ELECTRONIC CIRCUITRY

EE 303

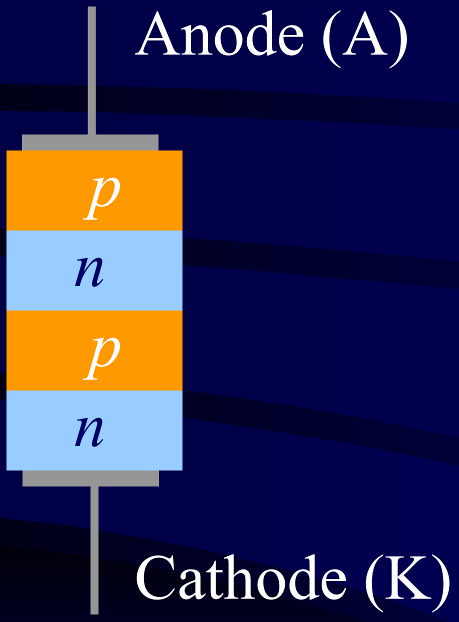
Main Topics

- Thyristors and Other Devices
- Operational Amplifiers
- Op-Amp Frequency Response
- Basic Op-Amp Circuits and Applications
- Active Filters
- Oscillators
- Voltage Regulators

Thyristors

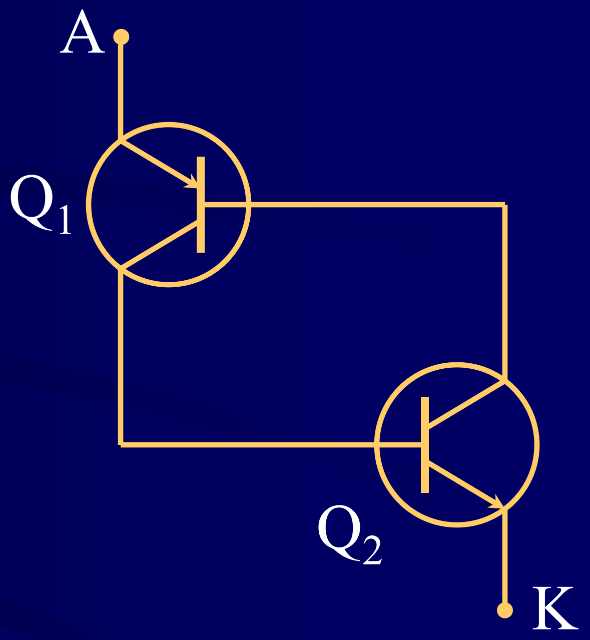
- Thyristors are devices constructed of four semiconductor layers (*pnpn*).
- Thyristors include: Shockley diode, silicon-controlled rectifier (SCR), diac and triac.
- They stay on once they are triggered, and will go off only if current is too low or when triggered off.
- Usage: lamp dimmers, motor speed controls, ignition systems, charging circuits, etc.

The Shockley Diode



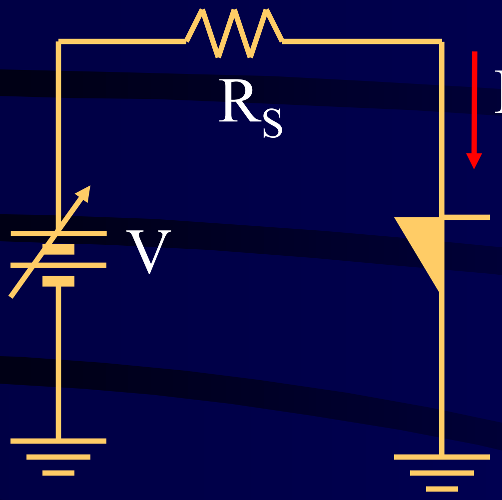
Basic Construction

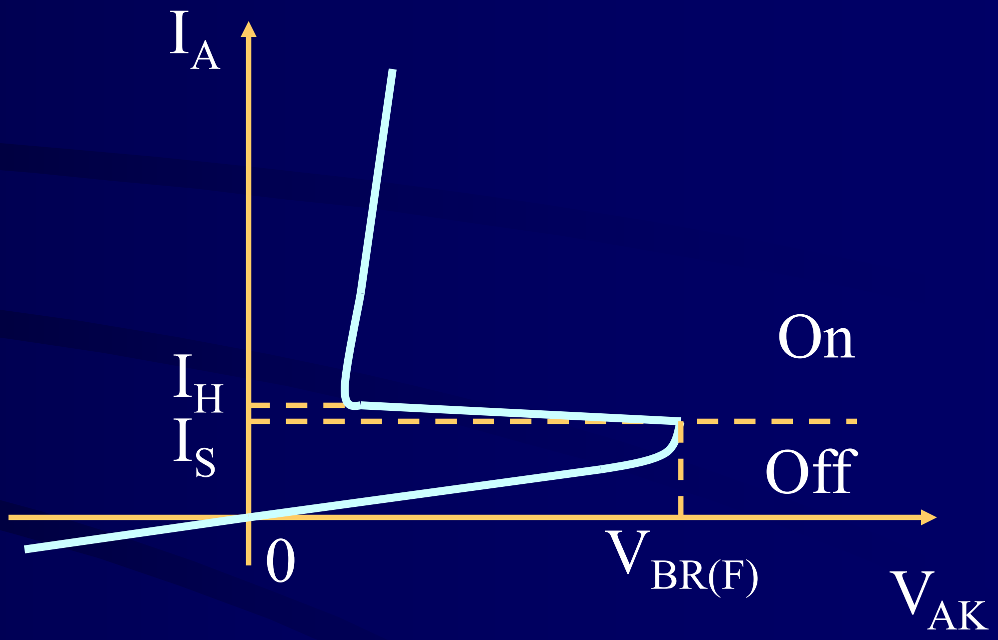
Schematic Symbol



Equivalent Circuit

Shockley Diode Characteristic Curve



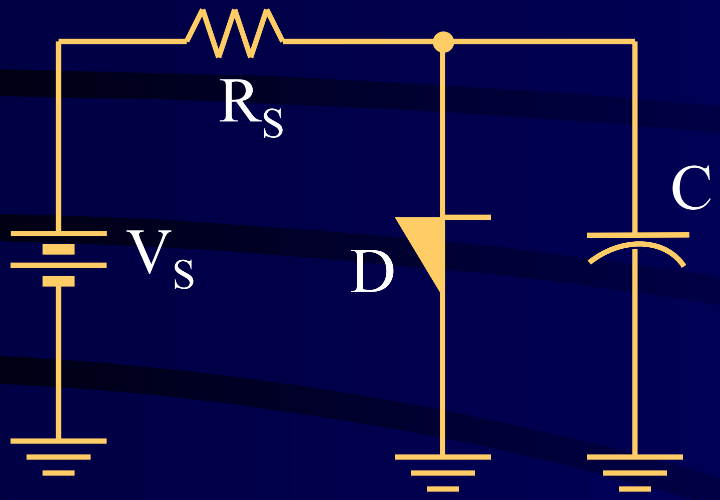


$V_{BR(F)}$ = forward-breakover voltage
I_S = switching current
I_H = holding current

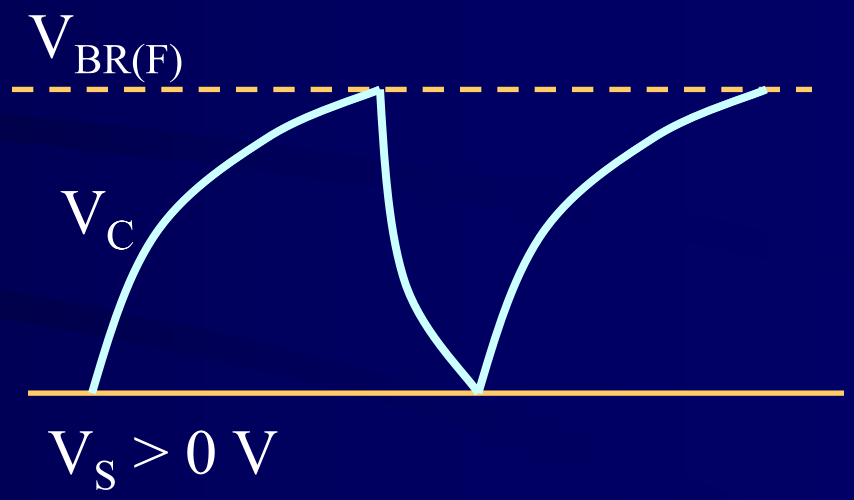
Shockley Diode Basic Operation

- Between 0 V and $V_{BR(F)}$, the Shockley diode is in the *forward-blocking region*, i.e. off state.
- At ≈$V_{BR(F)}$, the diode switches to the forward-conduction region and V_{AK} drops to $V_{BE}+V_{CE(sat)}$; I_A increases rapidly.
- When I_A is reduced to $< I_H$, the diode rapidly switches back to the off state.

A Shockley Diode Application



Relaxation Oscillator



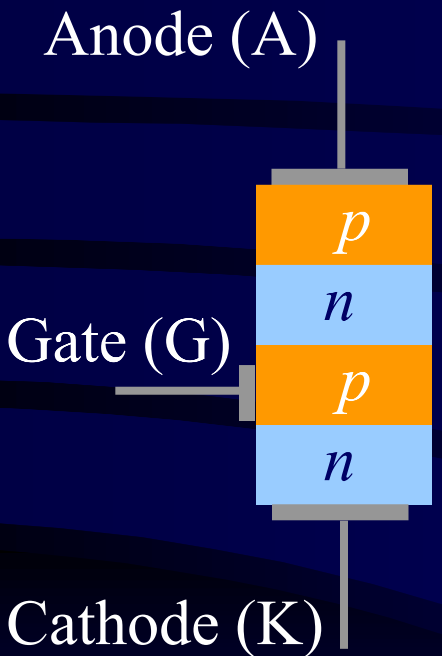
Voltage Waveform

Capacitor charges through R_S and discharges through D.

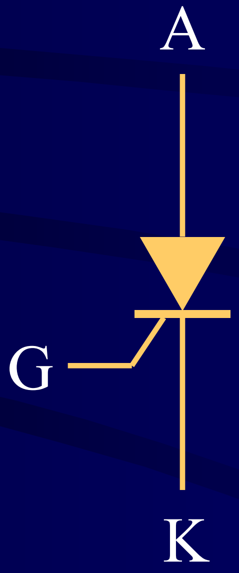
Silicon-Controlled Rectifier

- SCR is another four-layer *pnpn* device.
- Has 3 terminals: anode, cathode, and gate.
- In off state, it has a very high resistance.
- In on state, there is a small on (forward) resistance.
- Applications: motor controls, time-delay circuits, heater controls, phase controls, etc.

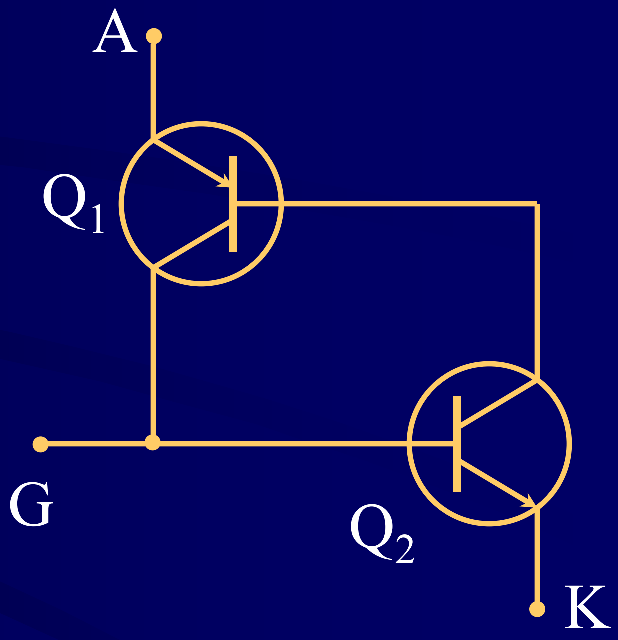
SCR



Basic Construction

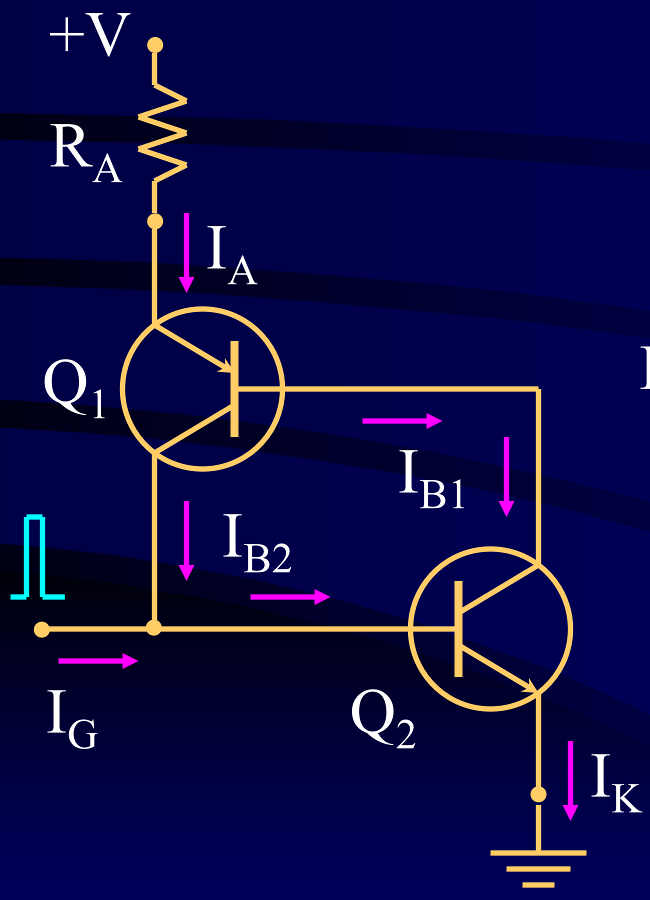


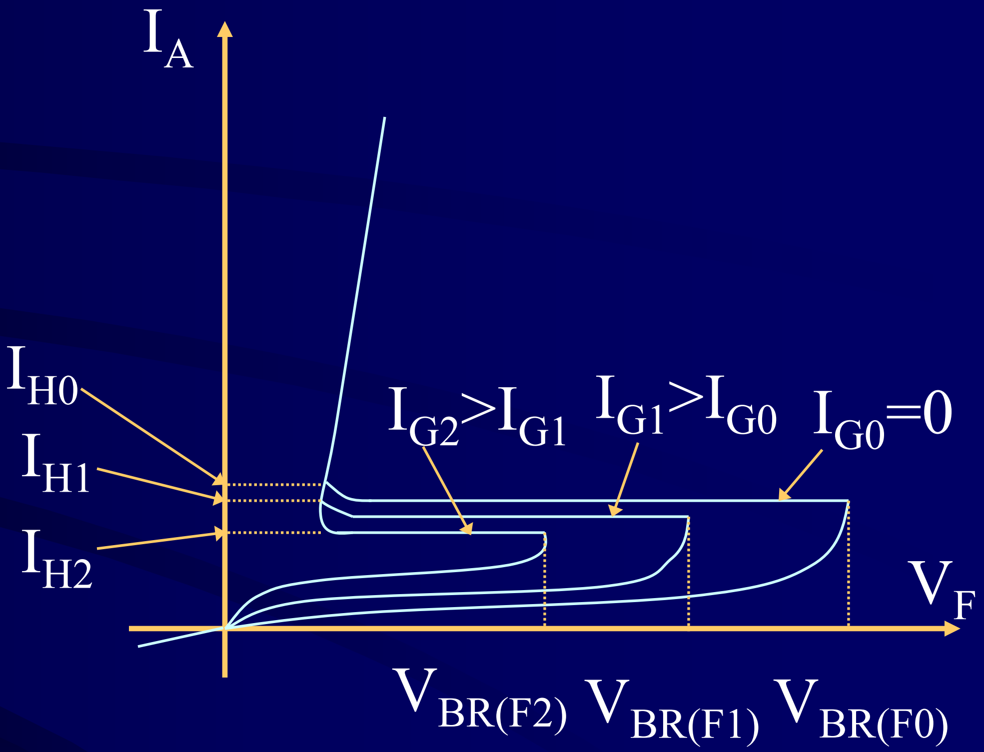
Schematic Symbol



Equivalent Circuit

Turning The SCR On



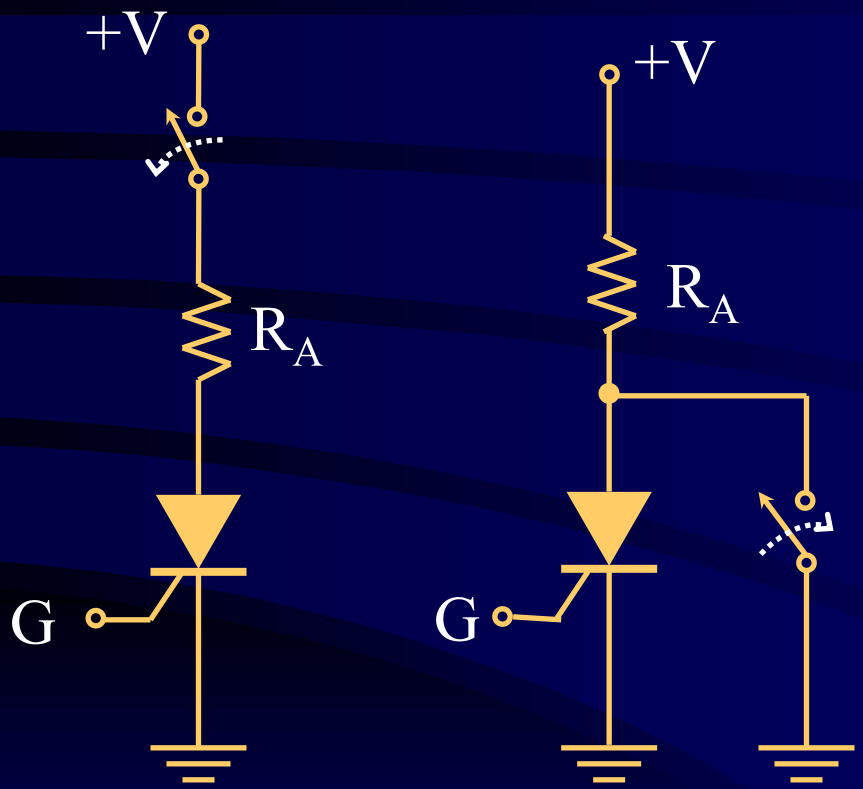


SCR characteristic curves for different I_G Values

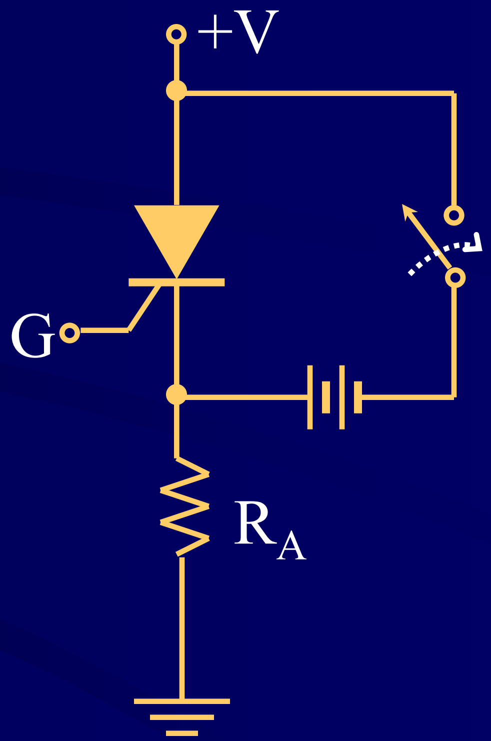
Notes on SCR Turn-On

- The positive pulse of current at the gate turns on Q_2 providing a path for I_{B1}.
- Q_1 then turns on providing more base current for Q_2 even after the trigger is removed.
- Thus, the device stays on (latches).
- The SCR can be turned on without gate triggering by increasing V_{AK} to 👓 $V_{BR(F0)}$.
- But I_G controls the value of the forward-breakover voltage: $V_{BR(F)}$ decreases as I_G is increased.

