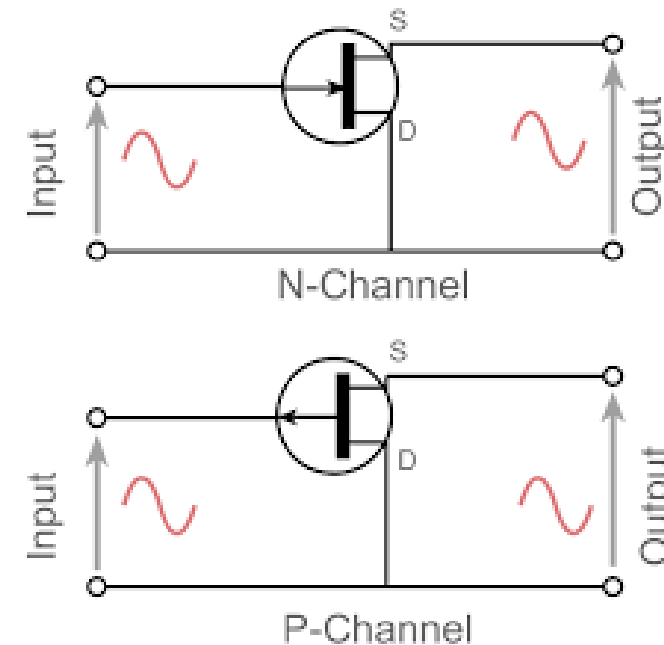
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Common-Drain (Source-Follower) Amplifier

- Generally referred to as a **Source-Follower** amplifier
 - **Source** voltage follows **input** voltage
 - Exhibits **unity voltage gain**
- Used as a **buffer amplifier** to couple low impedance loads or protect sensitive circuits
- Used when a **high input/low output impedance** is required



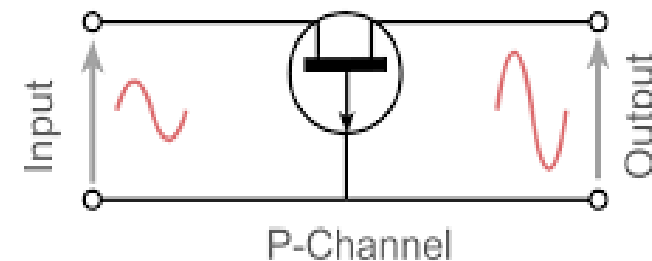
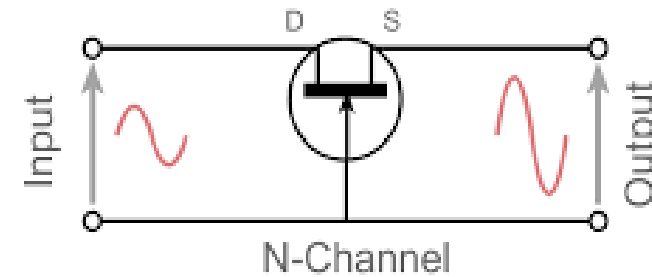
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Common-Gate Amplifier

- Exhibits ***unity current gain***
- Exhibits ***high voltage gain***
- Used when a **low input/high output impedance** is required
- Useful for Ham radio pre-amplifiers
- Often chosen as **pre-amplifiers** because their ***high voltage gain*** and ***low input impedance*** can match coaxial cable impedances



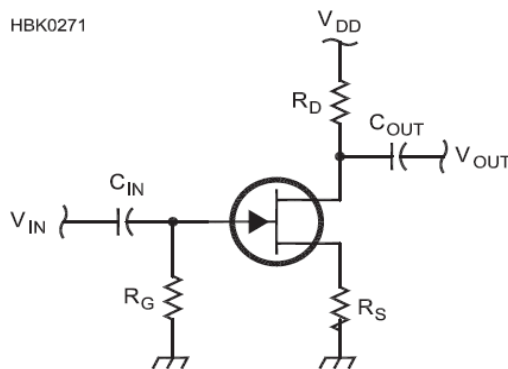
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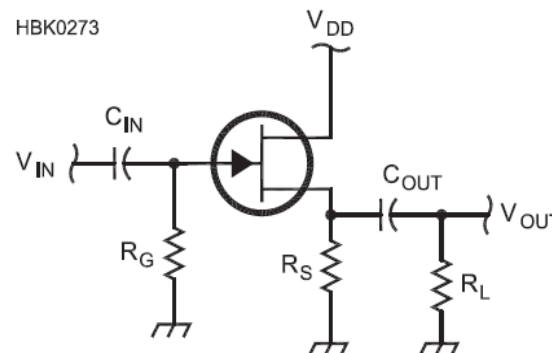
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Self-biased FET Amplifiers

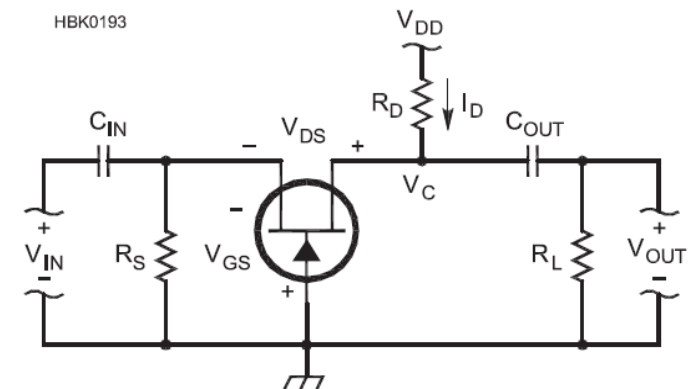
- FET amplifiers are usually self-biased to prevent DC voltage build up affecting conductivity (C_{IN} plus R_G or R_S)



Common-Source



Common-Drain



Common-Gate

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Field-Effect Transistor (FET) Comparison

JFET	MOSFET
Comparatively harder to fabricate	Comparatively easier to fabricate
Operated only in depletion mode	Can be operated in both depletion and enhancement modes
Drain resistance is 1 M Ω – Results in flatter output characteristics	Drain resistance is 50 k Ω
Gate leakage current is roughly 10^{-9} Amp	Gate leakage current is roughly 10^{-12} Amp
Input resistance is roughly $10^8 \Omega$	Input resistance is in the range of $10^{10} \Omega$ to $10^{15} \Omega$
Non-symmetrical device	Symmetrical device – Source and Drain terminals can be interchanged

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Field-Effect Transistor (FET) Amplifiers

- Because of their advantages, *MOSFETs are more widely used* than JFETs
- MOSFETs are widely used in analog signal switching applications
- MOSFETs are *highly susceptible to overload voltages* – Care must be taken during handling and installation not to damage with static charges

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Operational Amplifiers (Op Amps)

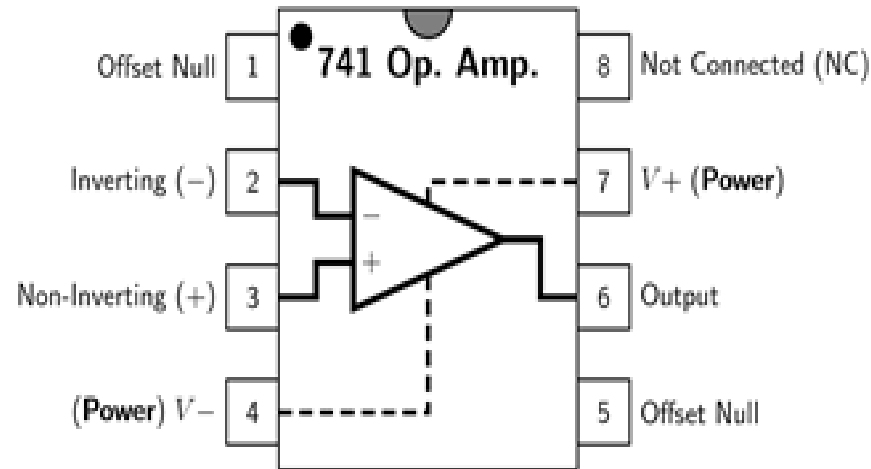
- One of the most ***widely used*** linear IC devices
- Built as a ***package*** to ***ensure close matching*** of circuit ***components***
- **Much higher performance** than similar circuits built using discrete components
 - ***Infinite input impedance***
 - ***Zero output impedance***
 - ***Open loop voltage gain near infinity***

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Operational Amplifiers (Op Amps)



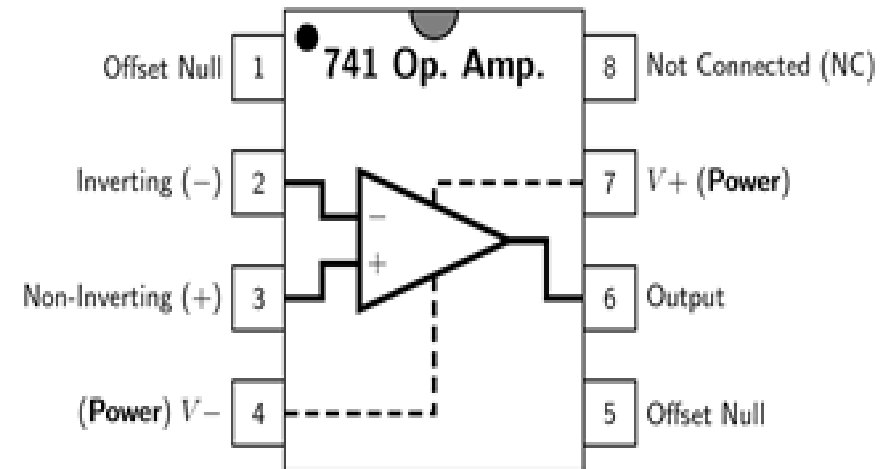
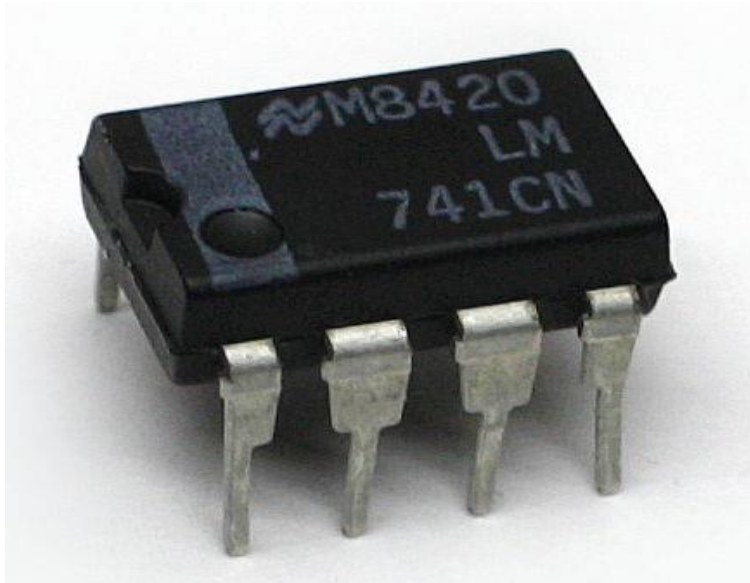
- Though the Op Amp is valued for its nearly infinite input impedance, current in the ***nanoAmp range*** does actually flow
- At times, a ***small (mV) DC offset voltage***, known as an ***input offset voltage***, is applied to the input terminals through a potentiometer (The **741** Op Amp has pins for this purpose)

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Operational Amplifiers (Op Amps)

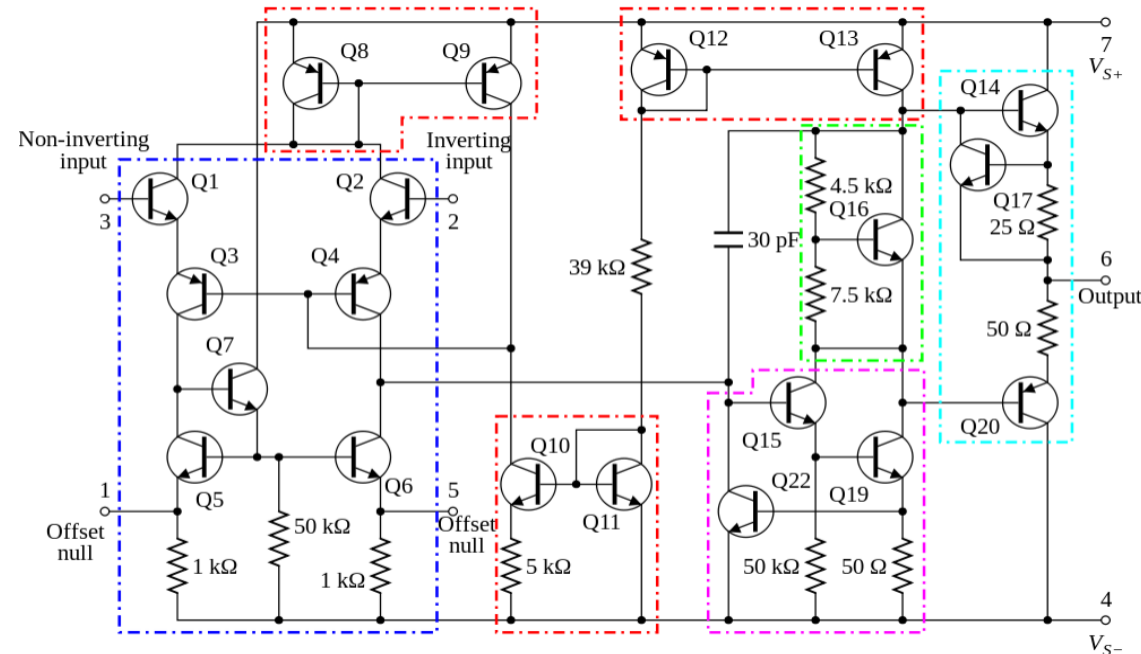


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Operational Amplifiers (Op Amps)



A component-level diagram of the common 741 op amp. Dotted lines outline: ■ current mirrors; ■ differential amplifier; ■ class A gain stage; ■ voltage level shifter; ■ output stage.

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Operational Amplifiers (Op Amps)

- Like transistors, Op Amps have a *limited frequency response*
- The upper bandwidth limit is called its ***Gain-Bandwidth Product (GBW)***
 - GBW is the **maximum product of gain & frequency** available in the circuit
 - **Voltage Gain x Frequency = GBW**

Example: Calculate the maximum frequency for an Op Amp with a GBW of 10 MHz connected to a x40 voltage amplifier = **$\text{GBW}/\text{gain} = 10 \text{ MHz}/40 = 250 \text{ kHz}$**

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Operational Amplifiers (Op Amps)

- **Common Mode Signals (CMRR)** – Signals (many times noise) that appear equally at all terminals
 - Op Amps only respond to *differences in voltage* at the input terminals
 - CMRR signals appear as *equal voltages*, so are rejected
 - Very important for small signal circuits where noise could overpower desired signal
- **Power Supply Rejection Ratio (PSRR)** – The measure of an Op Amp's ability to continue performing well despite power supply imbalance or noise
 - Changes in power supply voltages translate to the Op Amp's internal circuitry
 - The ability to ignore these anomalies is highly desired

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Operational Amplifiers (Op Amps)

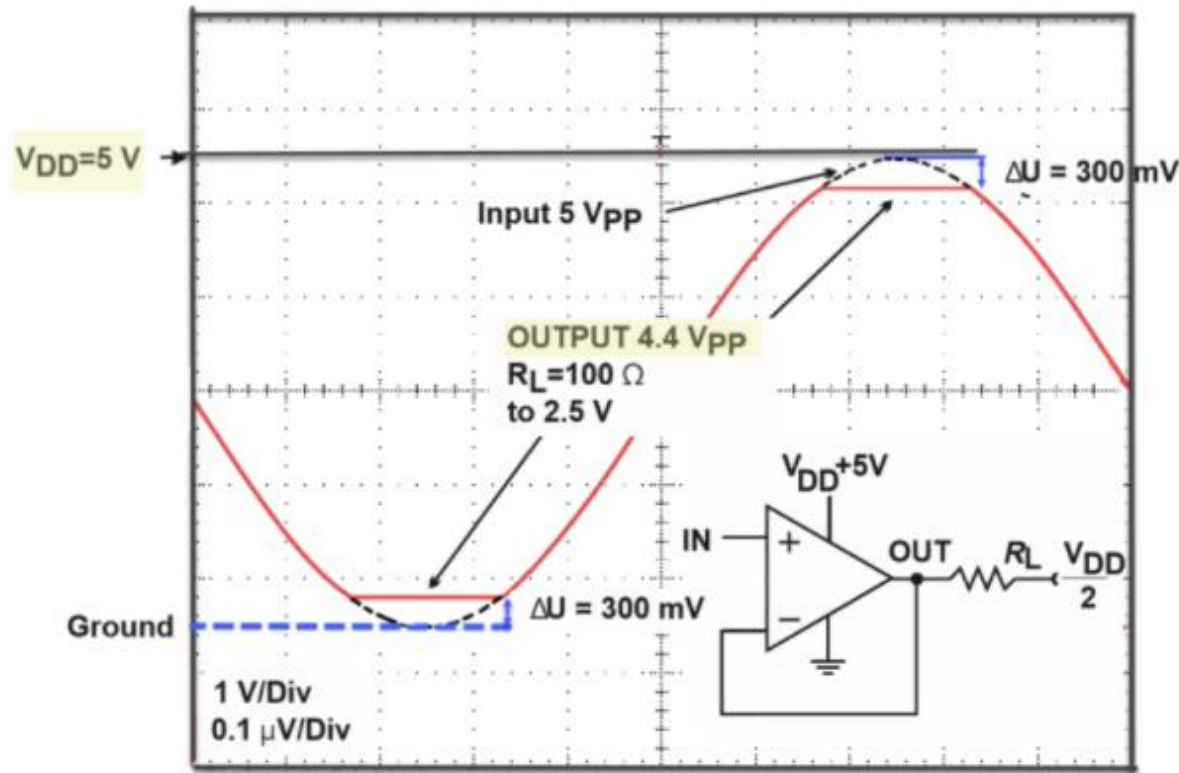
- **Rails** – The voltage signal limits that an Op Amp can accept and amplify
 - The *theoretical* limits are the upper and lower power supply voltages
 - The voltages can be symmetrical or non-symmetrical, similar or dissimilar polarities
 - *In practice*, Op Amps will clip the signal *roughly 0.7 V to 1.4 V prior to the rail*
 - More precise rail-to-rail Op Amps have been developed to *limit the clipping* level to within *tens of mV* of the rails

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Operational Amplifiers (Op Amps)



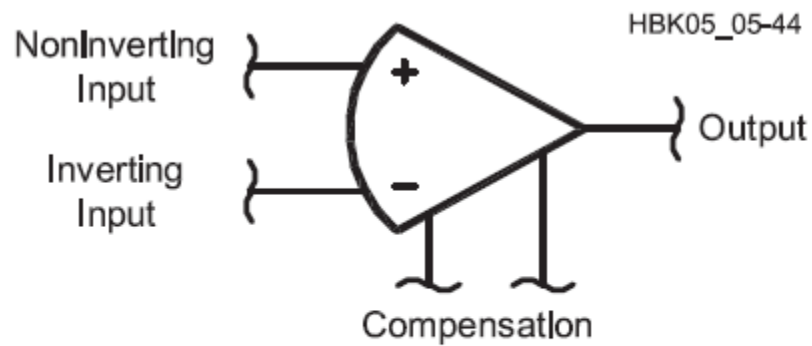
- In this circuit, the **rails are +5 V and Ground**
- The circuit **clips** the signals **4.4 V and 0.6 V**
- (The 300 mV figure is referred to as **headroom**)

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Op Amp Characteristics



Power supply pins (V_{CC} and V_{EE}) are identified on the chip layout.