Turning The SCR Off



a) Anode Current Interruption

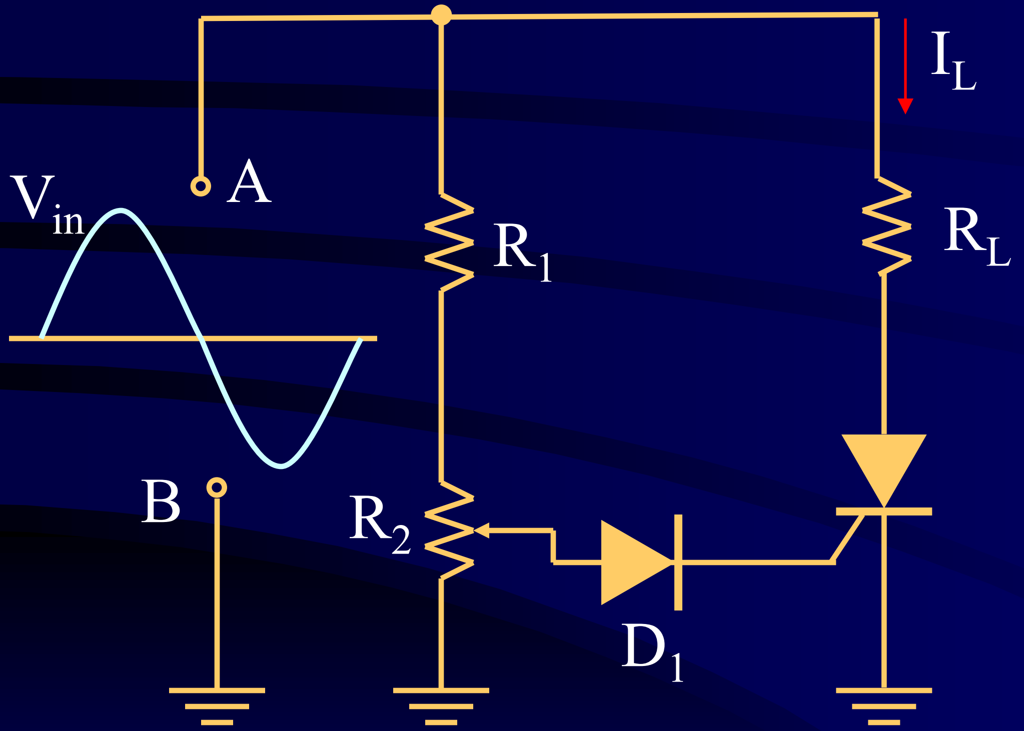


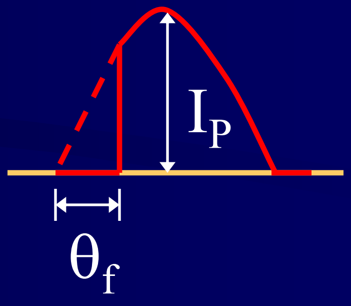
b) Forced Commutation

SCR Characteristics & Ratings

- Forward-breakover voltage, $V_{BR(F)}$: voltage at which SCR enters forward-conduction (on) region.
- Holding current, I_H: value of anode current for SCR to remain in on region.
- Gate trigger current, I_{GT}: value of gate current to switch SCR on.
- Average forward current, $I_{F(avg)}$: maximum continuous anode current (dc) that the SCR can withstand.
- Reverse-breakdown voltage, $V_{BR(R)}$: maximum reverse voltage before SCR breaks into avalanche.

Half-Wave Power Control

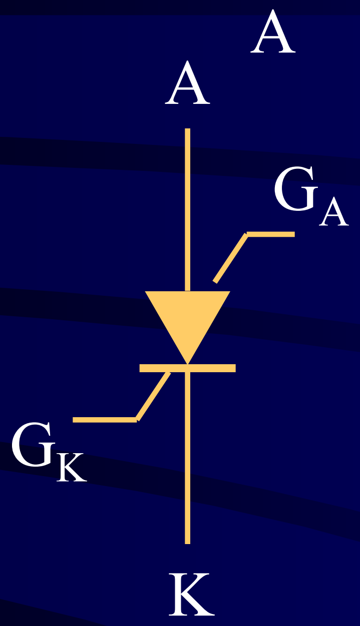




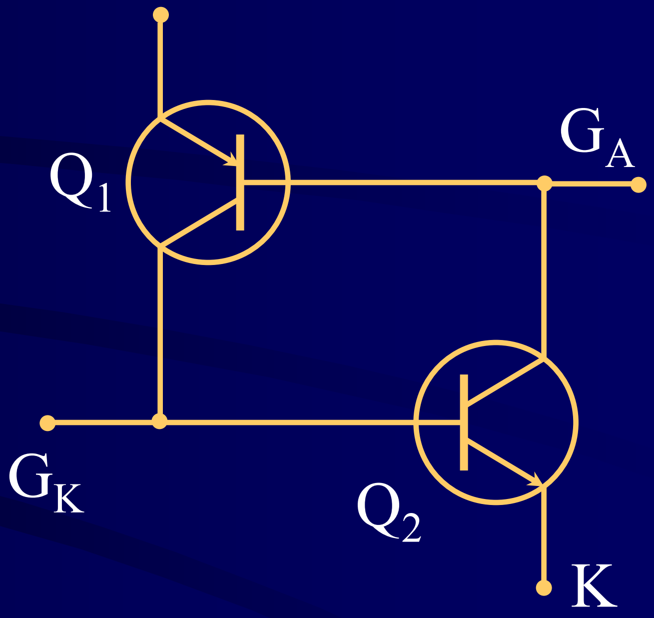
$$I_{L(AVG)} = \frac{I_P}{2\pi}(1+\cos\theta_f)$$

where θ_f = firing angle
= 90^0 max.

Silicon-Controlled Switch (SCS)



Schematic Symbol



Equivalent Circuit

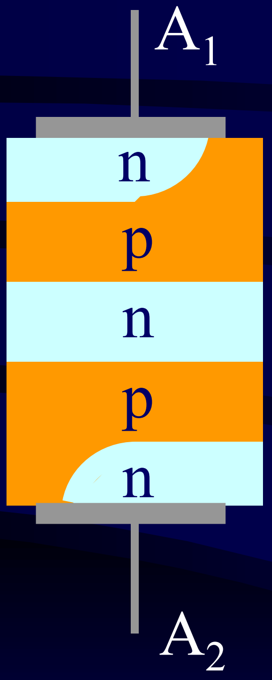
Notes On SCS

- SCS can be turned on either by a positive pulse at the cathode or a negative pulse at the anode.
- SCS can be turned off by using pulses of the reversed polarity or by anode current interruption methods.
- SCS and SCR are used in similar applications.
- SCS has faster turn-off with pulses on either gate terminal; but it has lower maximum current and voltage ratings than SCR.

The Diac and Triac

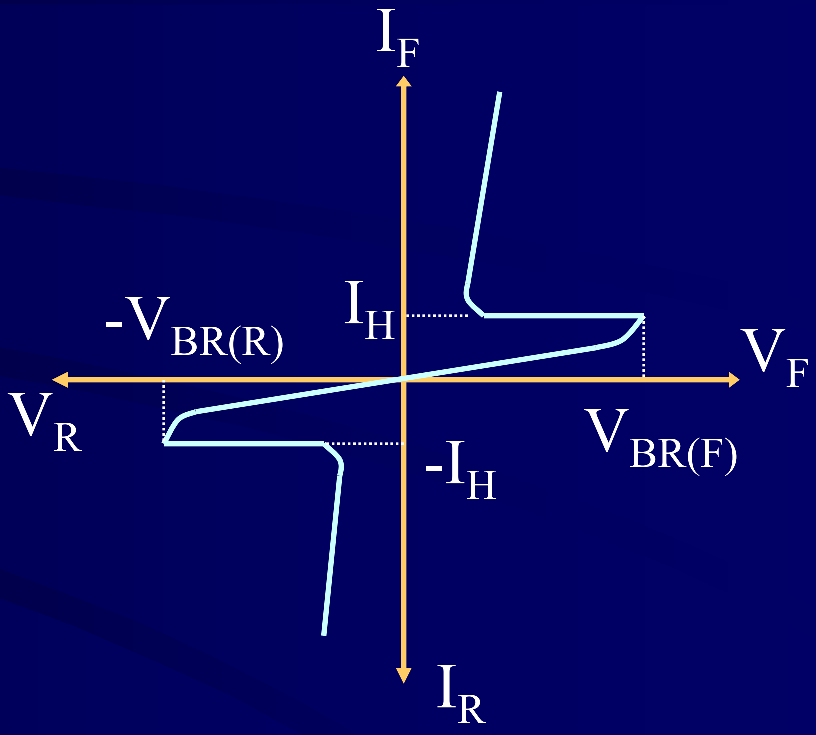
- Both the diac and the triac are types of thyristors that can conduct current in both directions (bilateral). They are four-layer devices.
- The diac has two terminals, while the triac has a third terminal (gate).
- The diac is similar to having two parallel Shockley diodes turned in opposite directions.
- The triac is similar to having two parallel SCRs turned in opposite directions with a common gate.

The Diac



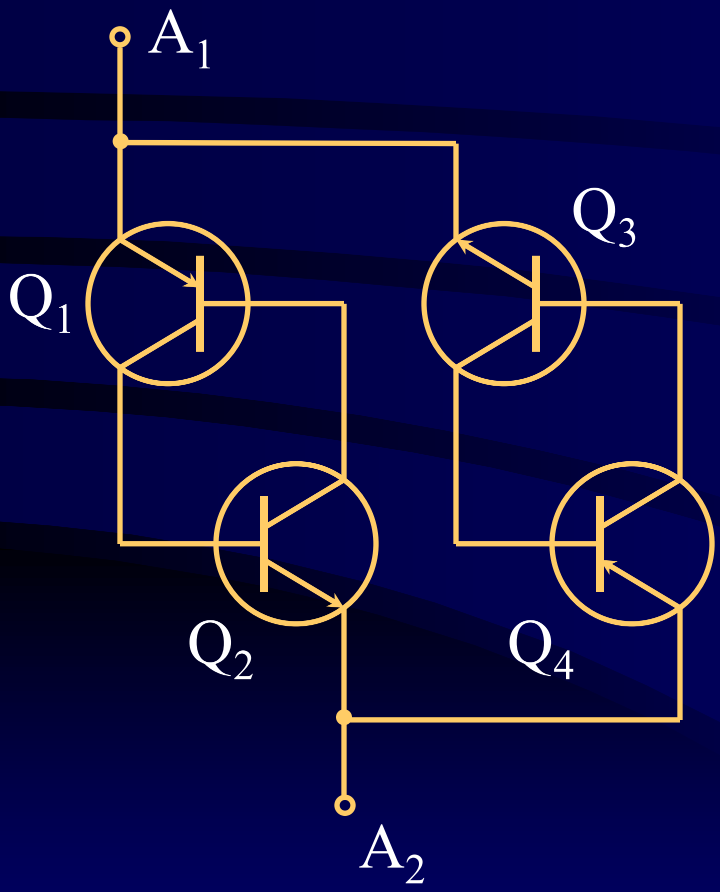
Basic Construction

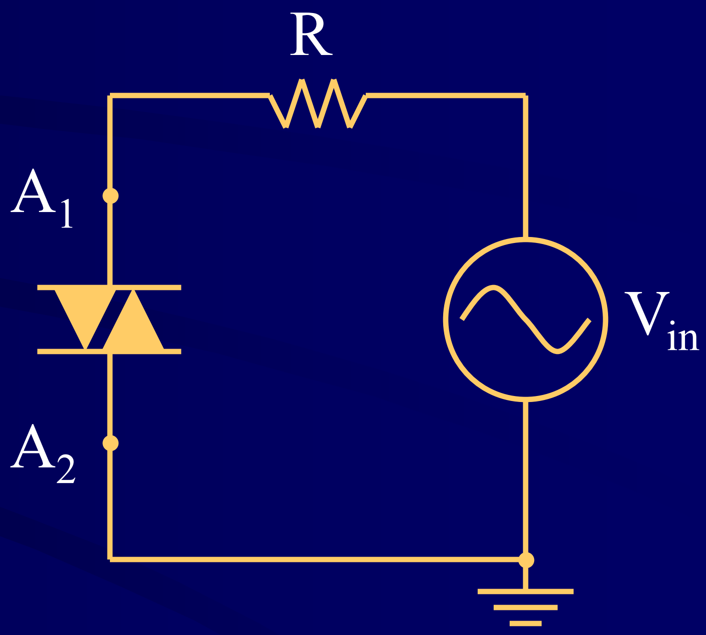
Symbol



Characteristic Curve

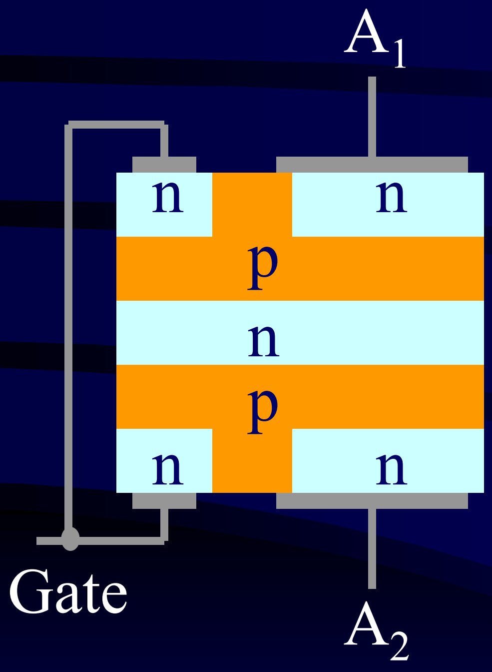
Diac Equivalent Circuit



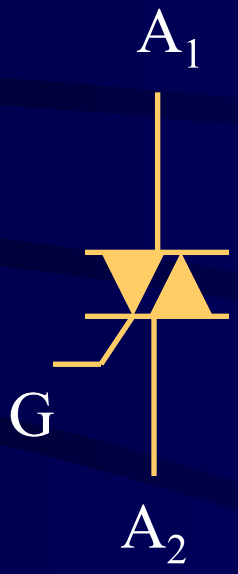


Current can flow in both directions

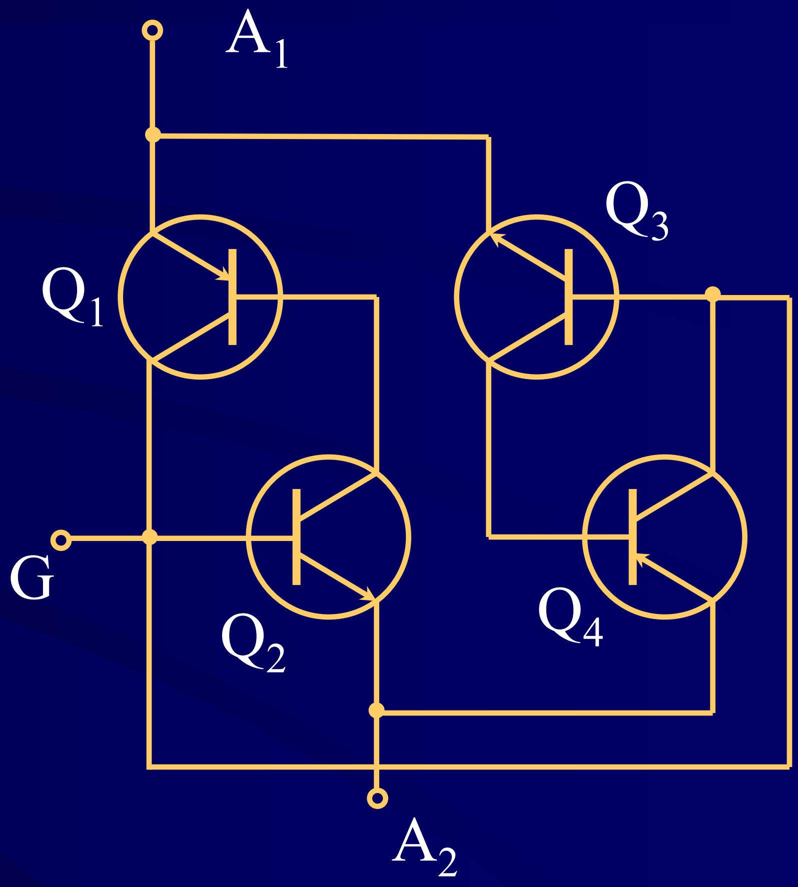
The Triac



Basic Construction

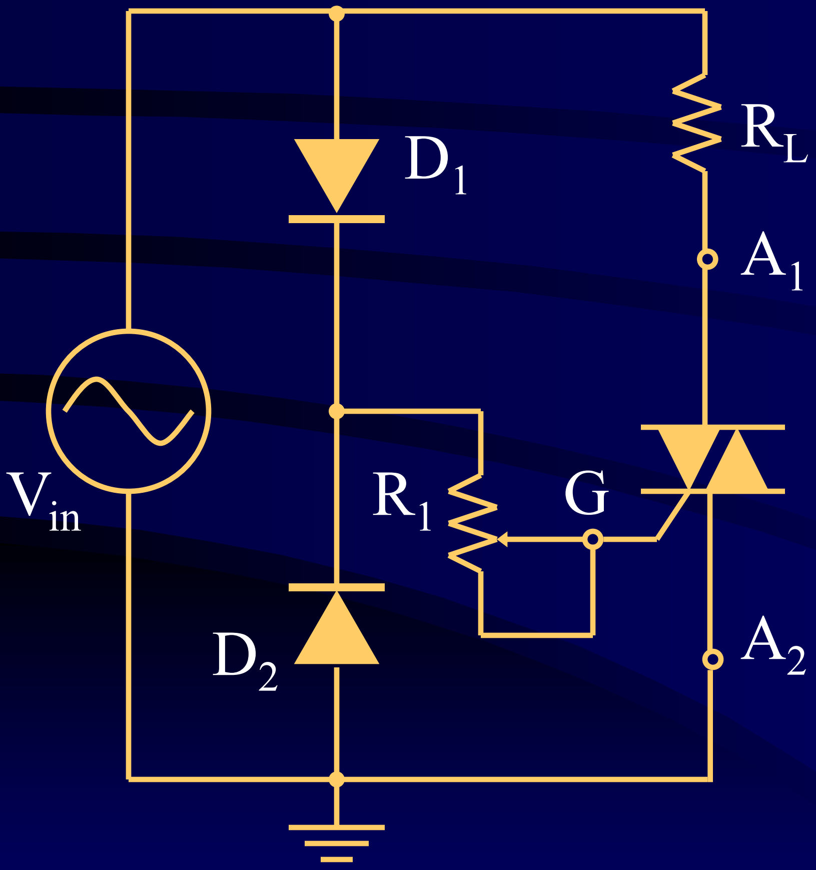


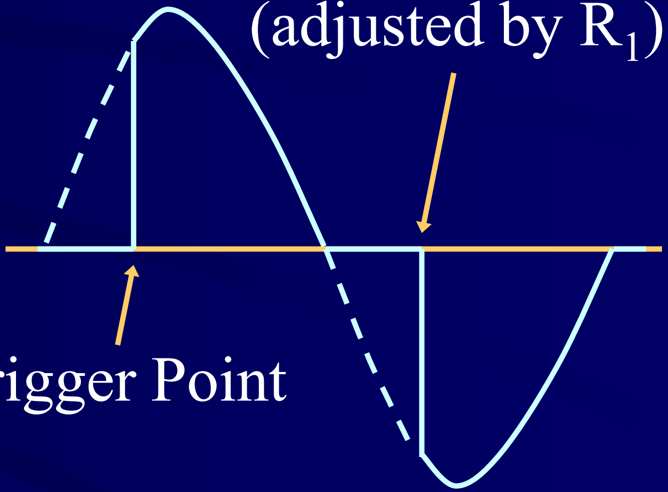
Symbol



Equivalent circuit

Triac Phase-Control Circuit



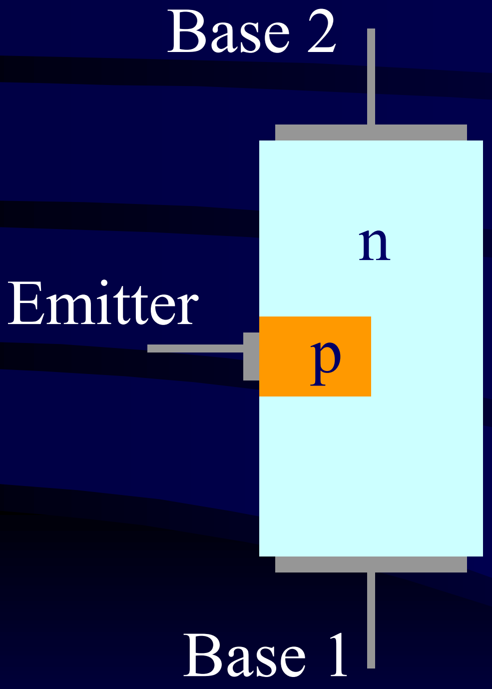


Trigger Point (adjusted by R_1)