Non-inverting – Input and output voltage polarity *remain the same*

Inverting – Input and output voltage polarity have an *inverse relationship*

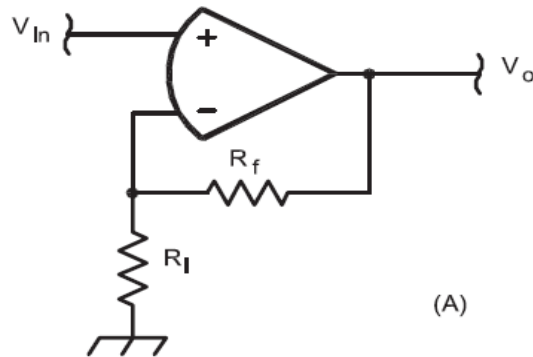
Compensation – Used in older Op Amps to prevent oscillation at very high frequencies, capacitor placed across pins

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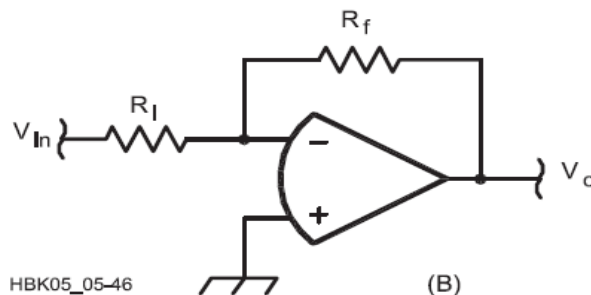
Operational Amplifiers (Op Amps)



Non-inverting Amplifier

Summing Junction (*Non-inverting Amp*) – Connection point for R_i and R_f and the inverting (-) terminal

Loop Error Signal – Difference in voltage between the inverting and non-inverting terminals



Inverting Amplifier

Summing Junction (*Inverting Amp*) – Connection point for R_i and R_f and the non-inverting (+) terminal

Negative Feedback (*Both Amps*) – Return signal from the output opposing the input to stabilize the amp and prevent runaway

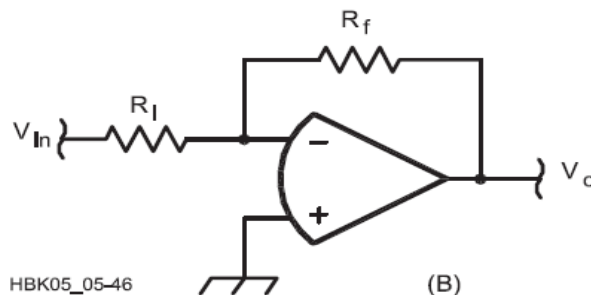
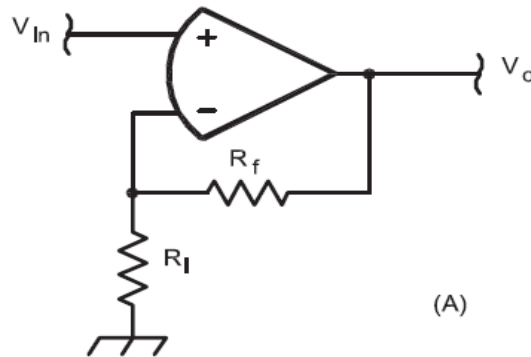
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Operational Amplifiers (Op Amps)



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*With the non-inverting Op Amp, we calculate the **summing junction** voltage $V_{INV} = V_o (R_i / R_i + R_f)$ at time zero, when signal is first applied

*Eventually, the **loop error signal** will equal **0 V**; that is, the voltage at (-) is equal to V_{in} , so $V_{INV} = V_{in}$

*Given this situation, **Gain** is calculated as $V_o / V_{in} = ((1 + (R_f / R_i)))$

***Gain** for the non-inverting Op Amp can vary **from 1 to the Op Amp's maximum**

*With the inverting Op Amp, (+) is connected to circuit reference (ground)

*The current through R_i is balanced by an equal but opposite current through R_f

***Gain** is calculated as $V_o / V_{in} = -(R_f / R_i)$ The output signal is inverted, hence the (-)

***Gain** for the inverting Op Amp can vary **from 0 to the Op Amp's maximum** (0-1 attenuate; 1 and above amplify)

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Various Uses for Op Amps

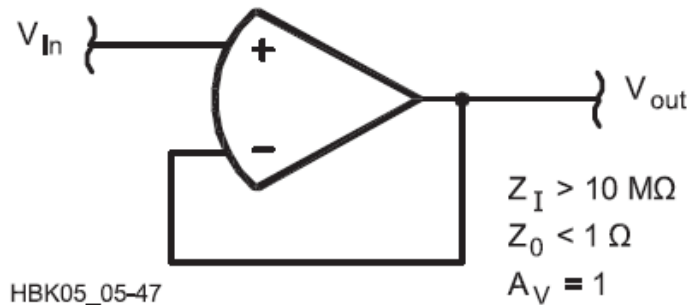
- **Unity-Gain Buffer (Voltage Follower) Amp**
- **Differential and Difference Amps**
- **Instrumentation Amp**
- **Comparator**
- **Active Filters**

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Unity-Gain Buffer (Voltage Follower) Amp



The **Unity-Gain Buffer (voltage follower)** is a special use of the Op Amp

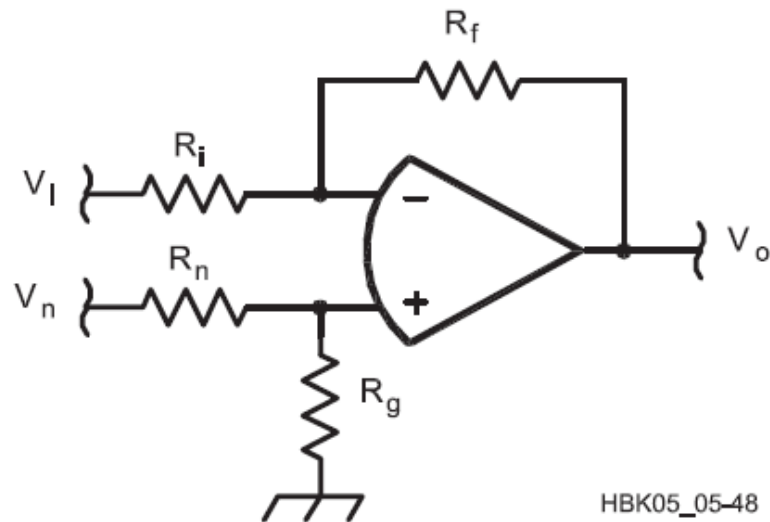
Used as a **buffer stage** – Maximum **input** impedance, minimum **output** impedance

Output and input voltages are equal – Can be thought of as a **repeater** within the circuit

Used in both RF and telephony circuits

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Differential and Difference Amps



The **Differential Amp** is also a special use of the Op Amp

Amplifies the ***difference*** between two analog signals

Primarily used for ***cancelling noise*** within the limits of CMRR

The calculation for differential amp operation is:

$$V_O = \frac{R_f}{R_i} \left[\frac{1}{\frac{R_n}{R_g} + 1} \left(\frac{R_i}{R_f} + 1 \right) V_n - V_i \right]$$

which, if the ratios R_i/R_f and R_n/R_g are equal, simplifies to:

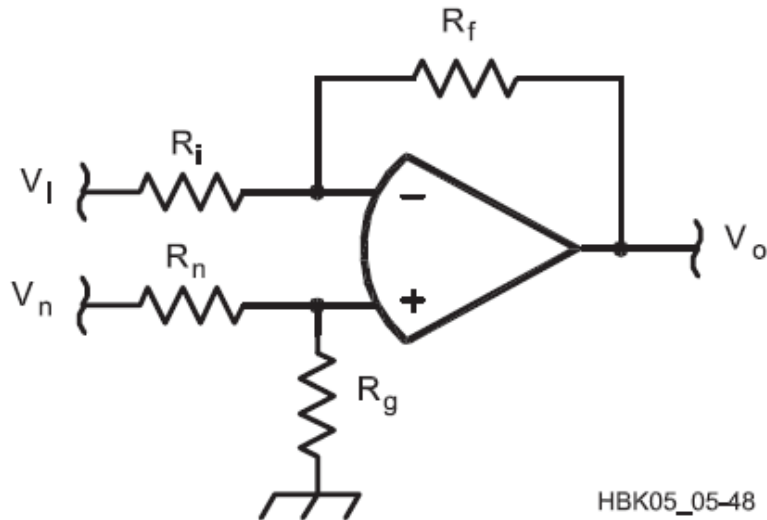
$$V_O = \frac{R_f}{R_i} (V_n - V_i)$$

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Differential and Difference Amps