Trigger Point

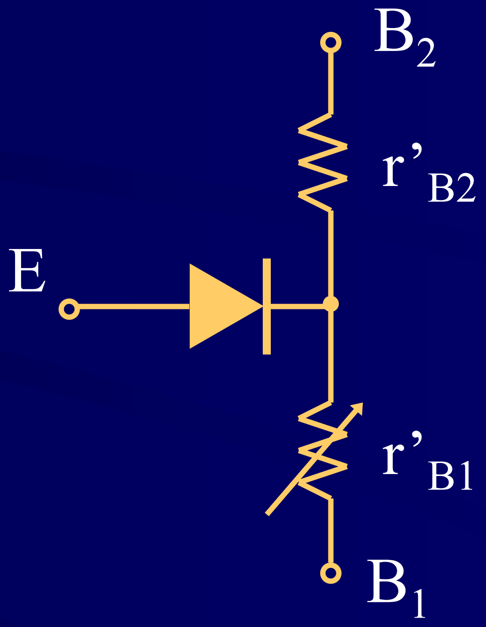
Voltage Waveform across R_L

The Unijunction Transistor



Construction

Symbol

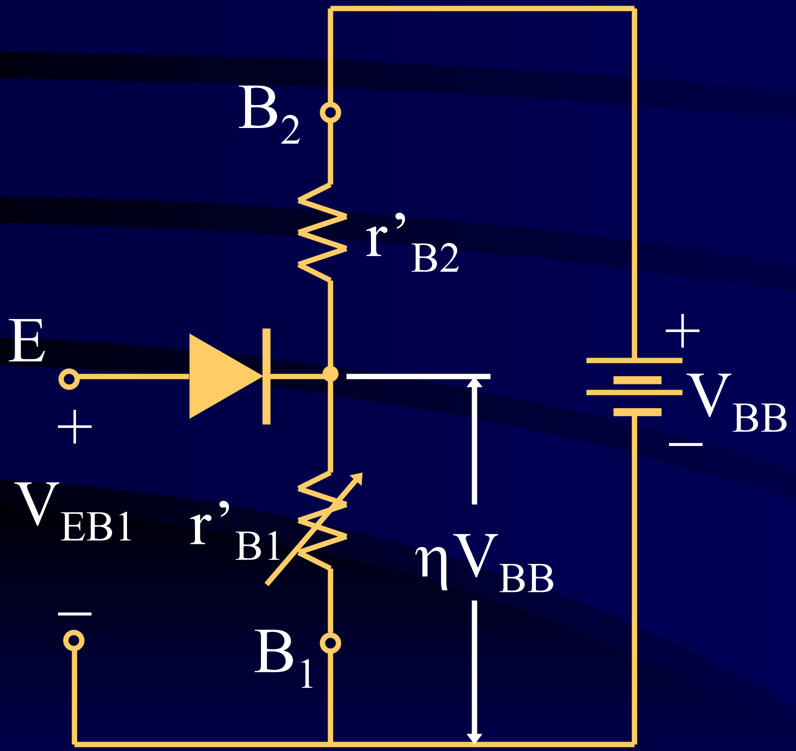


Equivalent Circuit

Notes on UJT

- UJT has only one pn junction.
- It has an emitter and two bases, B_1 and B_2.
- r'_{B1} and r'_{B2} are internal dynamic resistances.
- The interbase resistance, $r'_{BB} = r'_{B1} + r'_{B2}$.
- r'_{B1} varies inversely with emitter current, I_E
- r'_{B1} can range from several thousand ohms to tens of ohms depending on I_E.

Basic UJT Biasing



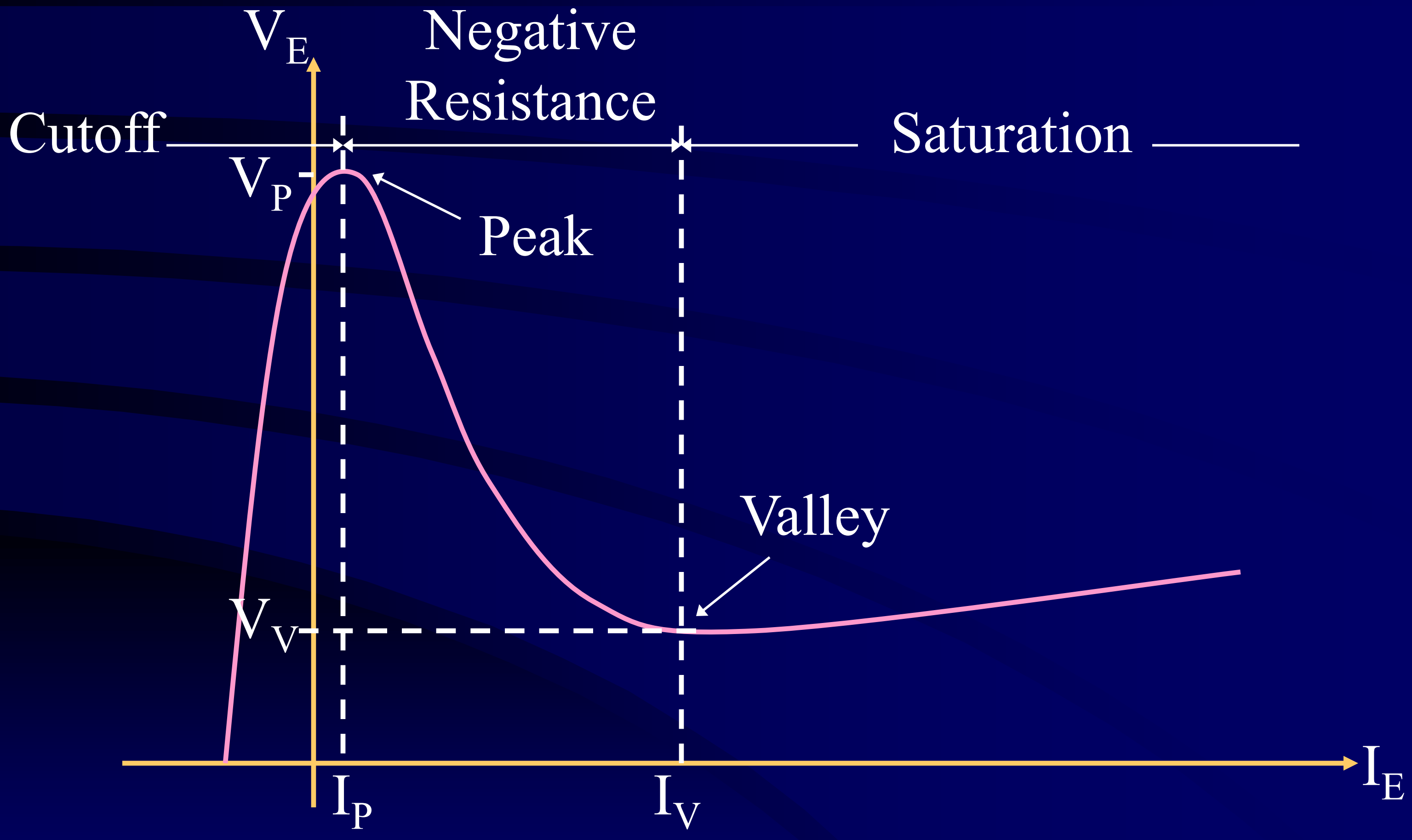
$V_{r'B1} = \eta V_{BB}$

$\eta = r'_{B1}/r'_{BB}$ is the standoff ratio.

If $V_{EB1} < V_{r'B1} + V_{pn}$, I_E 📫 0 since pn junction is not forward biased (V_{pn} = barrier potential of pn junction)

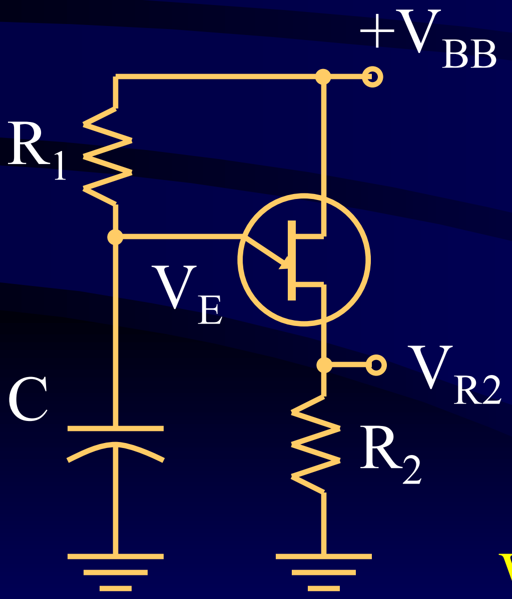
At $V_P = \eta V_{BB} + V_{pn}$, the UJT turns on and operates in a negative resistance region up to a certain value of I_E.
It then becomes saturated and I_E increases rapidly with V_E.

UJT Characteristic Curve

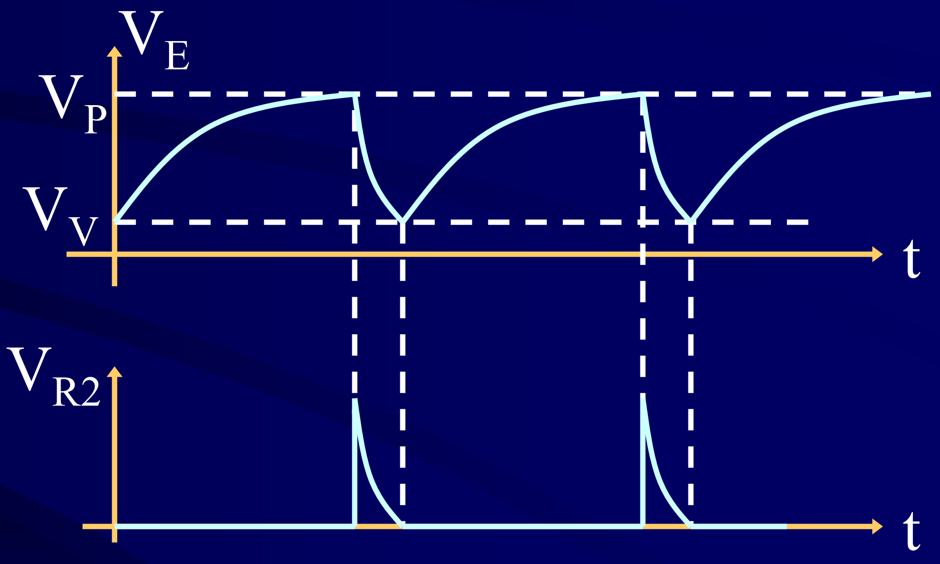


Applications of UJT

UJT can be used as trigger device for SCRs and triacs. Other applications include nonsinusoidal oscillators, sawtooth generators, phase control, and timing circuits.



Relaxation oscillator



Waveforms for UJT relaxation oscillator

Conditions For UJT Oscillator Operation

- In the relaxation oscillator, R_1 must not limit I_E at the peak point to less than I_P at turn-on, i.e., $V_{BB} - V_P > I_P R_1$.
- To ensure turn-off of the UJT at the valley point, R_1 must be large enough that I_E can decrease below I_V, i.e., $V_{BB} - V_V < I_V R_1$.
- So, for proper operation:

$$\frac{V_{BB} - V_P}{I_P} > R_1 > \frac{V_{BB} - V_V}{I_V}$$

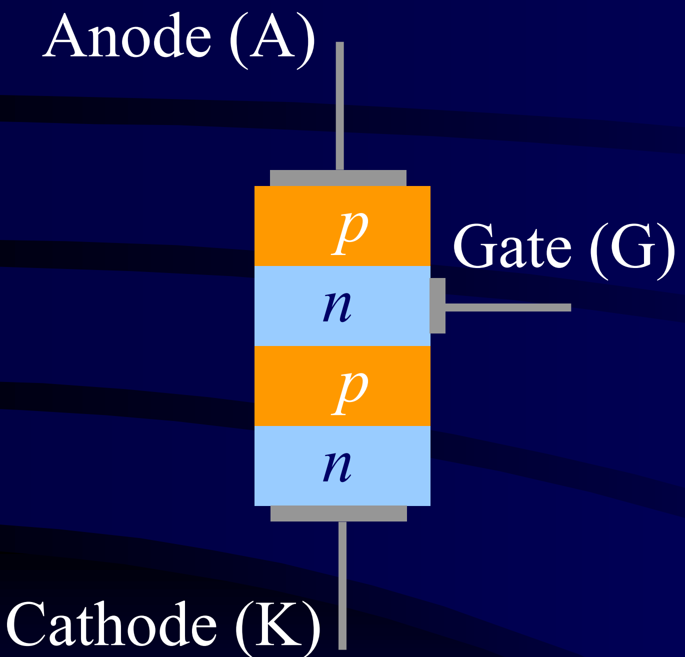
R_2 is usually << R_1, and the frequency of oscillations is

$$f_o = \left[R_1 C \ln\left(\frac{V_{BB} - V_V}{V_{BB} - V_P} \right) \right]^{-1}$$

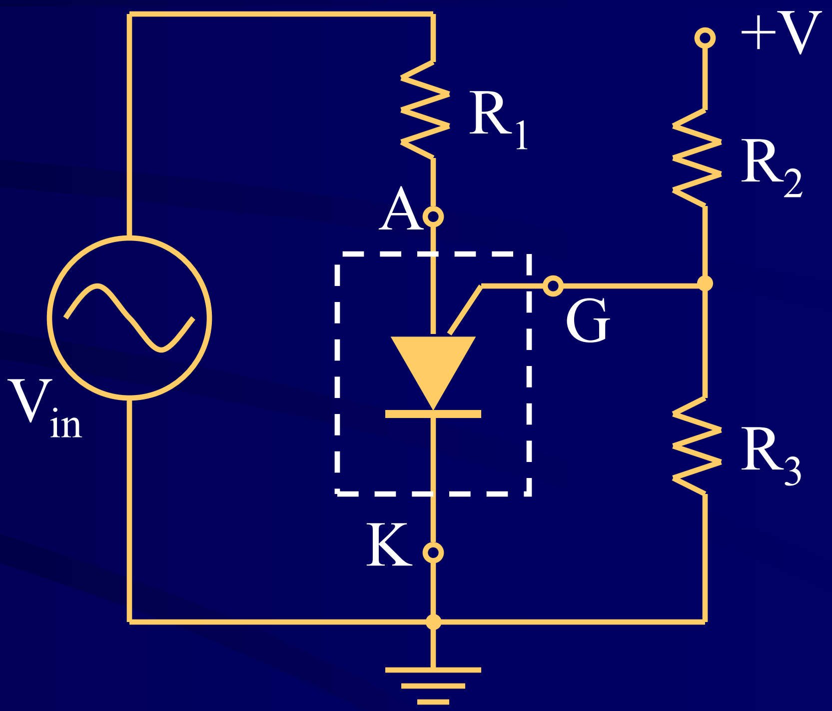
The Programmable UJT

- The PUT is actually a type of thyristor
- It can replace the UJT in some oscillator applications.
- It is more similar to an SCR (four-layer device) except that its anode-to-gate voltage can be used to both turn on and turn off the device.

PUT Construction & Symbol



Basic Construction



PUT Symbol and Biasing

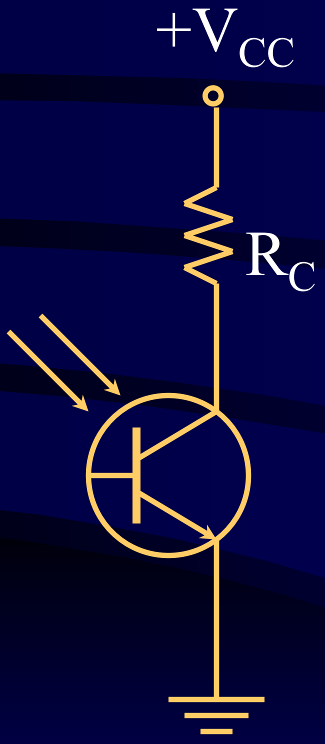
Notes On PUT

- Notice that the gate is connected to the *n* region adjacent to the anode.
- The gate is always biased positive with respect to the cathode.
- When $V_A - V_G > 0.7$ V, the PUT turns on.
- The characteristic plot of V_{AK} versus I_A is similar to the V_E versus I_E plot of the UJT.

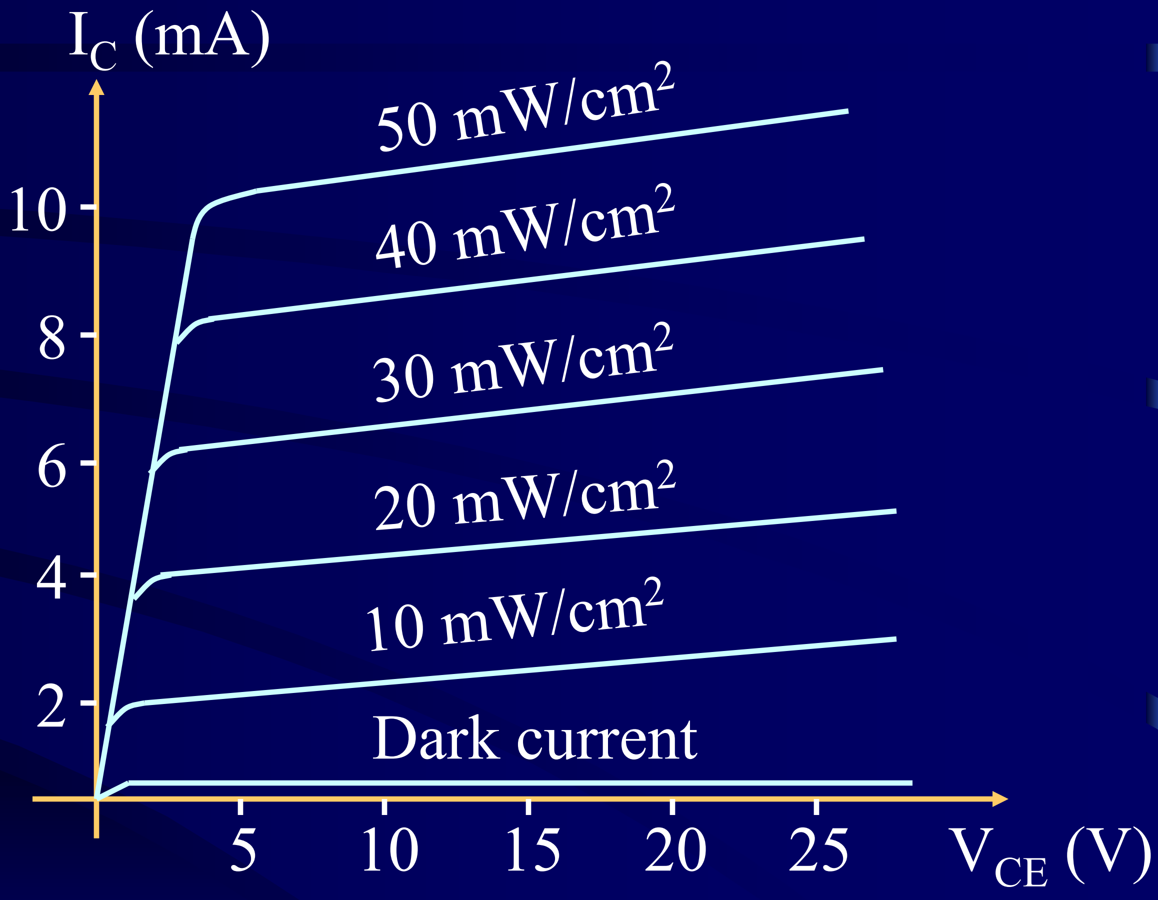
The Phototransistor

- The phototransistor has a light-sensitive, collector-base junction and is exposed to light through a lens opening in the transistor package.
- When there is no incident light, there is a small thermally generated leakage current, I_{CEO}, called the dark current and is typically in the nA range.
- When light strikes the collector-base *pn* junction, a base current, I_λ, is produced that is directly proportional to the light intensity.

Symbol & Characteristic of Phototransistor



Bias circuit



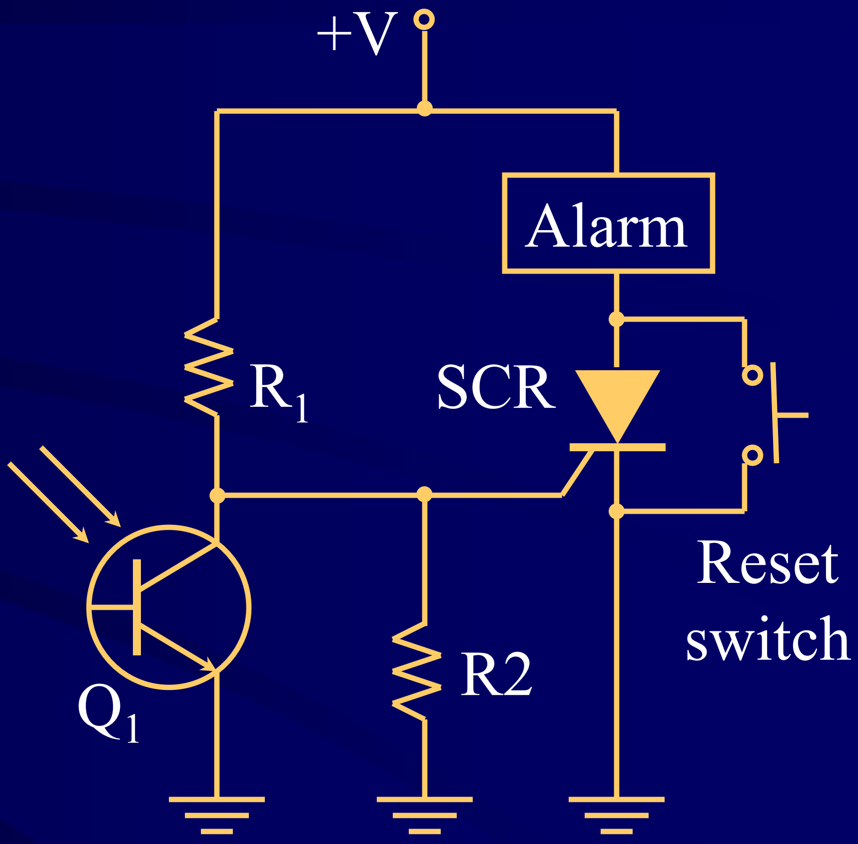
Collector characteristic curves

Notes on Phototransistor

- A phototransistor can be either a two-lead or three-lead device.
- The collector characteristic curves show the collector current increasing with light intensity.
- Phototransistors are sensitive only to light within a certain range of wavelengths as defined by their spectral response curve.
- Photodarlingtons have higher light sensitivity than phototransistors but slower switching speed .

Applications of Phototransistors

- Phototransistors are used in a wide variety of applications such as automatic door activators, process counters, and various light-activated alarms.

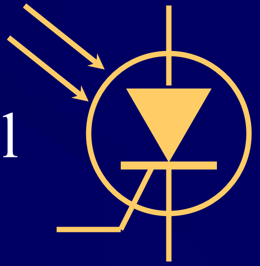


Light-interruption alarm

The Light-Activated SCR

- The light-activated SCR (LASCR) operates essentially as does the conventional SCR except it can also be light-triggered.
- Most LASCRs have an available gate terminal for conventional triggering.
- The LASCR is most sensitive to light when the gate terminal is open.

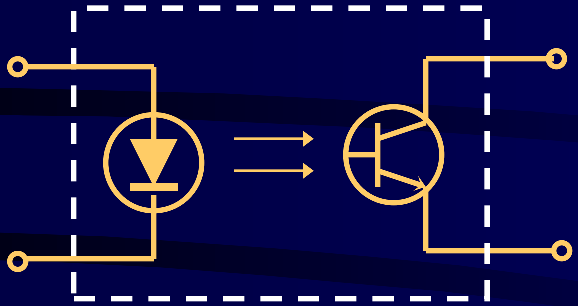
Symbol



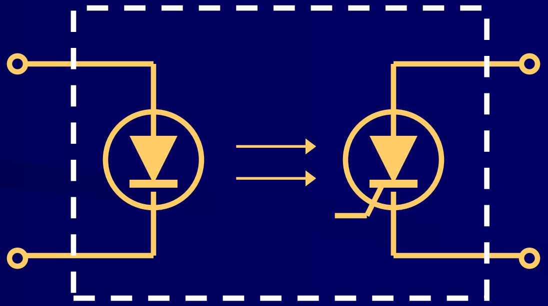
Optical Couplers

- Optical couplers provide complete electrical isolation between an input circuit and an output circuit.
- They provide protection from high voltage transients, surge voltage, and low-level noise.
- They also allow voltage level translation, and different grounds for interfacing circuits.
- Input circuit of optical coupler is typically an LED
- Output circuit can take many forms.

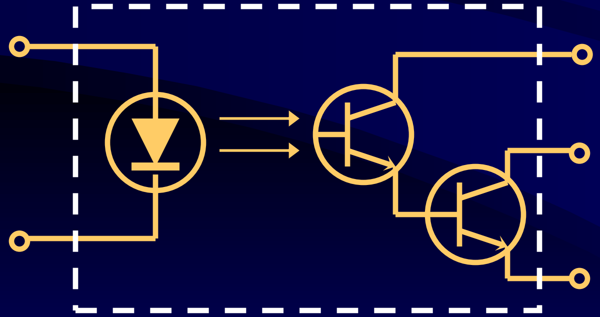
Common Types of Optical-Coupling Devices



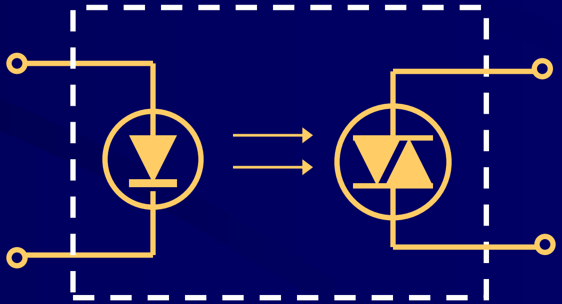
Phototransistor Output



LASCR Output



Photodarlington Output

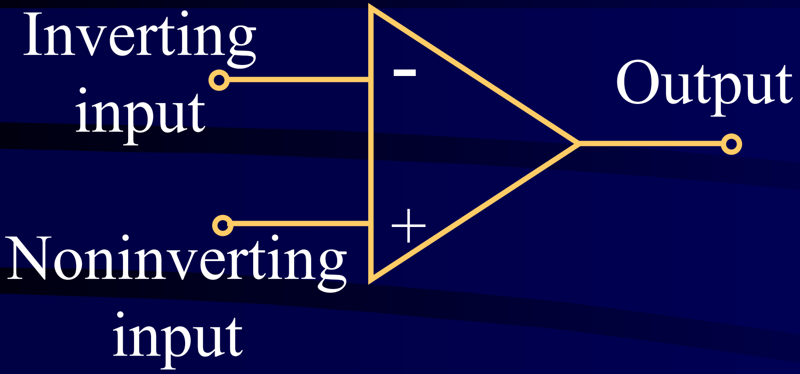


Phototriac Output

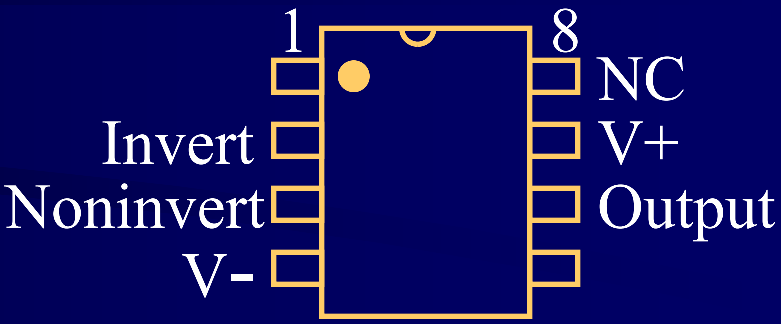
Optocoupler Parameters

- Isolation Voltage is the maximum voltage between the input and output terminals without dielectric breakdown; typically 7500 V ac peak.
- DC Current Transfer Ratio = I_{out}/I_{in} (in %); typically 2 to 100% for phototransistors.
- LED Trigger Current is the current (mA) required to trigger light-activated thyristor output devices.
- Transfer Gain = V_{out}/I_{in} applies to optically isolated ac linear couplers; typically 200 mV/mA.

Introduction To Operational Amplifiers



Symbol



Typical Package

- Op-amps are linear IC devices with two input terminals, and one output terminal. One input is inverting (-), and the other noninverting (+).
- Standard symbol usually does not show dc supply terminals.

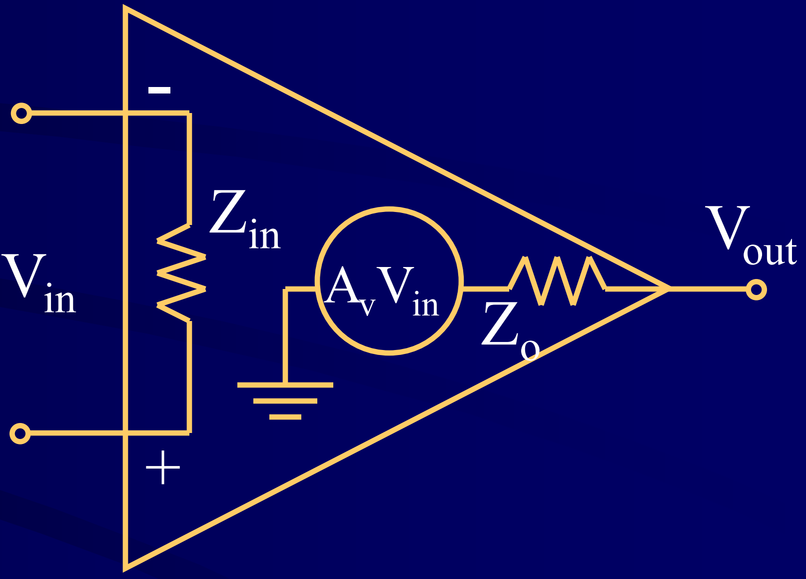
Ideal versus Practical Op-Amp

Ideal op-amp characteristics:

Z_{in} = 🗐; A_v = 🗐;
bandwidth = 🗐; $Z_{out} = 0$

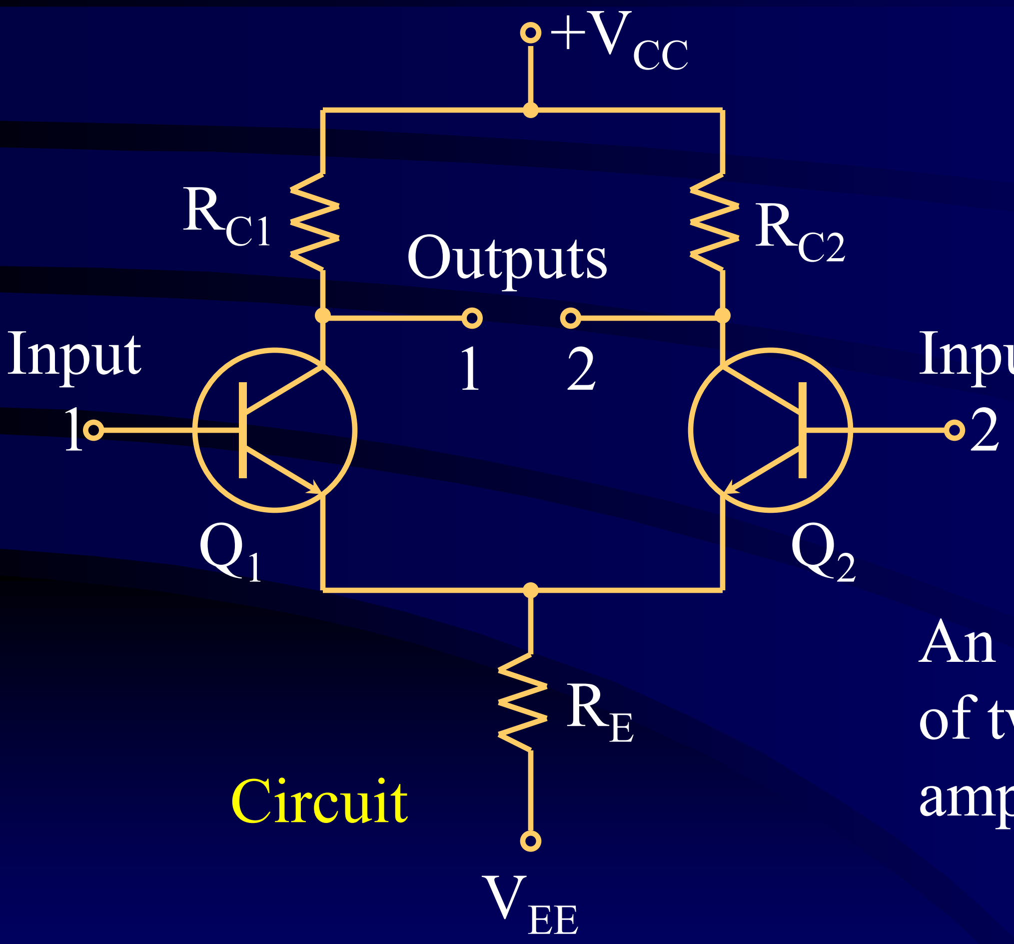
Practical op-amp characteristics:

Z_{in} = very high (MΩ);
A_v = very high (♋100,000);
Z_{out} = very low (<100 Ω)
bandwidth = few MHz range
V_{out} and I_{out} have limitations

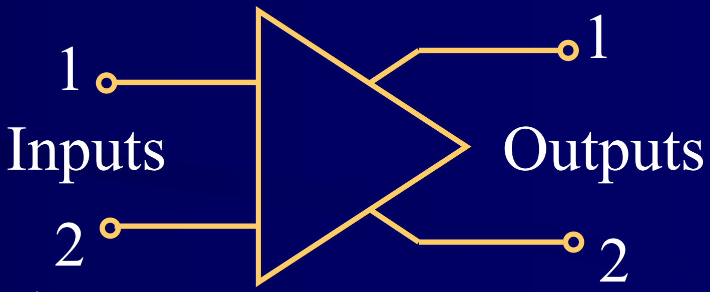


Op-amp representation

The Differential Amplifier



Circuit



Symbol

An op-amp typically consists of two or more differential amplifier stages.