The **Difference Amp** is a **Differential Amp** with *all four resistor values* being equal

Amplifies the ***difference*** between two analog signals

Primarily used for ***cancelling noise*** within the limits of **CMRR**

The calculation for **Difference Amp** operation is much simpler because **V_o** is just the ***difference*** of the two stages:

$$V_o = V_n - V_i$$

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Instrumentation Amp

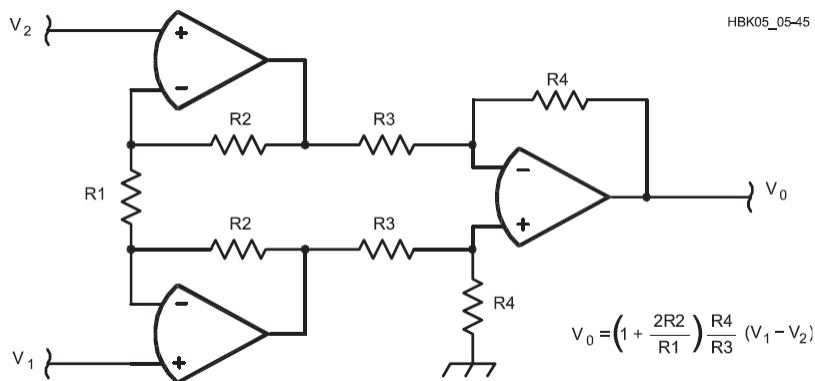
The **Instrumentation Amp** is a special purpose Op Amp used to further *improve the impedance, gain, and CMRR characteristics* of single Op Amps

Usually *manufactured in one IC* to match internal device and temperature characteristics

Usually employ *carefully matched external resistors*, many times an *integrated resistor pack*

The design is of the inputs connected to two non-inverting **Buffer Amps** (with Gain = $1 + R2/R1$), with their outputs connected to a **Differential Amp** (with Gain = $R4/R3$)

Result: A *higher performing amp* (impedance, gain, and CMRR) than any single Op Amp over a *wider temperature range*

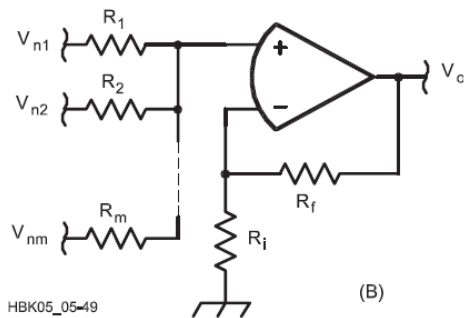
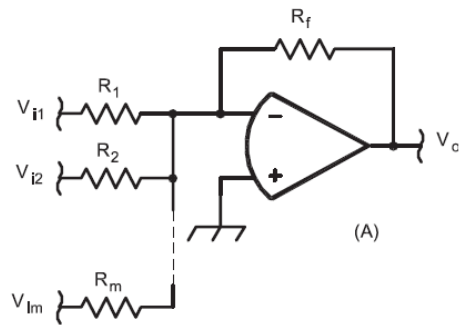


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Summing Amps



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The **Summing Amp** is a special purpose Op Amp that takes advantage of the Op Amp's high input impedance

Multiple input signals are **connected together (summed)** through resistors at the Op Amp's input

A few Amateur Radio summing applications:

<https://kb8fir.wordpress.com/2014/07/16/using-a-small-audio-mixer-for-ham-shack/>

<https://n0eck.wordpress.com/2013/09/05/connecting-a-mixer-to-your-ham-radios/>

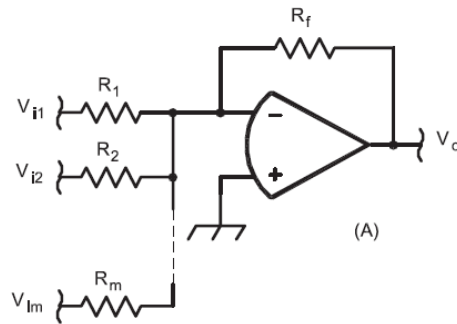
https://w3yy.com/audio_control_system.htm

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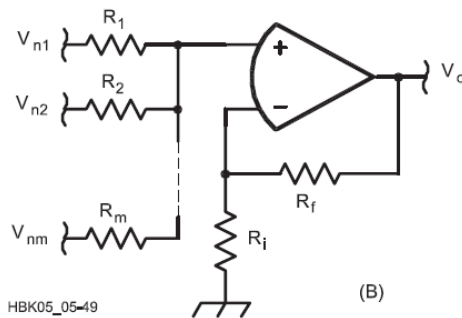
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Summing Amps – Determining Output



The **output** of the **inverting** Summing Amp is the ***sum of each input signal multiplied by its gain***

Recall that $V_o/V_{in} = (1 + R_f / R_i)$



Summing Amp output = $(V_{i1} + V_{i2} + \dots V_{im}) \times (1 + R_f / R_i)$

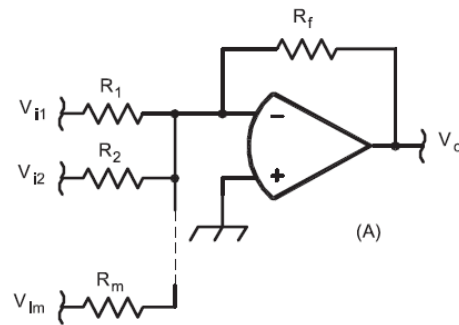
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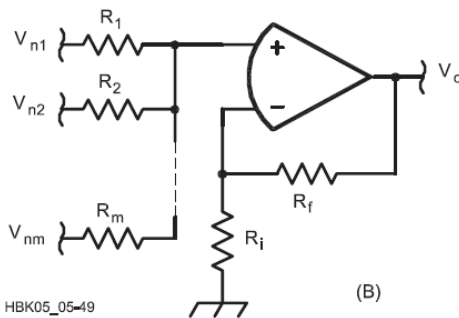


Analog Integrated Circuits and Components

Summing Amps – Determining Output



(A)



(B)

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The **output** of the **non-inverting** Summing Amp is the **gain times the weighted sum of the total (*m*) different input signals**

$$V_n = V_{n1} \frac{R_{p1}}{R_1 + R_{p1}} + V_{n2} \frac{R_{p2}}{R_2 + R_{p2}} + \dots$$

$$+ V_{nm} \frac{R_{pm}}{R_m + R_{pm}}$$

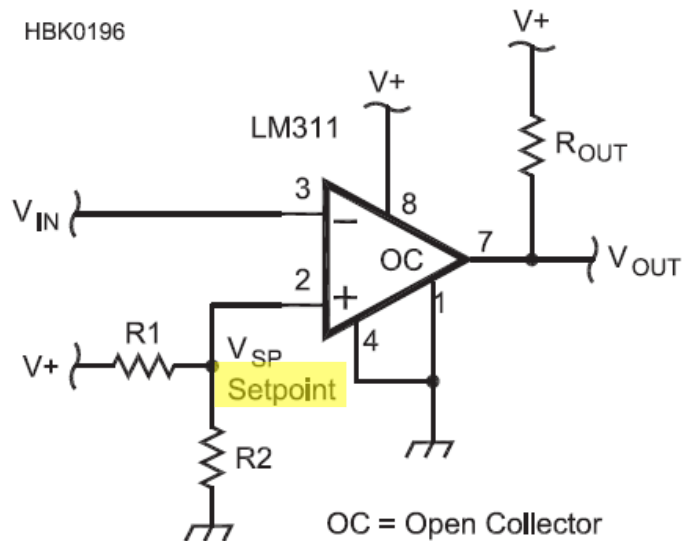
Where R_{pm} = the parallel resistance of all **m** resistors **excluding** R_m – **Example:** Three input signals, R_{p1} = the parallel combination of R_2 and R_3

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Comparators



A **Comparator** is another specialty Op Amp that **compares input voltages** and **determines TRUE or FALSE status** depending on which input is higher

If **non-inverting** input is **higher**, the result is given as **TRUE**

If **inverting** input is **higher**, the result is given as **FALSE**

TRUE usually means a **positive output voltage**; **FALSE** usually means a **negative or zero output voltage**