Basic Operation of Diff-Amp

Assuming the transistors are perfectly matched and both inputs are grounded: $I_{E1} = I_{E2} = I_{RE}/2$ where

$$I_{RE} = \frac{V_E - V_{EE}}{R_E} = \frac{-0.7 - V_{EE}}{R_E}$$

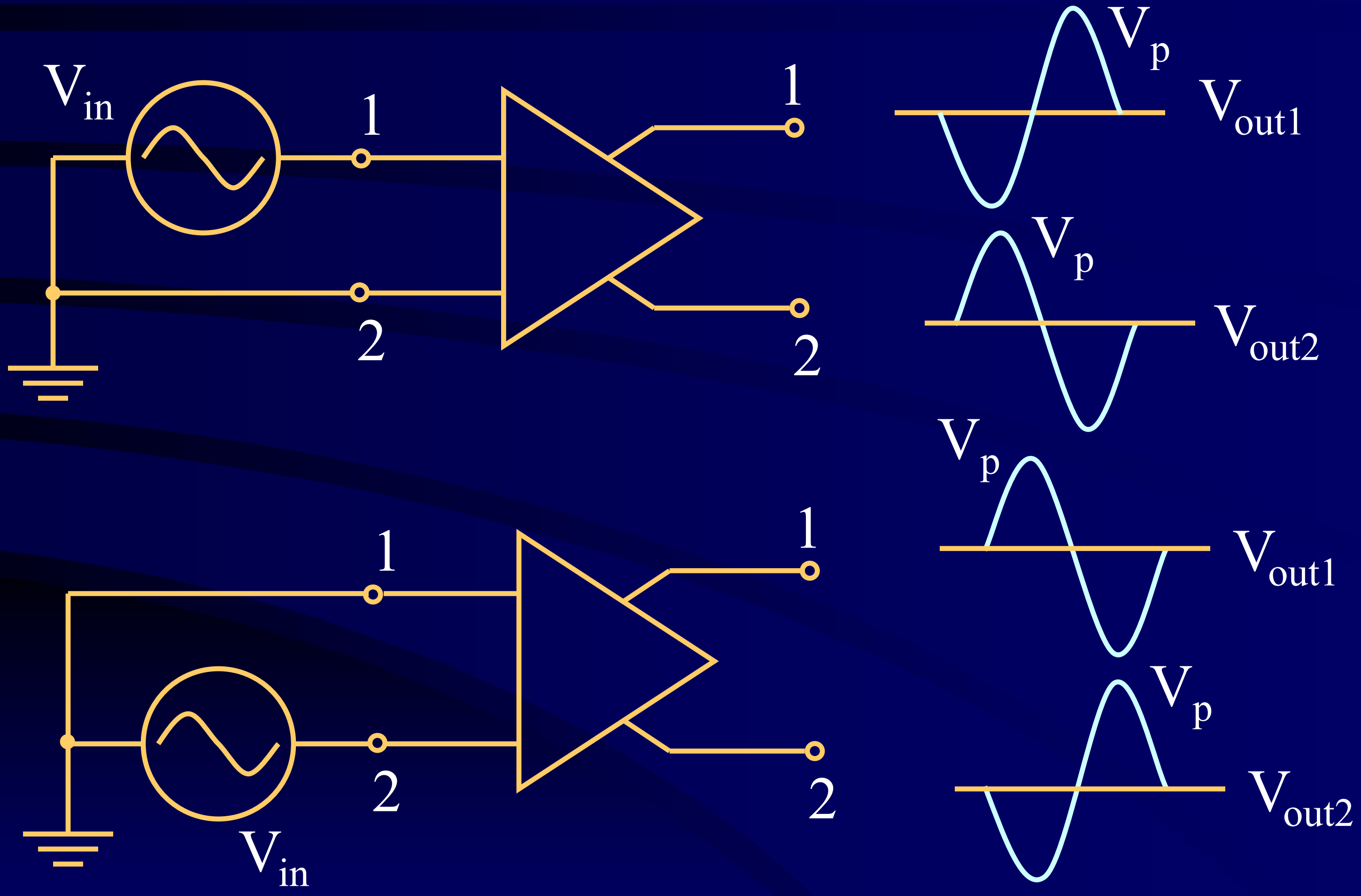
Also, $I_{C1} = I_{C2} \cong I_{E1}$

and $V_{C1} = V_{C2} = V_{CC} - I_{C1}R_{C1}$

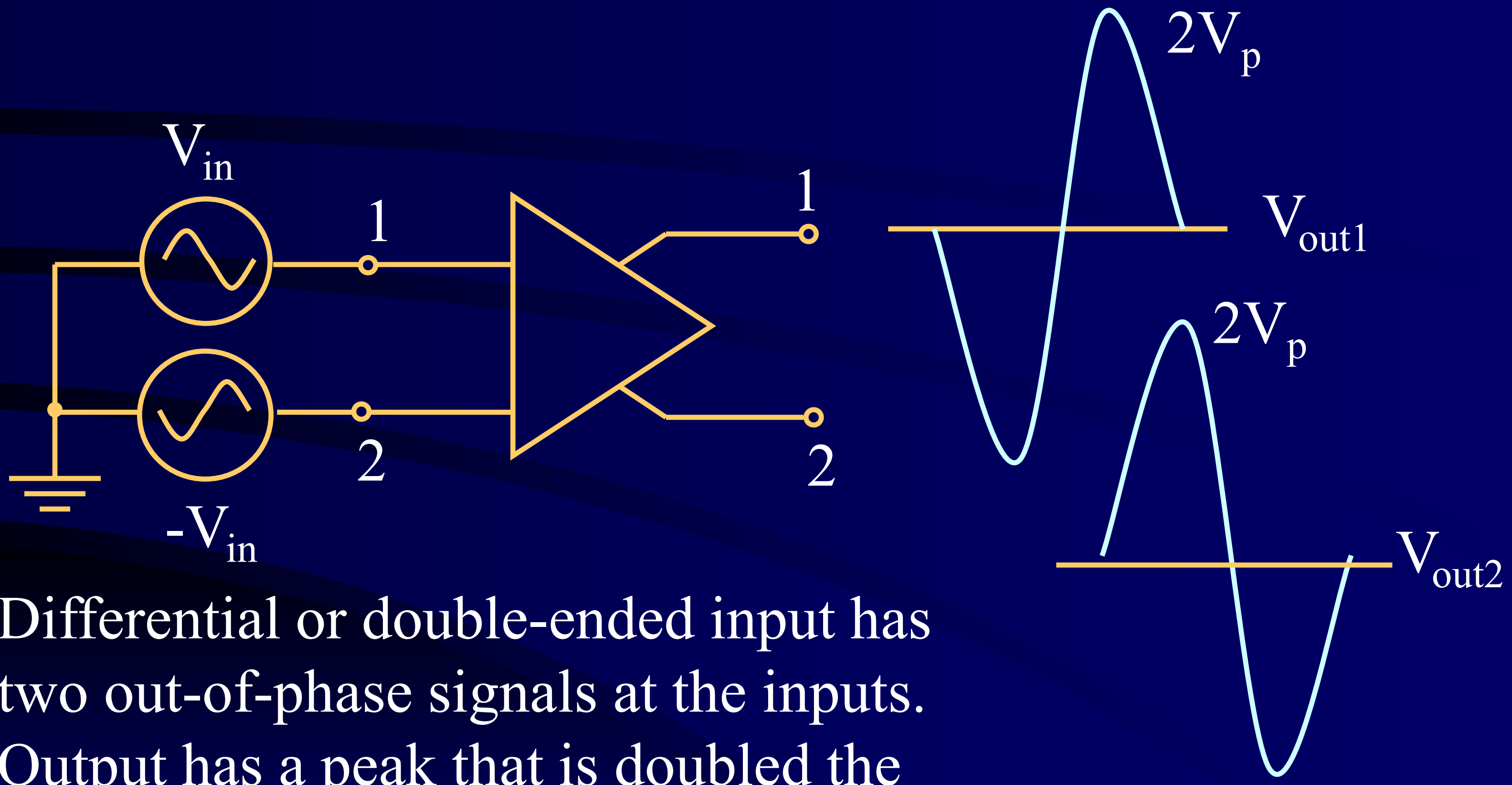
If input 2 is grounded but a positive voltage is applied to input 1, I_{C1} increases, V_{C1} decreases, and $V_E = V_{B1} - 0.7$ rises. This causes V_{BE2} to decrease, I_{C2} to decrease and V_{C2} to increase.

Similarly, if input 1 is grounded, but a positive voltage is applied to input 2, I_{C2} increases, V_{C2} decreases, I_{C1} decreases and V_{C1} increases. A negative input would have the reversed effects.

Single-Ended Input Operation

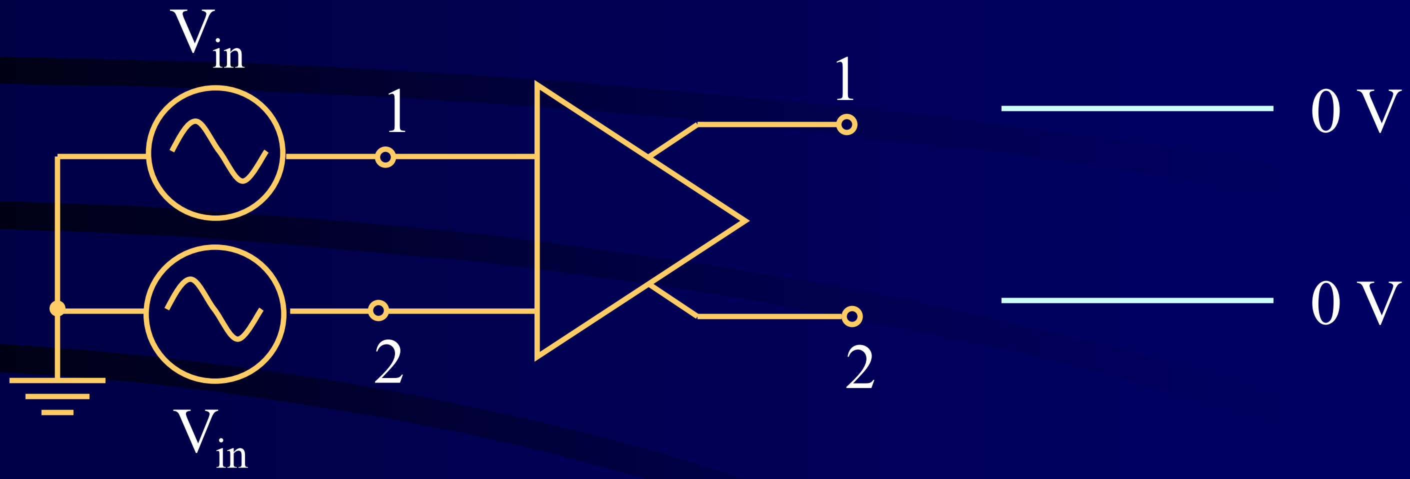


Differential Input Operation



Differential or double-ended input has two out-of-phase signals at the inputs. Output has a peak that is doubled the peak (Vp) for single-ended operation.

Common-Mode Input Operation



Two signals with the same phase, frequency, and amplitude are applied to the inputs. Output is zero due to cancellations. Thus, unwanted signals (noise) appearing at both input lines are essentially cancelled by the diff-amp and do not appear at the outputs.

Common-Mode Rejection Ratio

- Ideally, a diff-amp provides a very high gain for desired signals (single-ended or differential), and zero gain for common-mode signals.
- Common-mode rejection ratio (CMRR) is a measure of the amplifier's ability to reject common-mode signals and is the ratio of the differential voltage gain ($A_{vd} = |v_{o1}/v_{in}|$) to the common mode gain ($A_{cm} = |v_{o1(cm)}/v_{in(cm)}|$):

$$CMRR = \frac{A_{vd}}{A_{cm}}; or\ 20\log\left(\frac{A_{vd}}{A_{cm}}\right) in\ dB$$

Op-Amp Parameters

- Input Offset Voltage, V_{OS} is the difference in the voltage between the inputs that is necessary to make $V_{out(error)} = 0$. $V_{out(error)}$ is caused by a slight mismatch of V_{BE1} and V_{BE2}. Typical values of V_{OS} are ✁ 2 mV.
- Input Offset Voltage Drift specifies how V_{OS} changes with temperature. Typically a few µV/°C.
- Input Bias Current is the dc current required by the inputs of the amplifier to properly operate the first stage. By definition, it is the average of the two input bias currents, $I_{BIAS} = (I_1 + I_2)/2$.

Op-Amp Parameters (cont'd)

- Differential Input Impedance is the total resistance between the inverting and non-inverting inputs.
- Common-mode Input Impedance is the resistance between each input and ground.
- Input Offset Current is the difference of the input bias currents: $I_{OS} = |I_1 - I_2|$, and $V_{OS} = I_{OS}R_{in(CM)}$. Typically in nA range.
- Output Impedance is the resistance viewed from the output terminals.
- Open-Loop Voltage Gain, A_{ol}, is the gain of the op-amp without any external feedback connections.

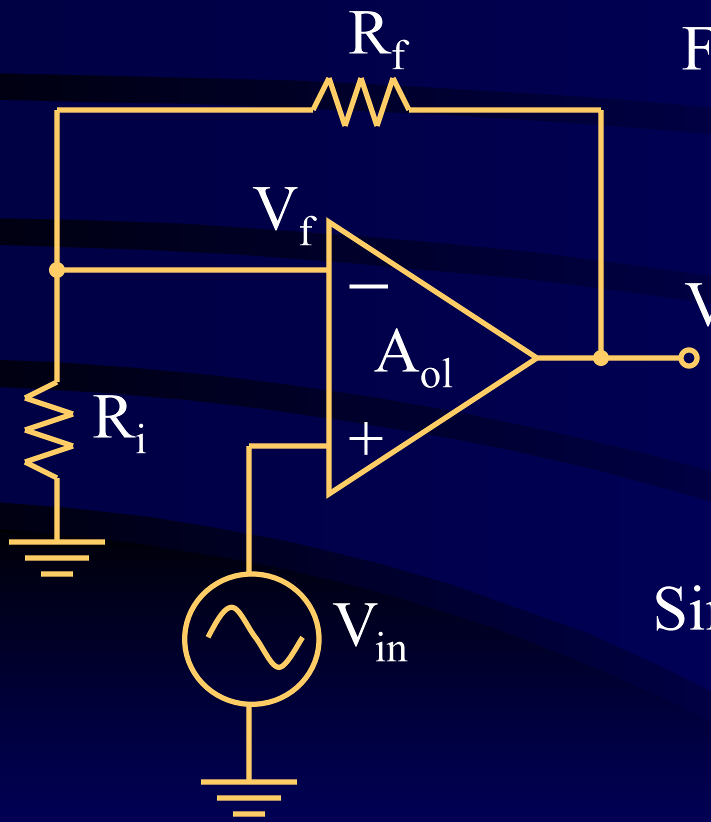
Op-Amp Parameters (cont'd)

- Common-mode Rejection Ratio for op-amp is defined as CMRR = A_{ol}/A_{cm} or 20 log (A_{ol}/A_{cm}) in dB.
- Slew Rate is the maximum rate of change of the output voltage in response to a step input voltage. Slew rate = $\Delta v_{out}/\Delta t$, where $\Delta v_{out} = +V_{max} - (-V_{max})$. The units for slew rate is V/µs.
- Frequency Response is the change in amplifier gain versus frequency and is limited by internal junction capacitances.
- Other features include short circuit protection, no latch-up, and input offset nulling.

Negative Feedback

- Since the open-loop gain of the op-amp is very high, an extremely small input voltage (such as V_{OS}) would drive the op-amp into saturation.
- By feeding a portion of the output voltage to the inverting input of the op-amp (negative feedback), the closed-loop voltage gain (A_{cl}) can be reduced and controlled (i.e. stable) for linear operations.
- Negative feedback also provides for control of Z_{in}, Z_{out}, and the amplifier's bandwidth.

Noninverting Amplifier



Feedback voltage, $V_f = BV_{out}$, where

$$B = \frac{R_i}{R_i + R_f}$$

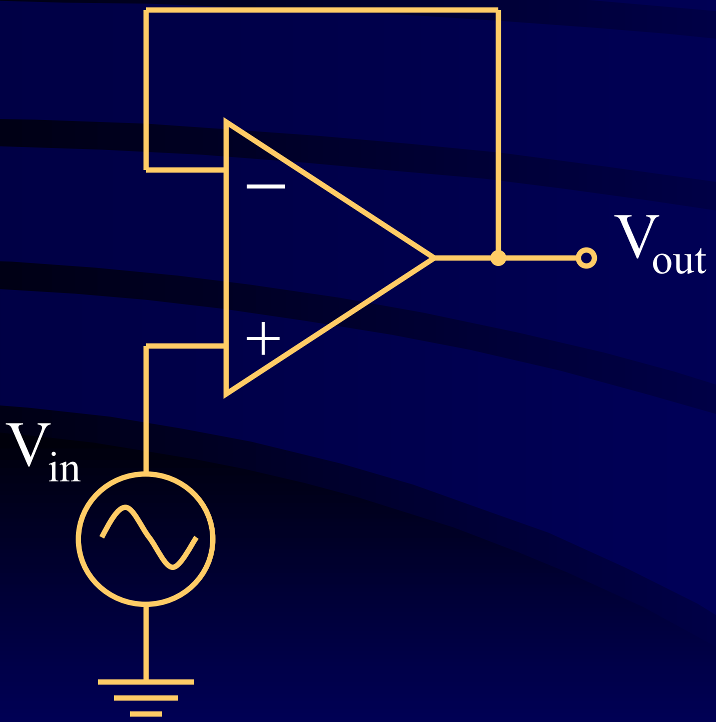
$$V_{out} = A_{ol}\,(V_{in} - V_f)$$

Rearranging, $$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + BA_{ol}}$$

Since $BA_{ol} \gg 1$,

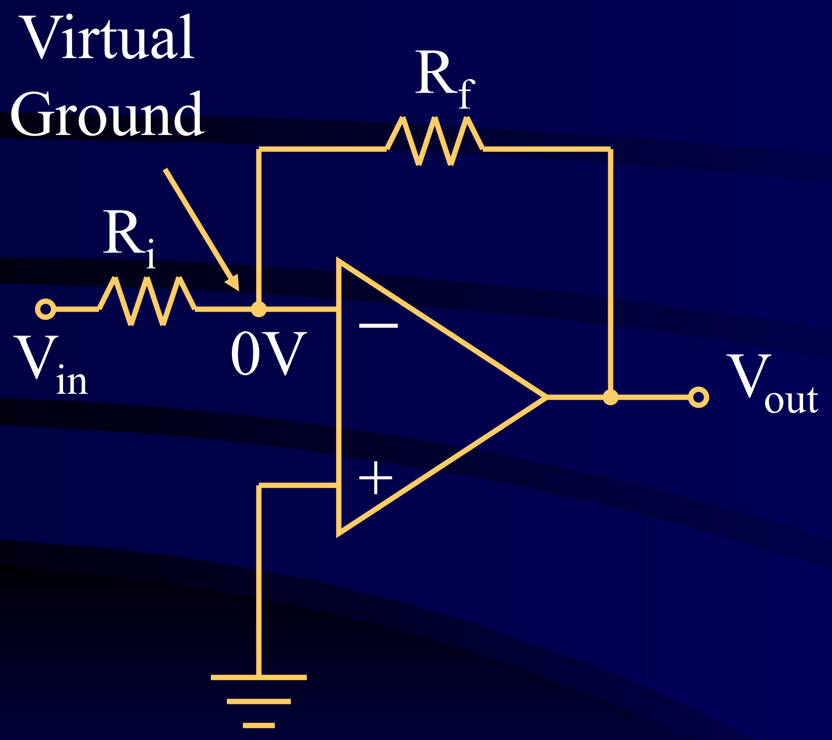
$$A_{cl(NI)} = \frac{V_{out}}{V_{in}} \approx \frac{1}{B} = 1 + \frac{R_f}{R_i}$$

Voltage-Follower



- VF is a special case of the non-inverting amplifier.
- Since B = 1, $A_{cl(VF)} = 1$
- It has a very high Z_{in}, and a very low Z_{out}
- Ideal as a buffer amplifier.

Inverting Amplifier



- Assuming Z_{in} between -ve and +ve terminals is infinite, current into -ve terminal is zero.
- Therefore, $I_{in} = V_{in}/R_i$ is equal to $I_f = -V_{out}/R_f$
- Rearranging,

$$A_{cl(I)} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

Impedances of Feedback Amplifiers

Noninverting Amplifier: $Z_{in(NI)} = (1 + BA_{ol})Z_{in}$

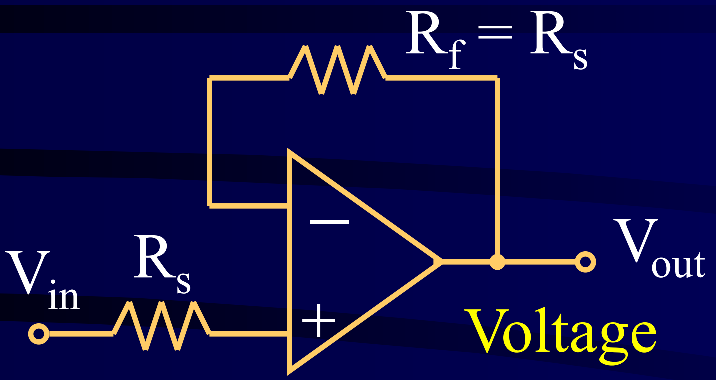
$$Z_{out(NI)} = \frac{Z_{out}}{1 + BA_{ol}}$$

Voltage Follower: $Z_{in(VF)} = (1 + A_{ol})Z_{in}$

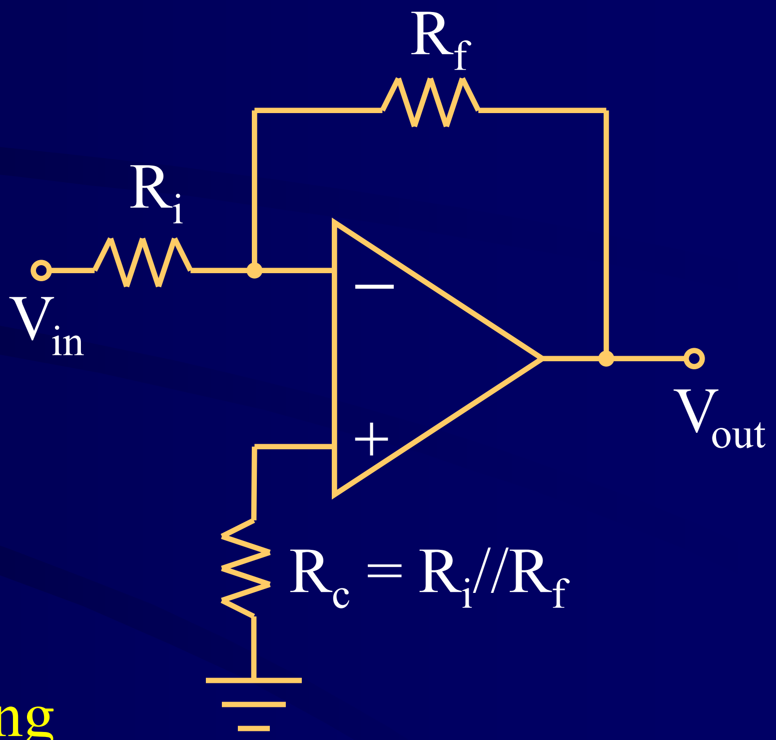
$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{ol}}$$

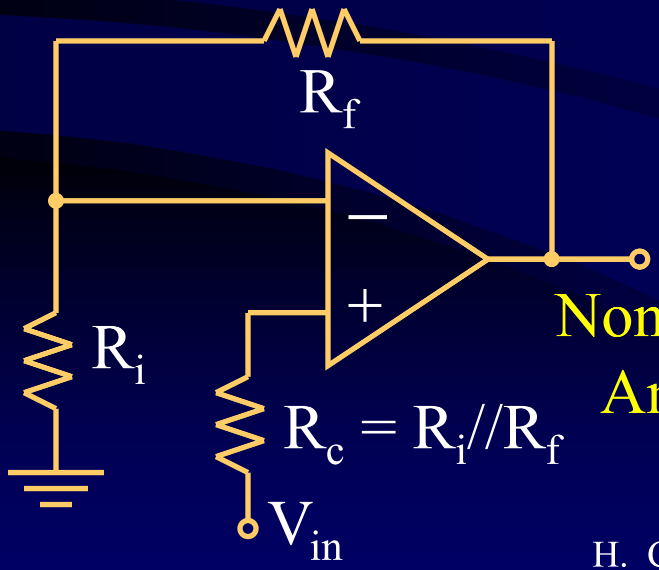
Inverting Amplifier: $Z_{in(I)} \cong R_i$; $Z_{out(I)} \cong Z_{out}$

Bias Current Compensation



Voltage Follower

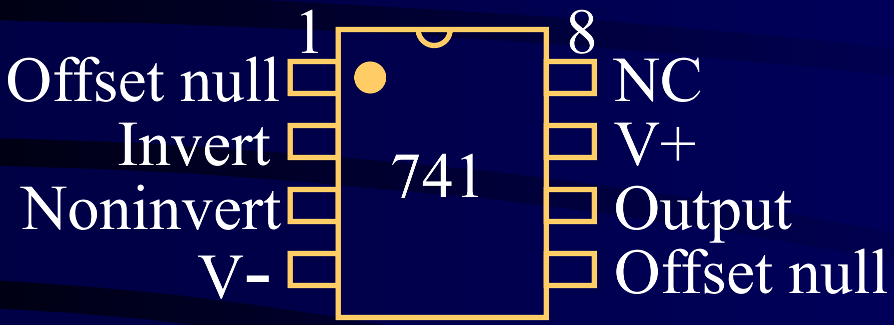




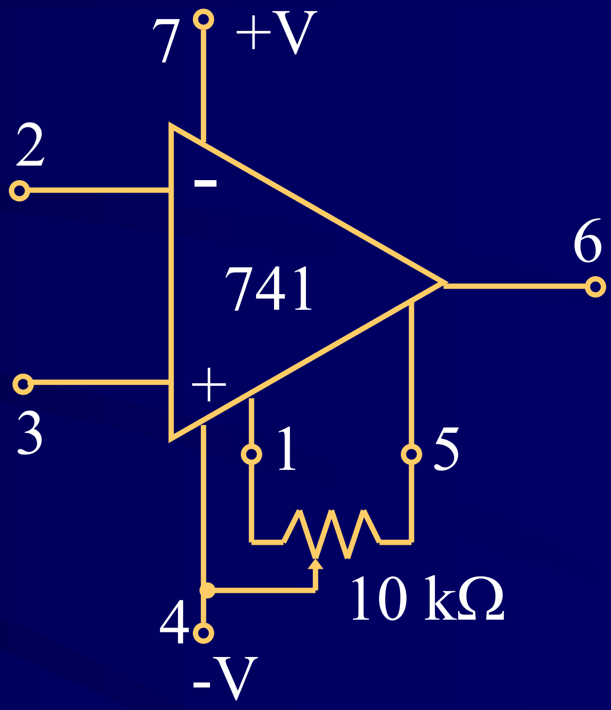
Noninverting Amplifier

Inverting Amplifier

Input Offset Voltage Compensation

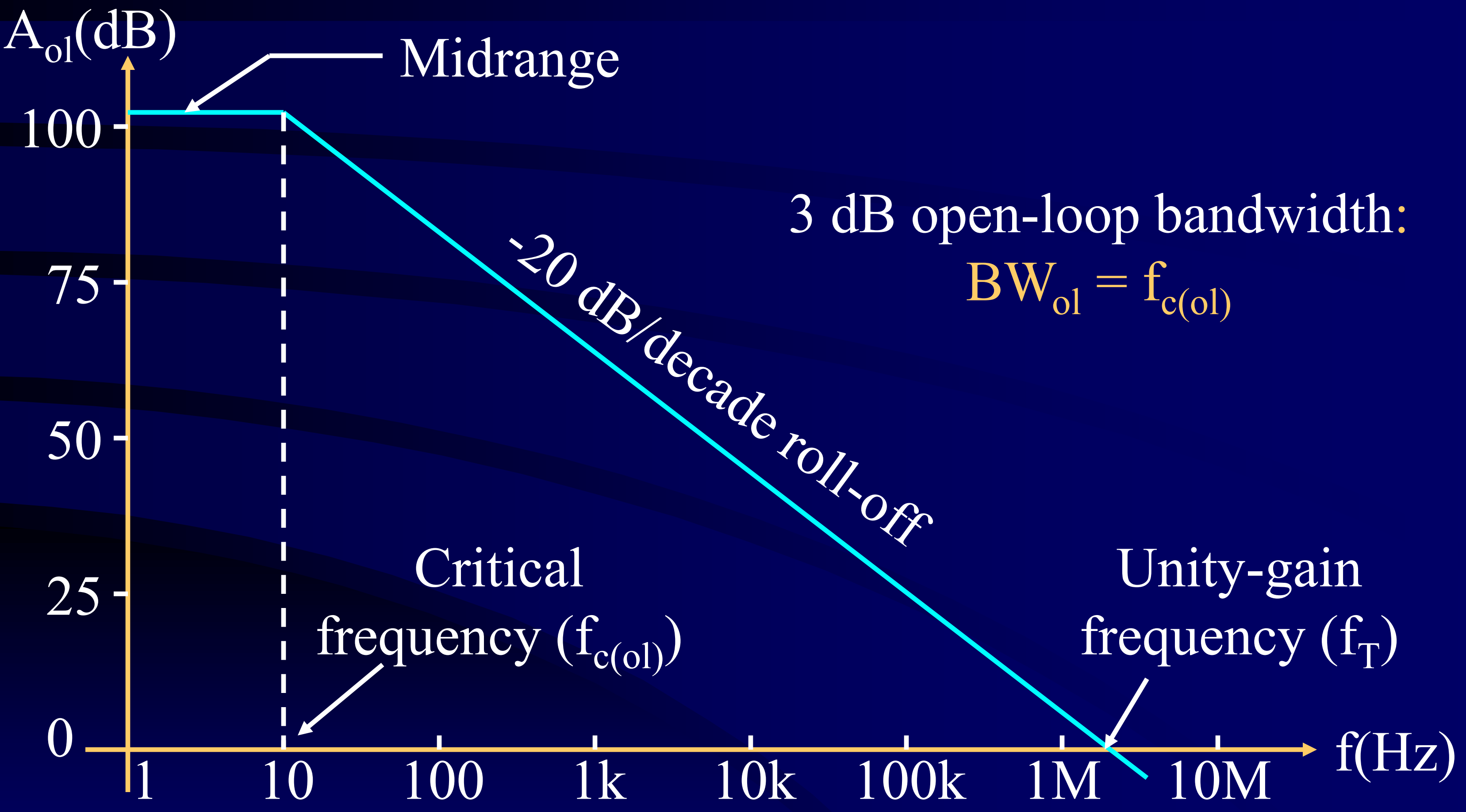


8-pin DIP
or SMT Package



With no input, the potentiometer is adjusted until the output voltage is 0V.

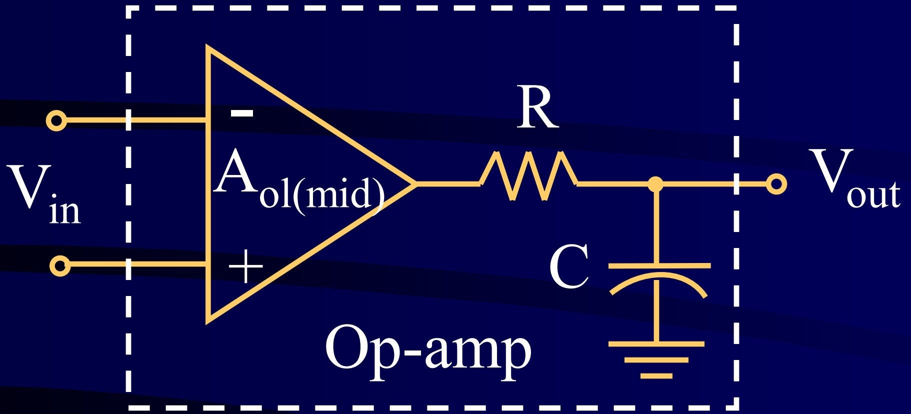
Bode Plot of Open-Loop Gain



3 dB open-loop bandwidth:

$BW_{ol} = f_{c(ol)}$

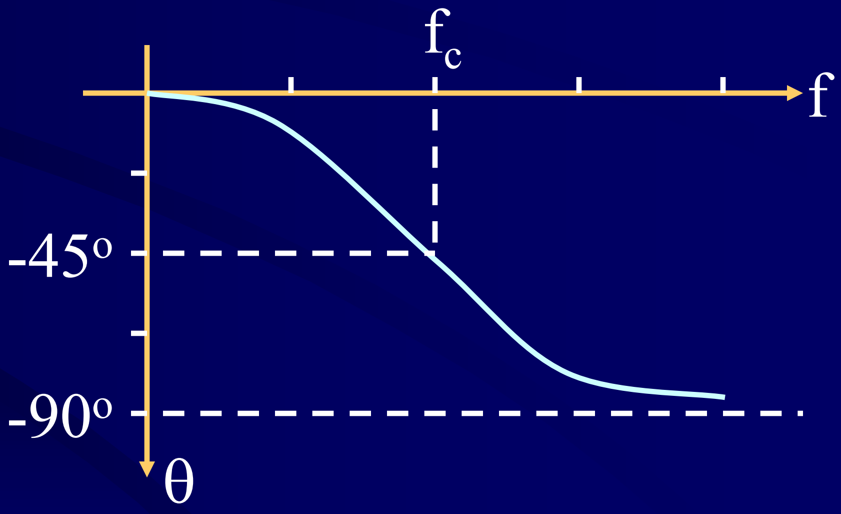
Op-Amp Representation



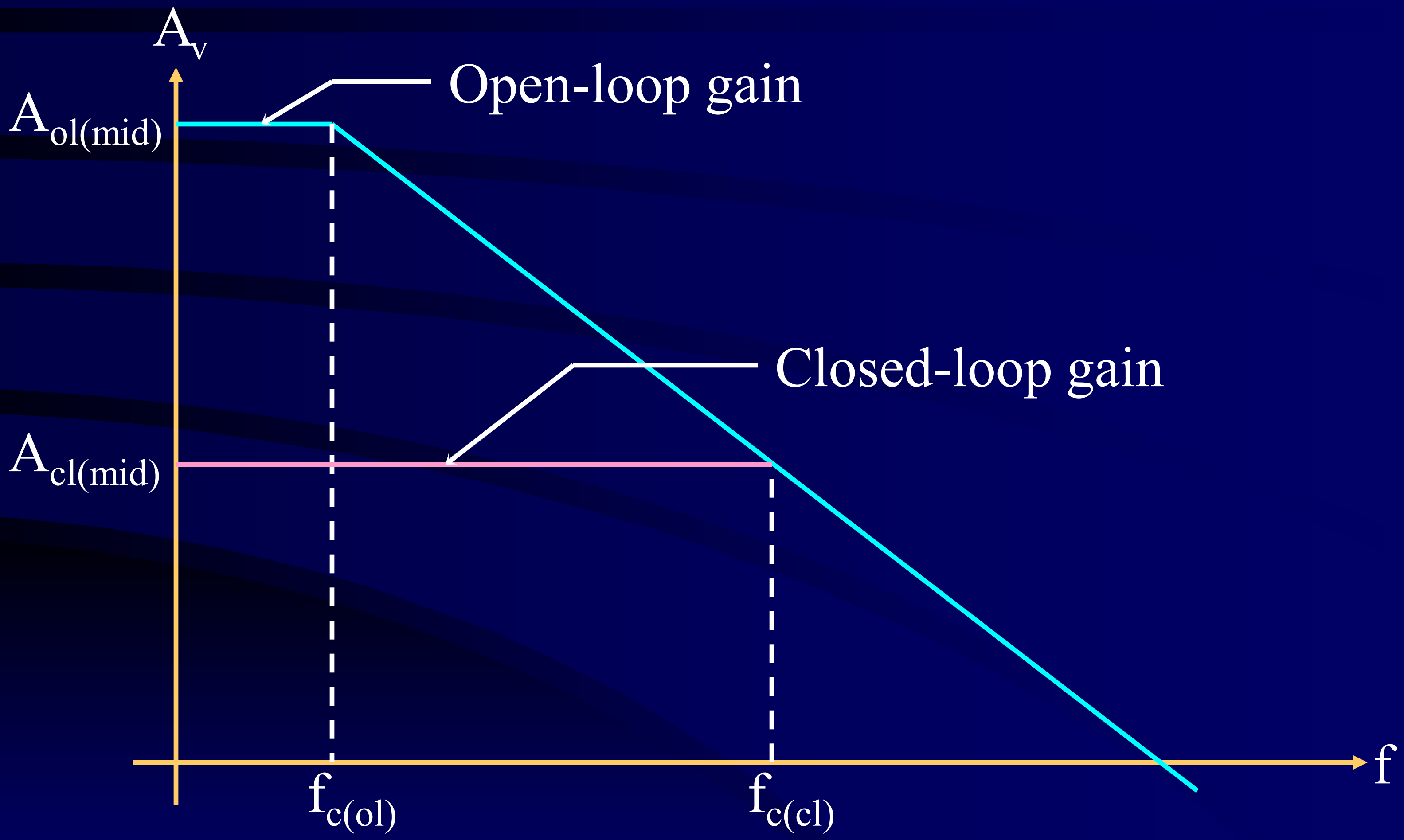
$$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1 + \left(\frac{f}{f_{c(ol)}}\right)^2}}$$

Phase shift:

$$\theta = -\tan^{-1}\left(\frac{f}{f_c}\right)$$



Closed-Loop vs Open-loop Gain



Op-Amp Bandwidth

- Open-loop bandwidth: $BW_{ol} = f_{c(ol)}$
- Closed-loop critical frequency:

  $$f_{c(cl)} = f_{c(ol)}(1 + BA_{ol(mid)})$$

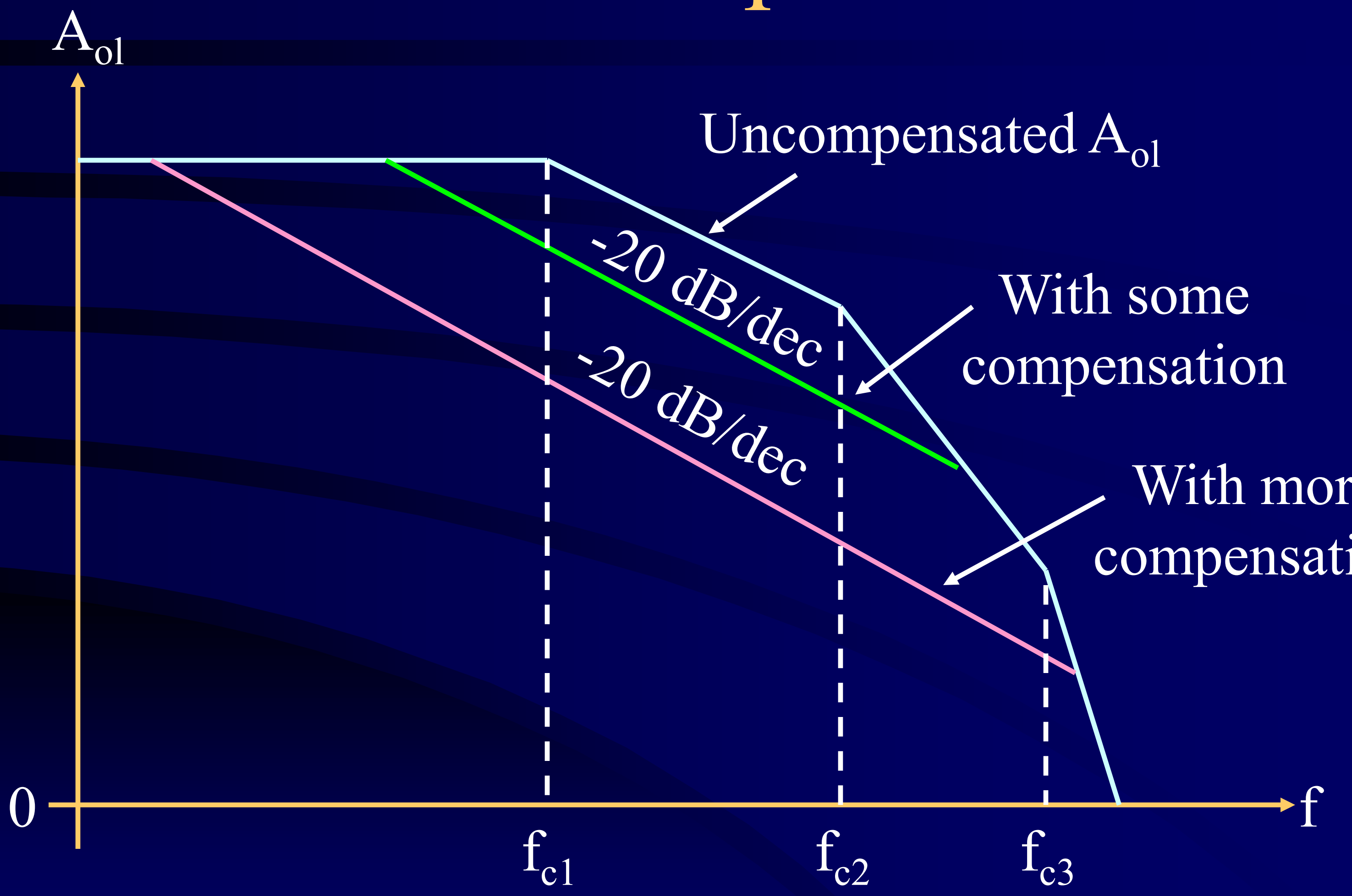
- Since $f_{c(cl)} = BW_{cl}$, the closed-loop bandwidth is: $BW_{cl} = BW_{ol}(1 + BA_{ol(mid)})$
- Gain Bandwidth Product is a constant as long as the roll-off rate is fixed:

  $$A_{cl}f_{c(cl)} = A_{ol}f_{c(ol)} = \text{unity-gain bandwidth}$$

Positive Feedback & Stability

- Positive feedback, where the output signal being fed back is in-phase to the input, will cause the amplifier to oscillate when the loop gain, $A_{ol}B > 1$.
- Phase margin, θ_{pm} , is the amount of additional phase shift required to make the total phase shift around the feedback loop 360^o.
- To ensure stability for all midrange frequencies, an op-amp must be operated with an A_{cl} such that the roll-off rate beginning at f_c is ✁ -20 dB/decade.