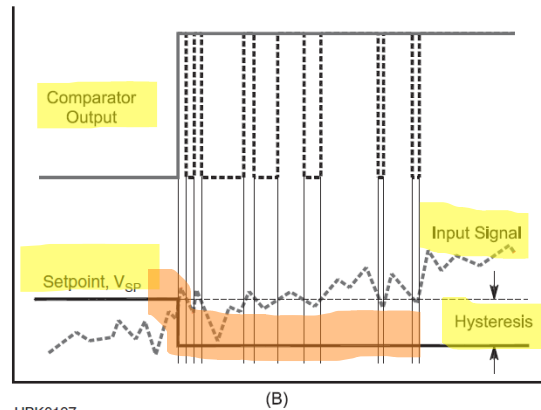
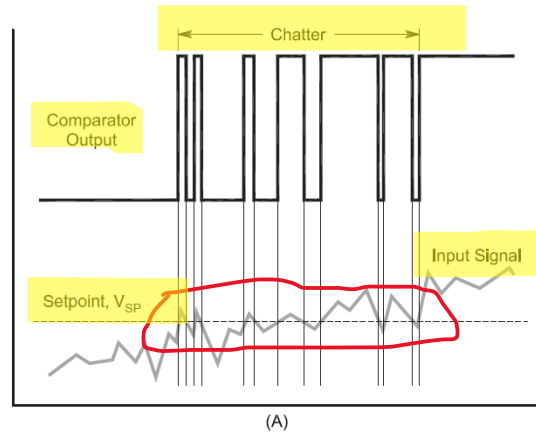
A **Setpoint** voltage can be established to compare **unknown signals** against – indicates if unknown voltage is above or below the **setpoint**

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Comparators



HBK0197

Chatter – Comparator output *switching rapidly* back and forth when the input is close to the **setpoint**

Hysteresis – A form of *positive feedback* that electrically *moves the setpoint* by a small amount (**mV**) in the direction *opposite* to that in which the input signal crossed the **setpoint**

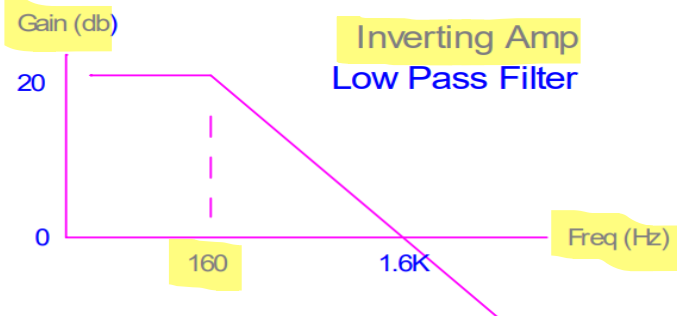
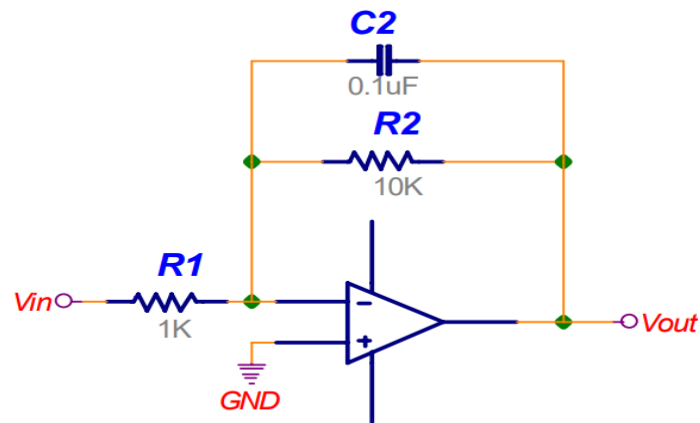
Comparator Uses – Detect connection of accessories, Repeater voting, Peak detector, CI-V band detection by Icom

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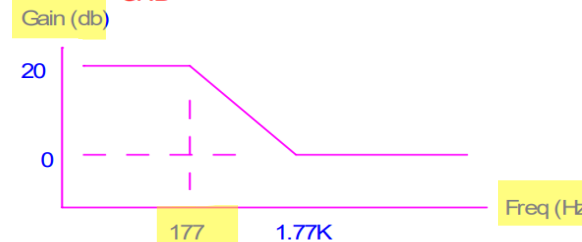
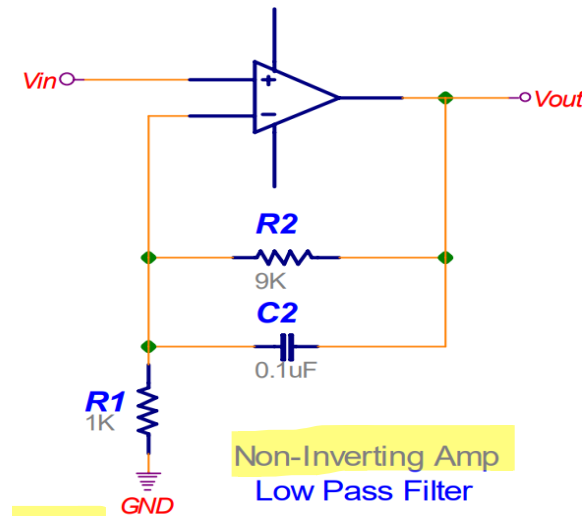


Analog Integrated Circuits and Components

Active Filters – Low Pass Filters



Inverting Amp
Low Pass Filter



Non-Inverting Amp
Low Pass Filter

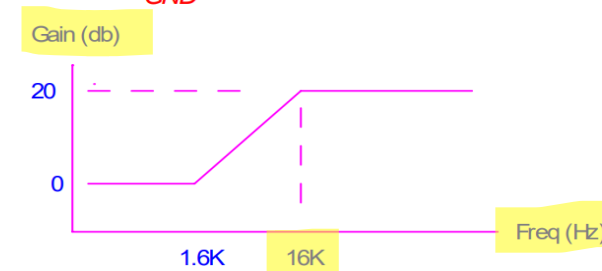
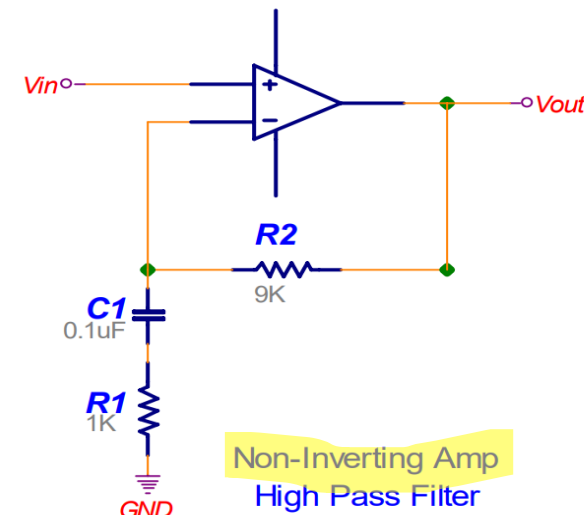
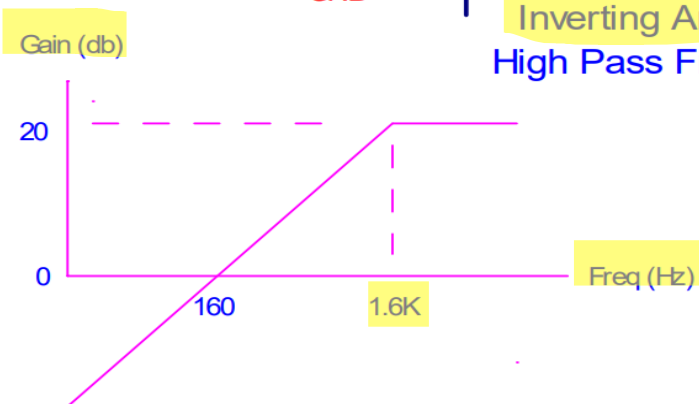
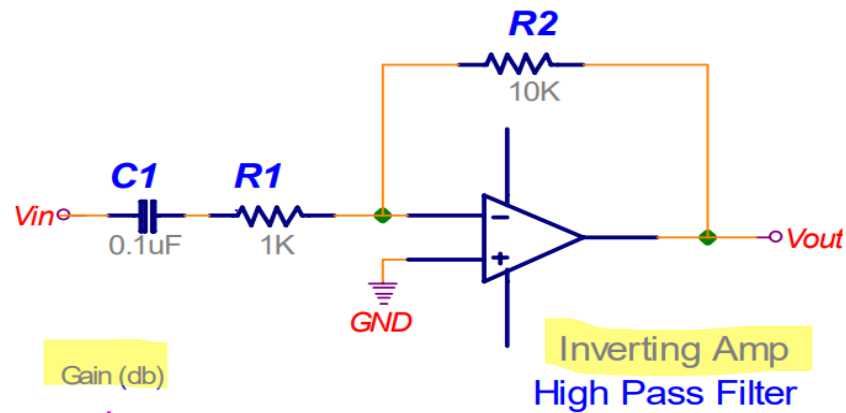
Source: http://www.physics.unlv.edu/~bill/PHYS483/op_amp_filt.pdf

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Active Filters – High Pass Filters