Phase Compensation



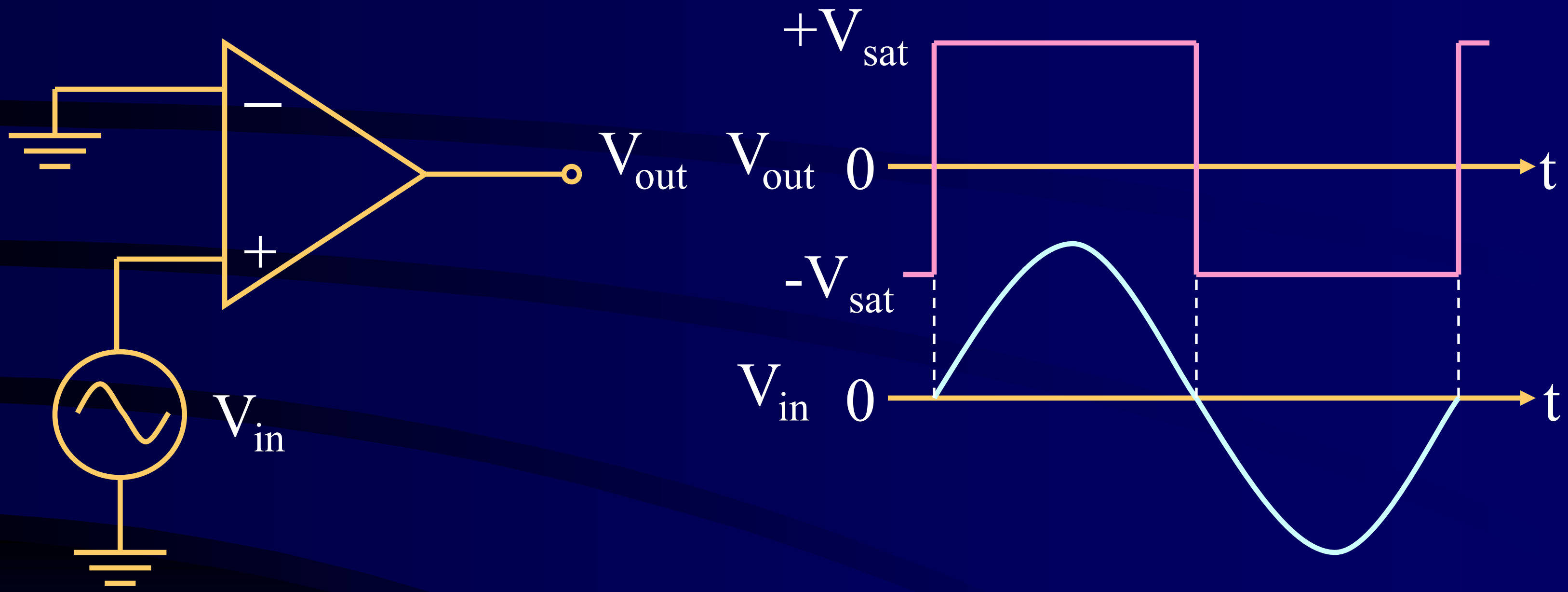
Compensating Circuit

- Compensation is used to either eliminate open-loop roll-off rates greater than -20 dB/dec or extend the -20 dB/dec rate to a lower gain.
- Two basic methods of compensation for IC op-amps: internal and external.
- In either case an RC series circuit is added so that its critical frequency is less than the dominant (i.e. lowest) f_c of the internal lag circuits of the op-amp.

Op-Amp Compensation

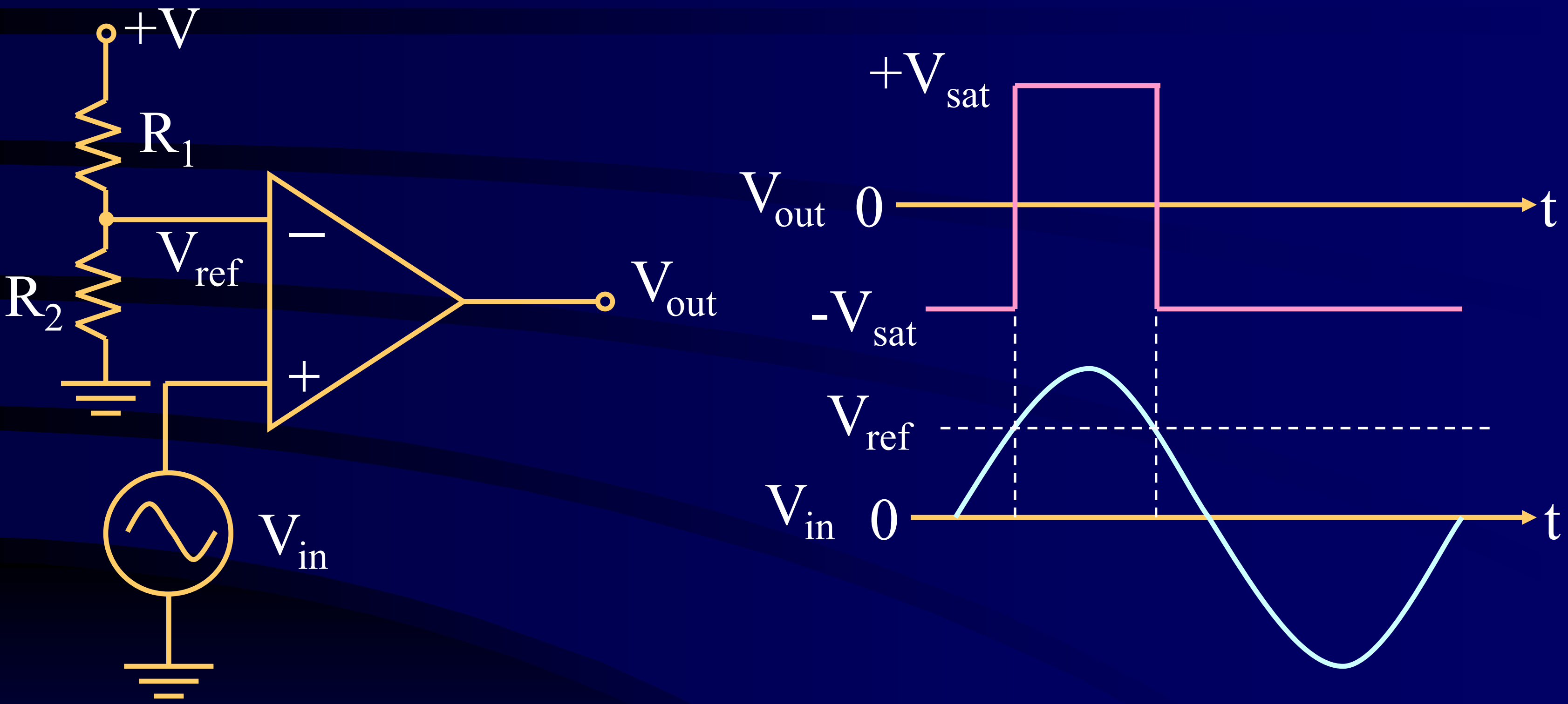
- Some op-amps (e.g. 741) are fully compensated internally, i.e., their -20 dB/dec slope is extended all the way down to unity gain. Hence, they are unconditionally stable.
- A disadvantage of fully compensated op-amps is that the bandwidth and slew rate are reduced.
- Many op-amps (e.g. LM101A) have provisions for external compensation with a small capacitor. This allows for optimum performance.

Zero-Level Detector



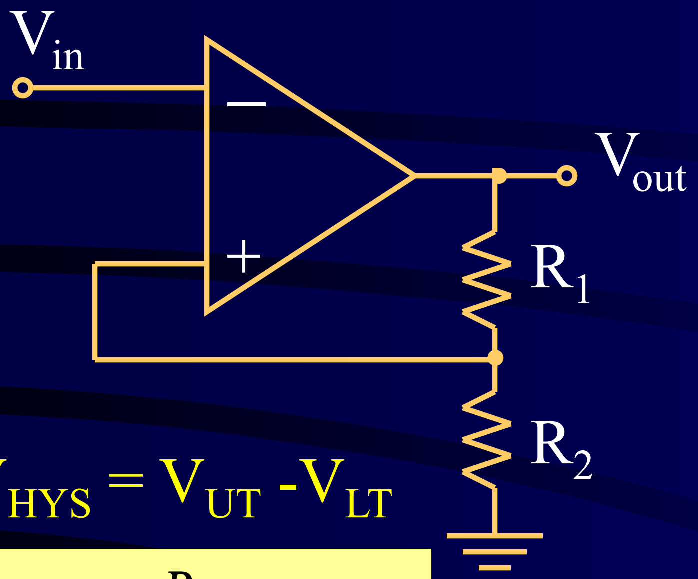
Because of the high open-loop voltage gain, a very small difference voltage between the + and - inputs drives the amplifier output into either $+V_{sat}$ or $-V_{sat}$.

Nonzero-Level Detector



V_{ref} can also be set by other means, e.g. a battery or a zener diode.

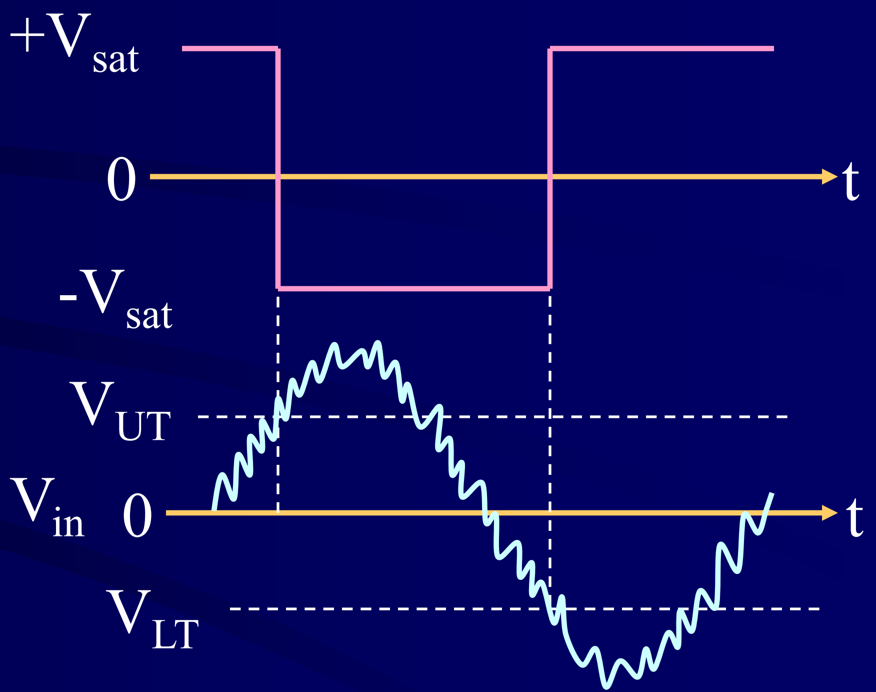
Comparator With Hysteresis (Schmitt Trigger)



$V_{HYS} = V_{UT} - V_{LT}$

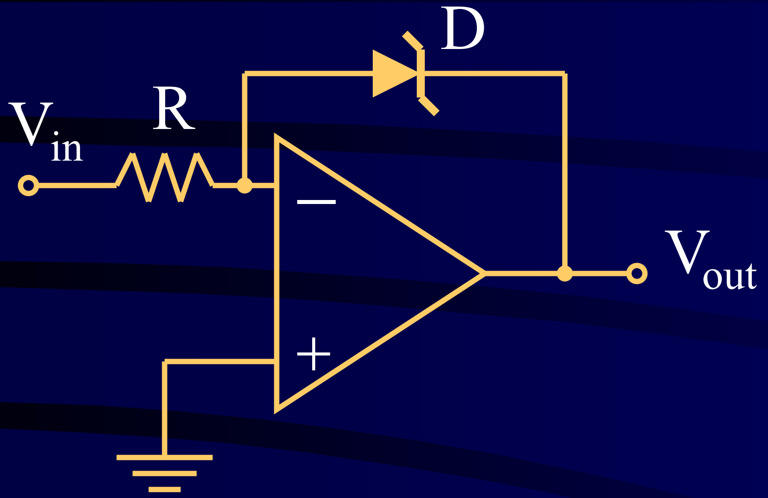
$$V_{UT} = \frac{R_2}{R_1 + R_2} V_{sat}$$

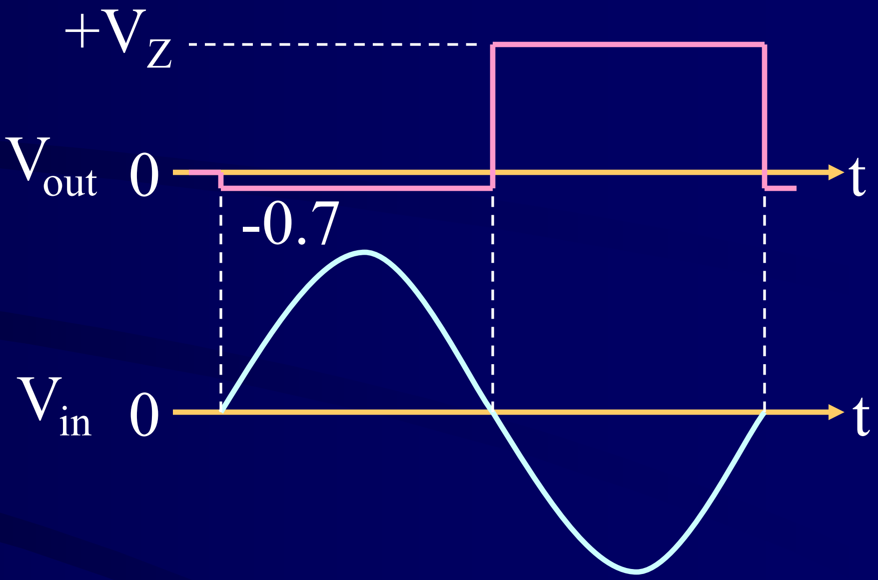
$$V_{LT} = \frac{R_2}{R_1 + R_2} (-V_{sat})$$



Hysteresis is achieved by positive feedback and makes the comparator less sensitive to noise on the input.

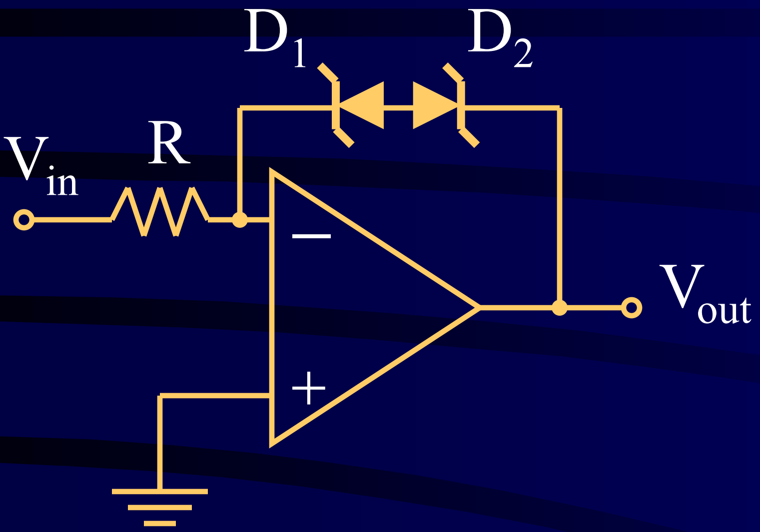
Output Bounding With One Zener

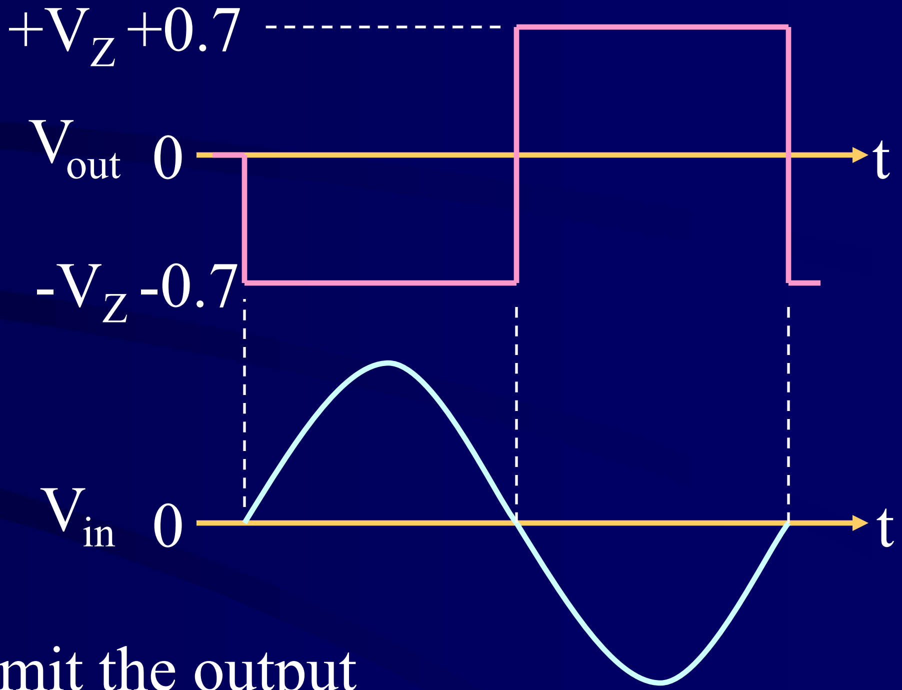




A single zener diode can be used to limit the output voltage to the zener voltage in one direction and to the forward diode on the other.