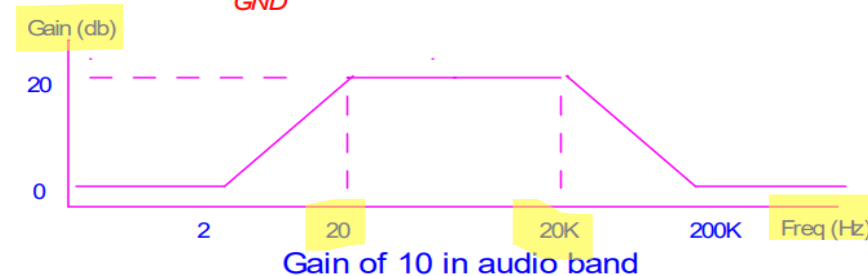
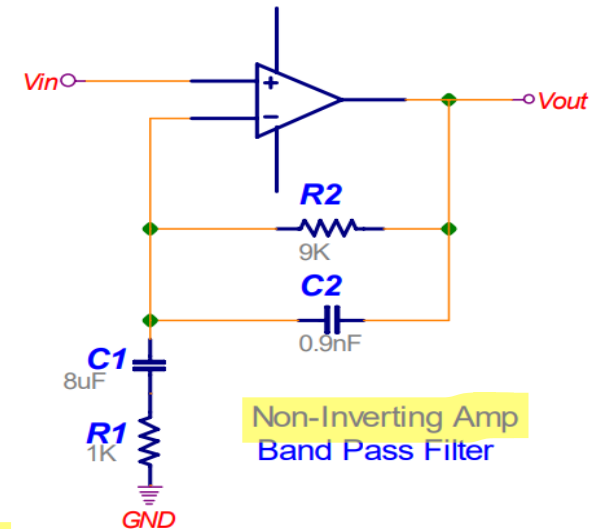
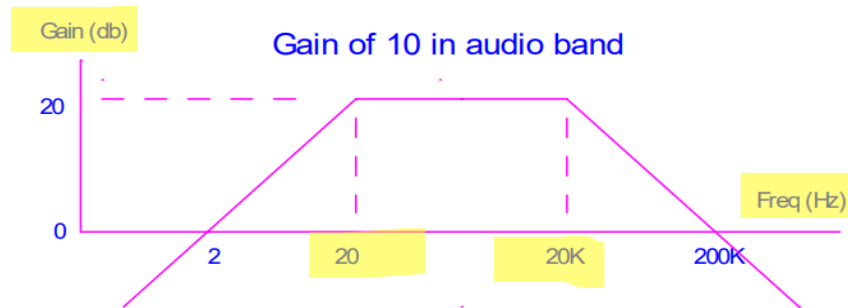
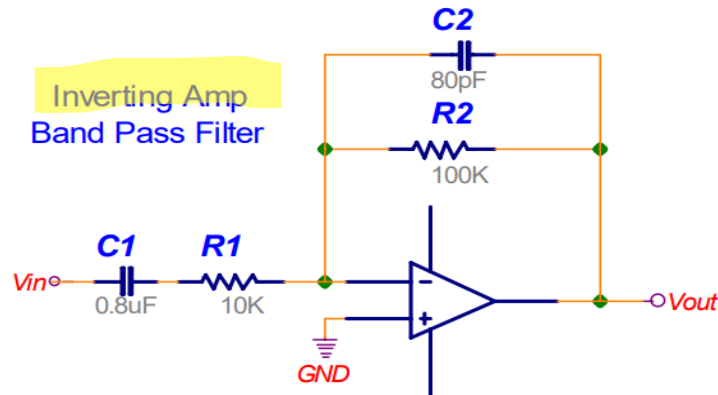
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Active Filters – Band Pass Filters



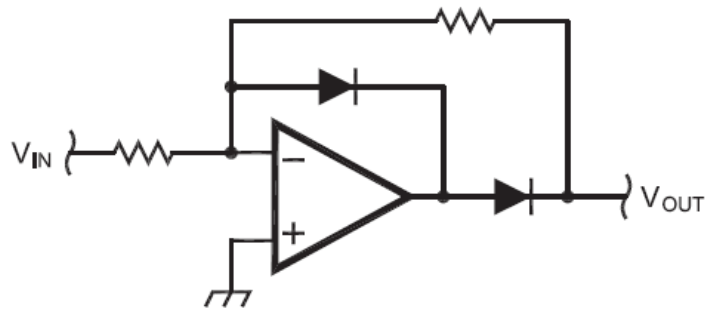
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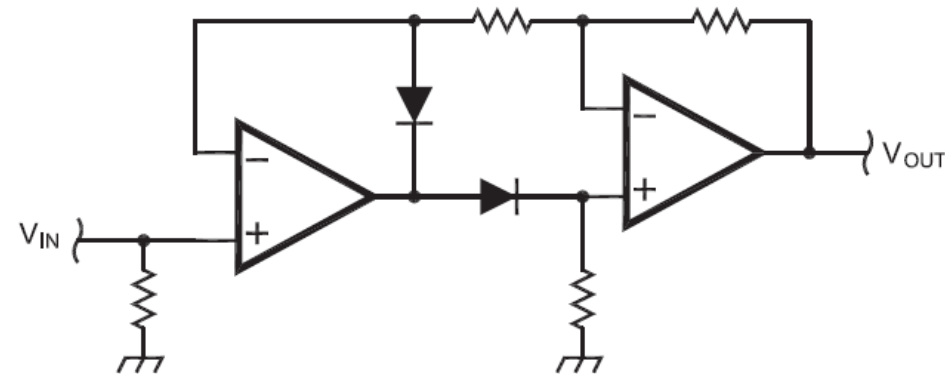
Rectifier



HBK0199

(A)

Half-wave Precision Rectifier



(B)

Full-wave Precision Rectifier

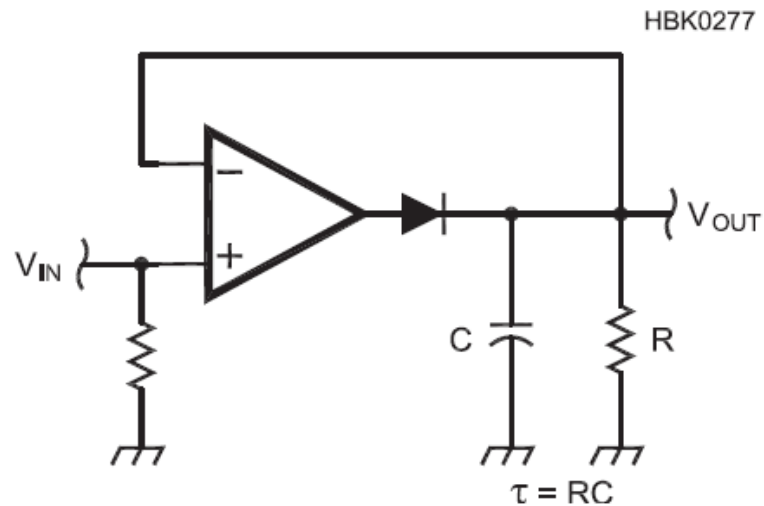
Using an **Op Amp Rectifier** instead of a **simple diode** rectifier is that the Op Amp *overcomes the voltage drop loss* (0.7 V) across the diode alone

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Peak Detector



The output **capacitor (C)** is charged when the Op Amp output goes positive

The capacitor is **held charged** by the blocking of the **diode** (current cannot flow backward through it)

The **resistor (R)** sets the capacitor **time constant** to determine its **rate of discharge**

A **transistor** in place of **(R)** could be used as a **reset switch**

Analog Integrated Circuits and Components

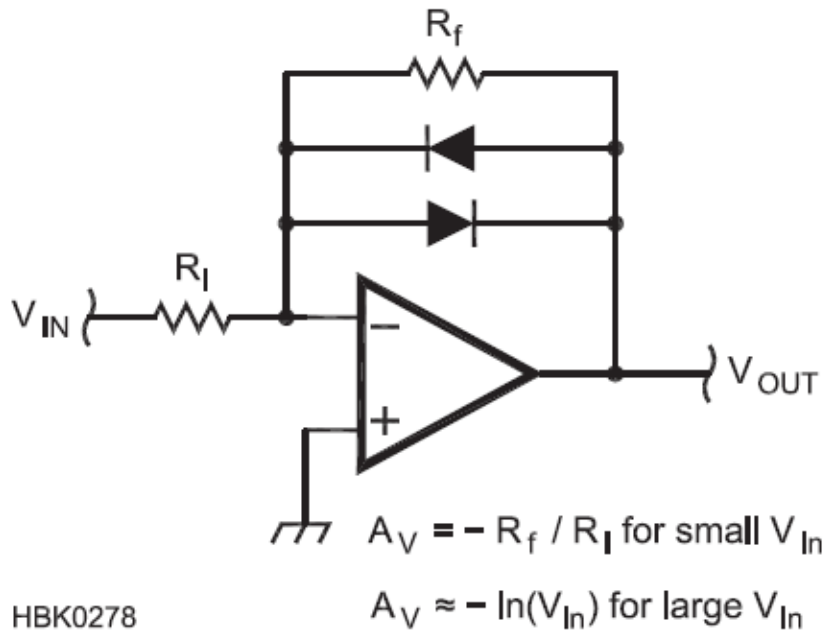
Log Amplifier

Called a **Log Amplifier** because its **large signal gain** is proportional to the **logarithm** of the input signal's amplitude
 $A_V = \ln(V_{in})$

Small signal inputs (those too small to cause current flow through the diodes) have a normal gain of a regular inverting amplifier $A_V = -R_f/R_i$

Small signals have to **increase less** (than large signals) to balance input voltages

The **larger the input voltage**, the **greater conduction** through the diodes, **lowering the gain** of the circuit **logarithmically**



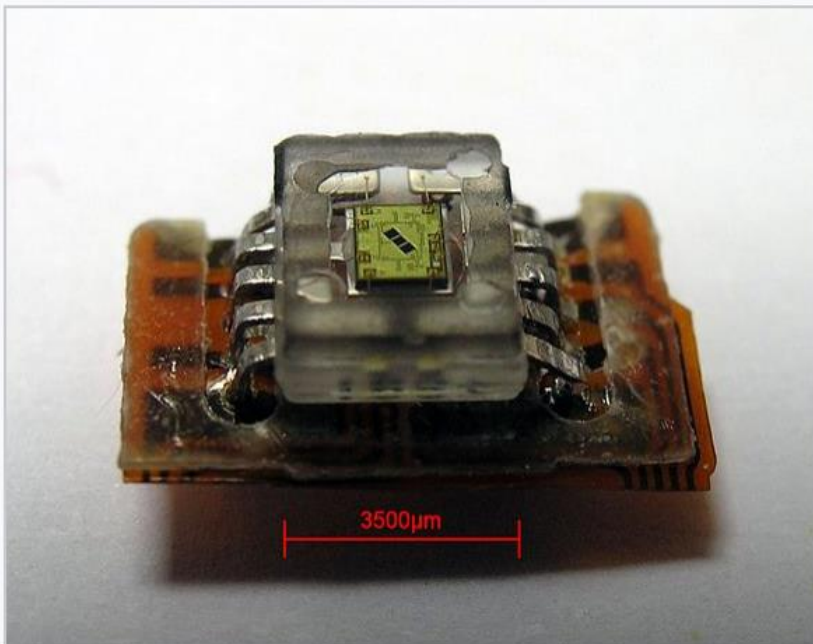
HBK0278

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Voltage-Current Converters



A photodetector salvaged from a CD-ROM drive. 
The photodetector contains three photodiodes, visible in the photo (in center).

Op Amps are used for ***Voltage-Current Converters*** due to their ***impedance characteristics***

The Op Amp's high input impedance insures ***very little chance of coupling*** between the input voltage source and the output current

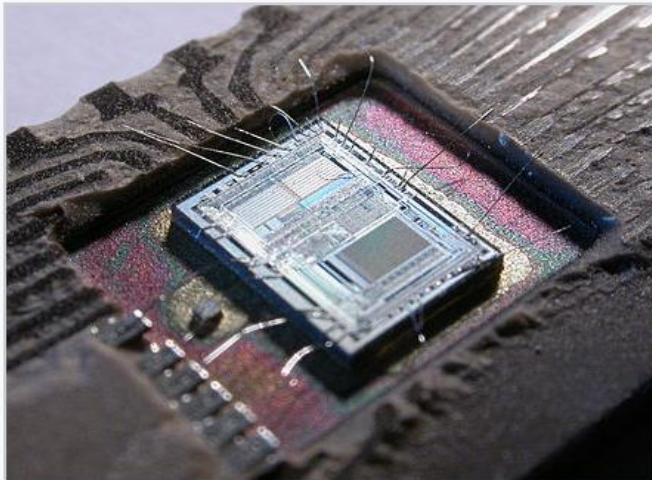
Frequently used to ***convert currents from sensors and detectors*** (see photodiode example at left) ***into voltages*** that are ***easier to measure*** (e.g., smoke detectors)

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Component Arrays



The die from an Intel 8742, an 8-bit NMOS microcontroller that includes a CPU running at 12 MHz, 128 bytes of RAM, 2048 bytes of EPROM, and I/O in the same chip

A huge advantage of integrated circuits is the ***ability to combine multiple components*** in one integrated package

These types of arrays can contain transistors, diodes, capacitors, resistors, storage, and even inductors

Known as **Application Specific Integrated Circuits (ASIC)**

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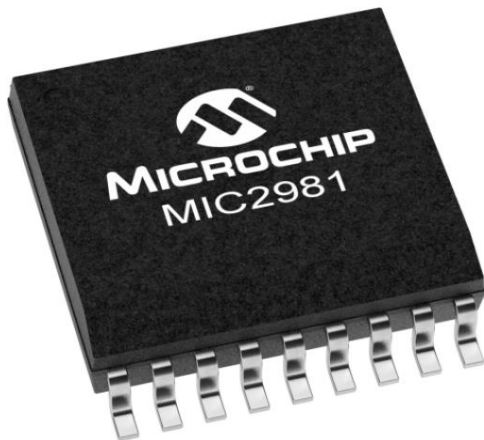
Transistor & Driver Arrays

Features

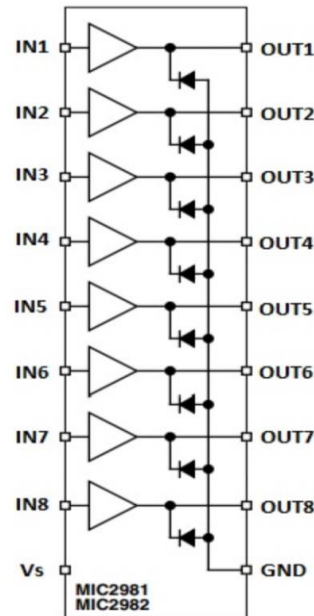
- Output voltage to **50V**
- Output current to **500mA**
- Transient-protected outputs
- Integral clamp diodes
- TTL, CMOS, or PMOS compatible inputs (**2V / 40mA**)

Applications

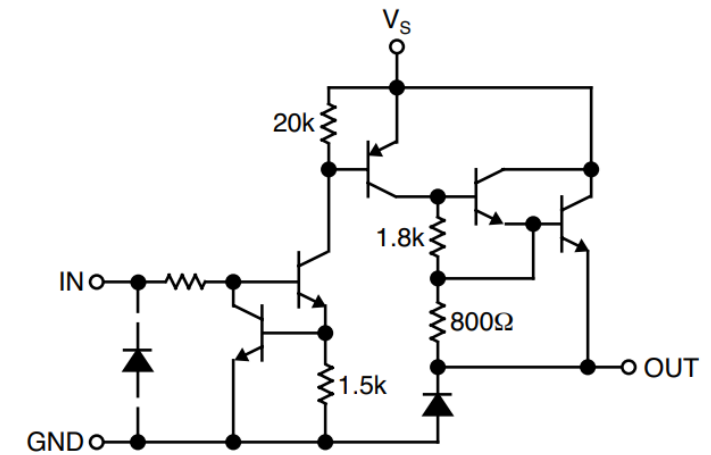
- Relay and solenoid switching
- Stepping motor
- LED and incandescent displays



**MIC2981/2982
Block Diagram**



High-Voltage High-Current Source Driver Array



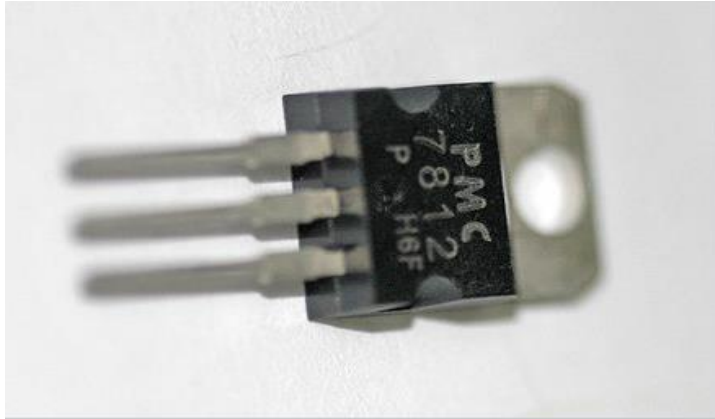
Typical MIC2981/2982 Source Driver

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Voltage Regulators



An integrated circuit voltage regulator



Voltage Regulator Controller – 500mA, 3.3V +/-2%



PWM 30A, 12V Solar Charge Controller/Voltage Regulator

Voltage Regulators/Controllers – *Three lead ICs* that contain all the circuit components to **provide voltage regulation**

Voltage can be **fixed** or **variable**



Variable Voltage Controller

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Timers (Multivibrators)

- **Multivibrator** – A circuit that *oscillates (vibrates)* between *two states*, most often generating a *square wave* or *pulse train* output
 - **Monostable (One Shot) Multivibrator**
 - **Astable Multivibrator**
 - **Bistable (Flip-Flop) Multivibrator**

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Analog Integrated Circuits and Components

555 Timer

By far, **the most common *timer (multivibrator)*** is the **555 timer** (*NE555 or LM555*)

Is used as the ***basic circuit*** for **monostable, astable, and bistable multivibrators**

Operates within the ***frequency range*** of **less than 1 Hz to several hundred kHz**

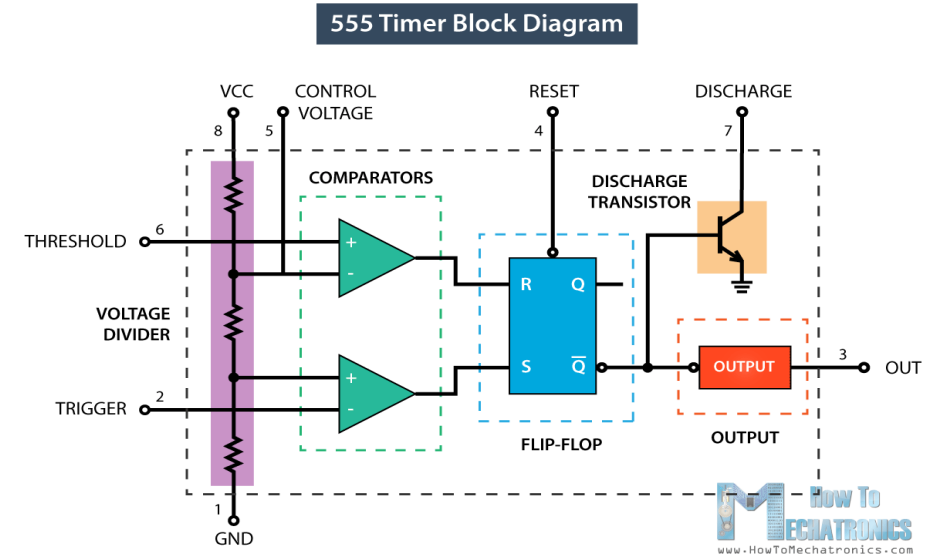
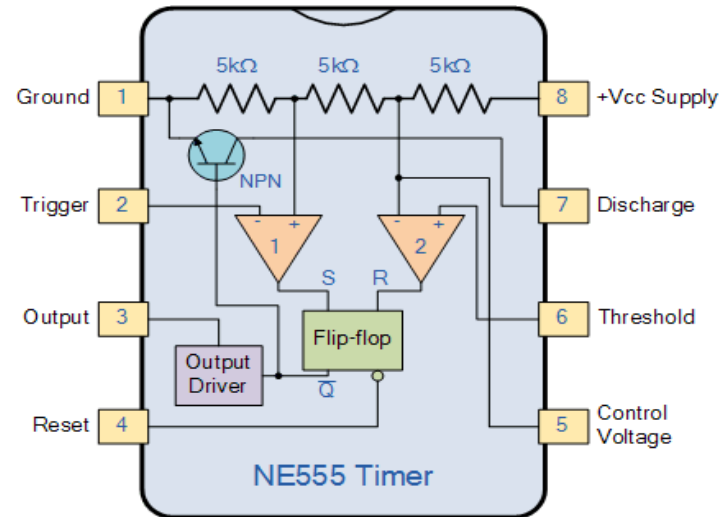


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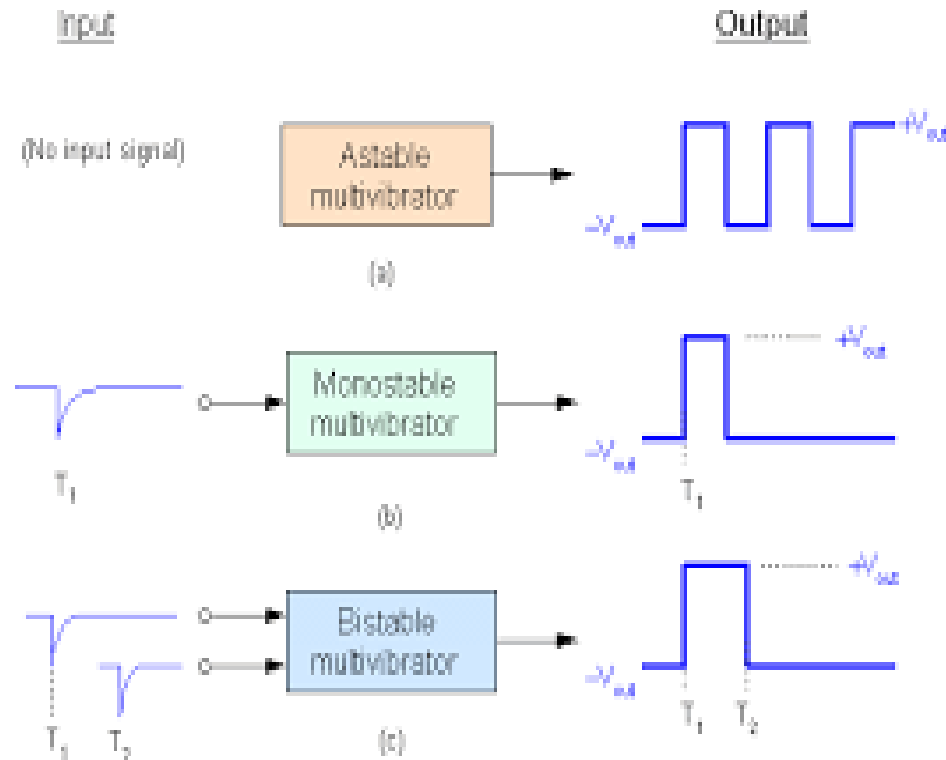
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555 Timer



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Timers (Multivibrators)



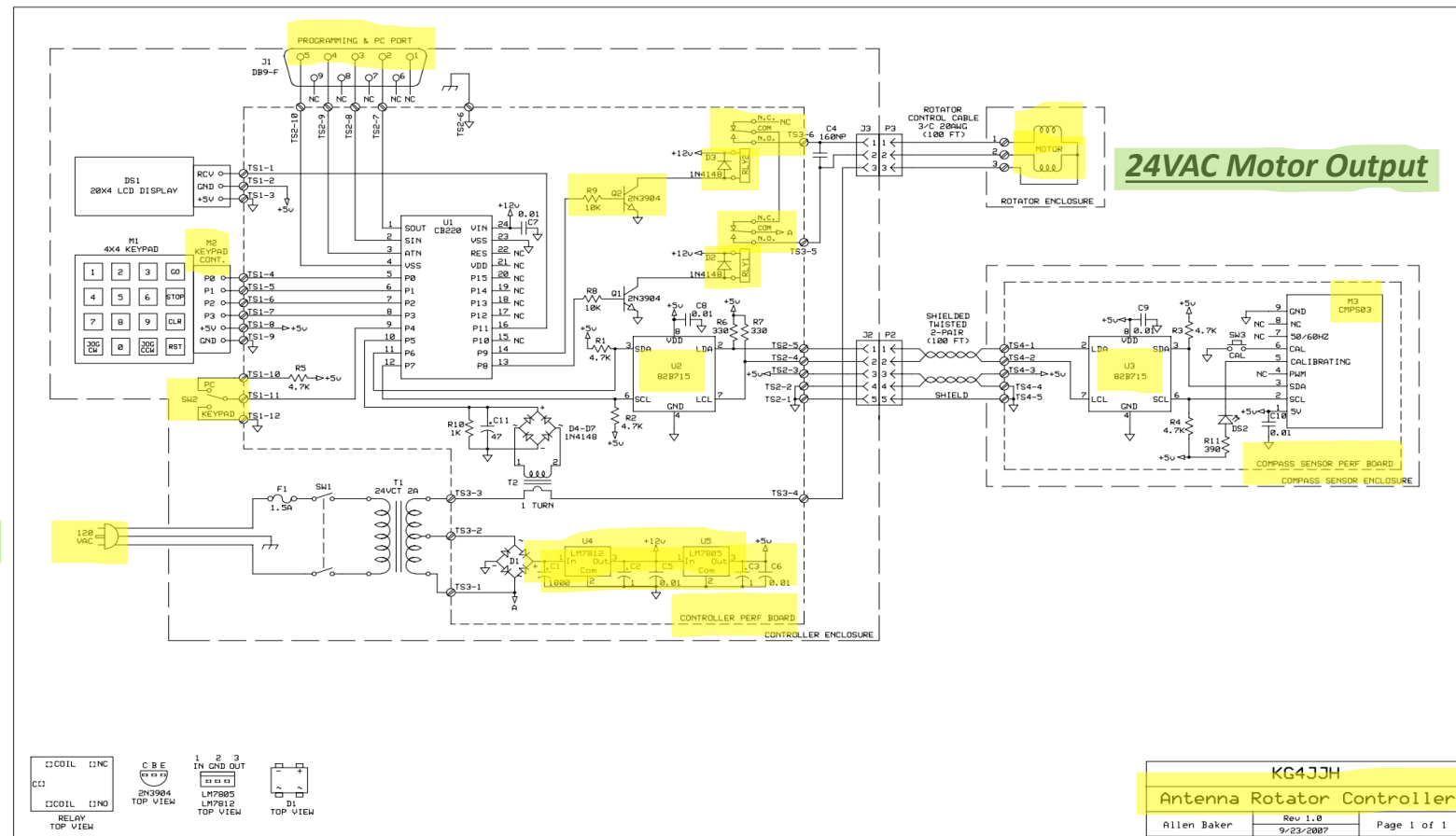
Once triggered, continues to change states at a predictable rate. **Common uses:** clock signals, timing signals, vehicle turn indicators, strobe lights, etc.

Once triggered, creates a perfect square wave (one), then returns to quiescent state until triggered again. **Common uses:** Pulse generator, circuit time delay, reduce pulse distortion in computer systems, etc.

Once triggered, remains in the high state until reset by a separate reset trigger. **Common uses:** Computer memory circuits, counting circuits, etc. Several different types of Bistable Multivibrators depending on the desired use

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Analog - Digital Interfacing



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Heat Management Principles

- **Heat dissipation** is ***extremely critical*** for safe and efficient operation of analog and digital circuits
- **Integrated Circuits** and **high-power discrete components** are particularly vulnerable to improper heat dissipation
- When considering heat dissipation, ***always calculate using Peak-to-Peak (not RMS) voltages*** of a circuit ***under full load*** (most devices list the average voltage on their packaging)
- **Rule of Thumb**: Choose devices with a **maximum power dissipation** of **twice the desired output power**
- Use “**Thermal Grease**” with heat sinks as specified by device manufacturer
- **Device resistance** will ***decrease 6% - 8% per Celsius degree*** until the device eventually offers too little resistance to current flow, and it fails
- **RF current** will often cause overheating where a similar level of **DC current** will not
- **DUST IS YOUR ENEMY!!**

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