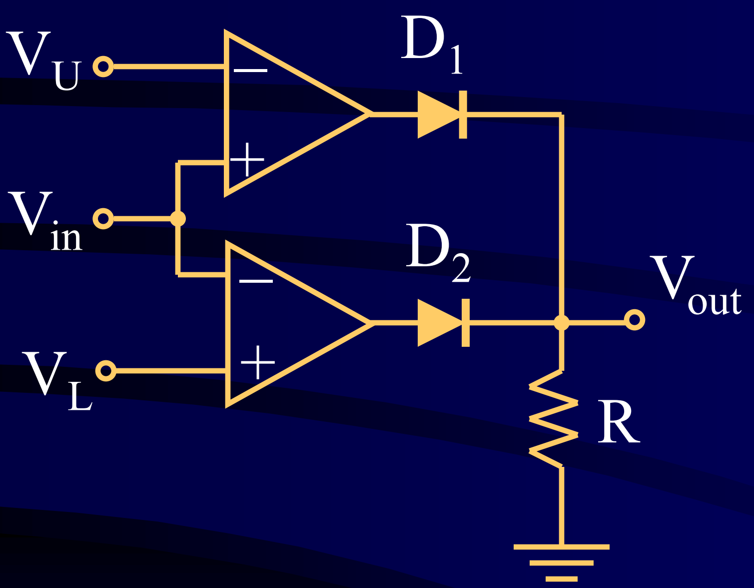
Output Bounding With two Zeners

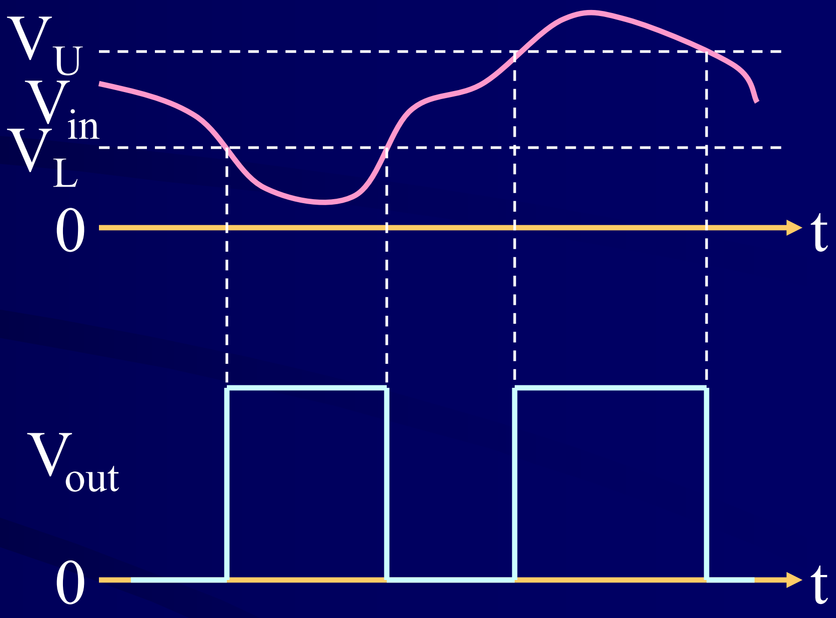




Two zener diodes would limit the output voltage to the zener voltage plus the forward voltage drop (0.7V) of the forward-biased zener .

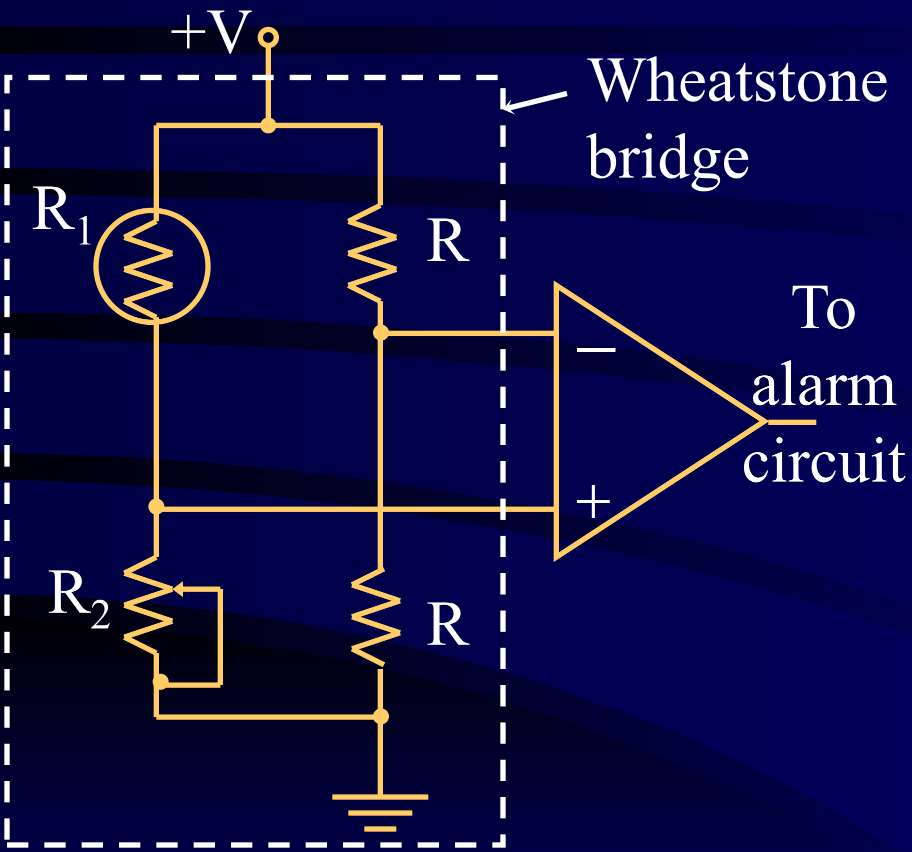
Window Comparator





The window comparator detects when an input voltage is between two limits, an upper and a lower, called a “window”.

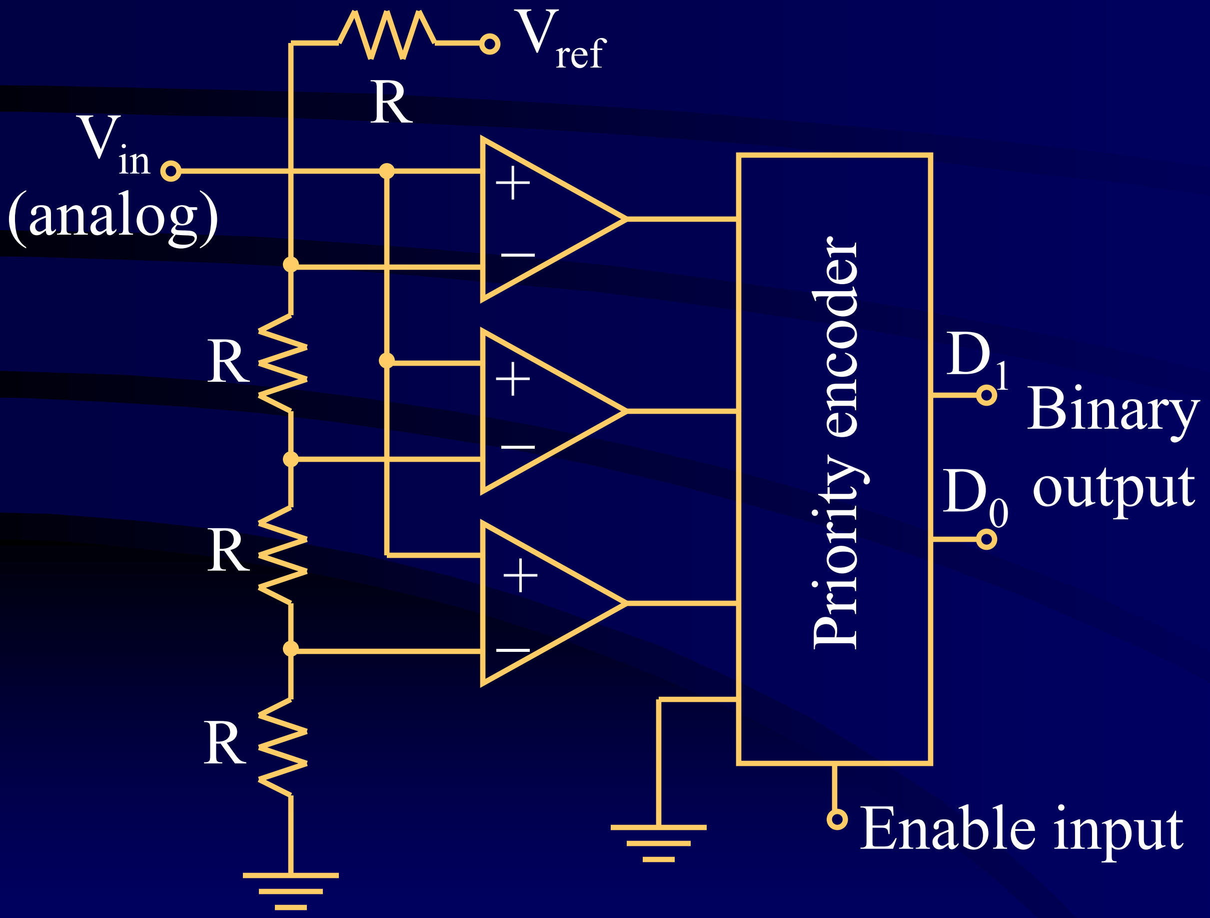
Comparator Application #1



Over-temperature sensing circuit

- R_1 is a thermistor.
- At temperatures below set value, $R_1 > R_2$; op-amp output is $-V_{sat}$ and does not trigger alarm circuit.
- When temperature rises and exceeds critical value, $R_1 < R_2$; op-amp output turns to $+V_{sat}$ which turns on alarm or initiate an appropriate response.

Comparator Application #2

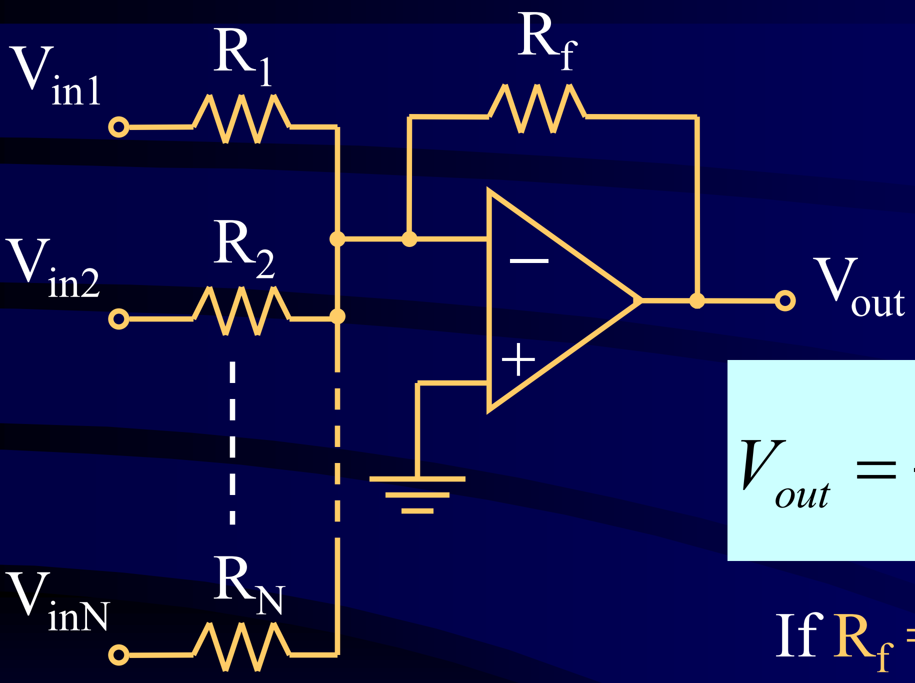


The simultaneous or flash analog-to-digital converter (ADC) uses parallel comparators to compare the linear input signal with various reference voltages developed by a voltage divider.

Operation of Flash ADC

- When V_{in} exceeds V_{ref} for a given comparator, its output becomes high.
- The priority encoder produces a binary number representing the highest value input.
- The encoder samples its input only when enabled.
- The higher the sampling rate the better the accuracy.
- $2^n - 1$ comparators are required for conversion to an n-digit binary number.

Summing Amplifier



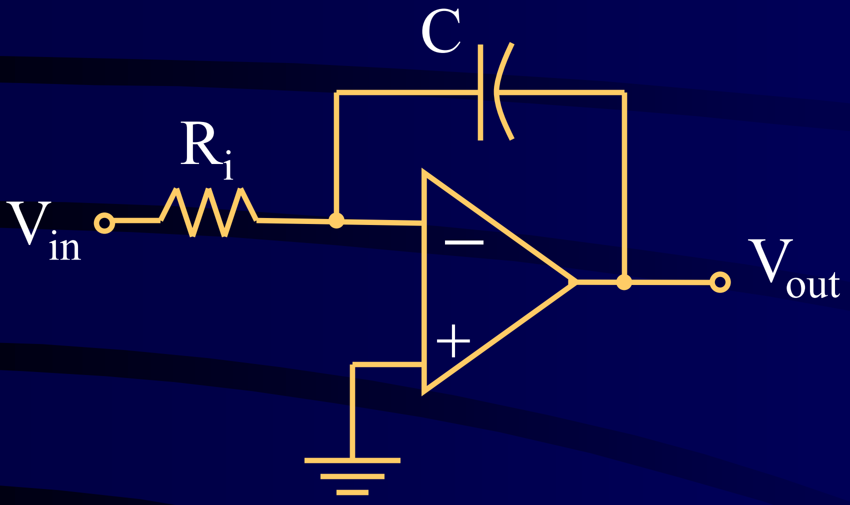
N-input summing amplifier

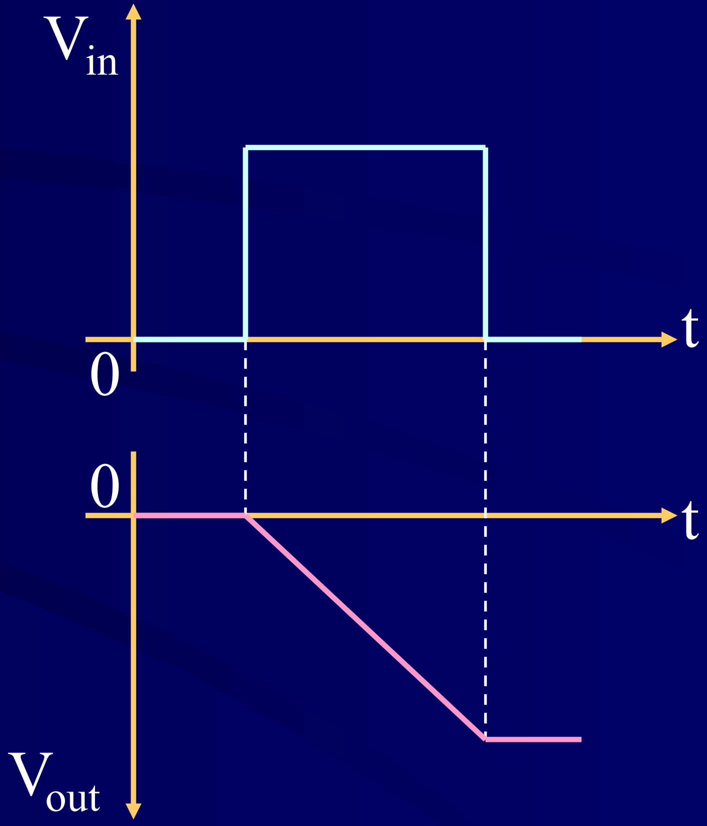
By making
$R_1 = R_2 = \ldots = R_N = R$:

$$V_{out} = -\frac{R_f}{R}(V_{in1} + V_{in2} + \ldots + V_{inN})$$

If $R_f = R$, it is a unity-gain summing amplifier. If $R_f = R/N$, it is an averaging amplifier.

Op-Amp Integrator

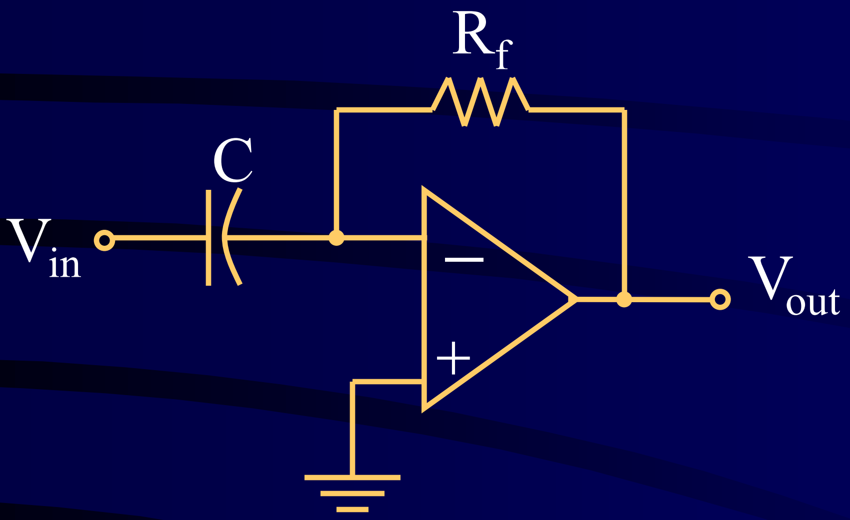


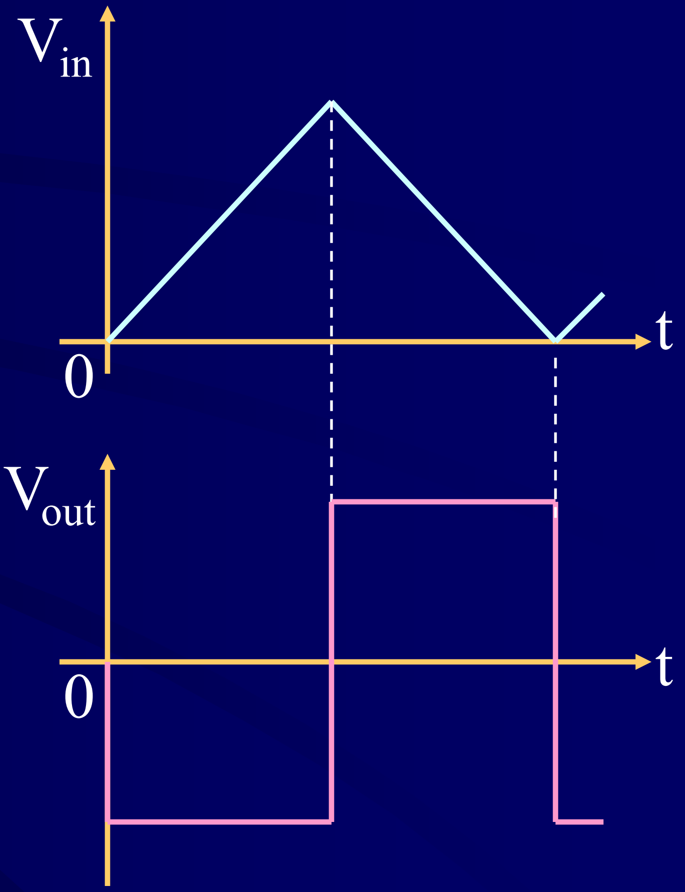


Slope of integrator:

$$\boxed{\frac{\Delta V_{out}}{\Delta t} = -\frac{V_{in}}{R_i C}}$$

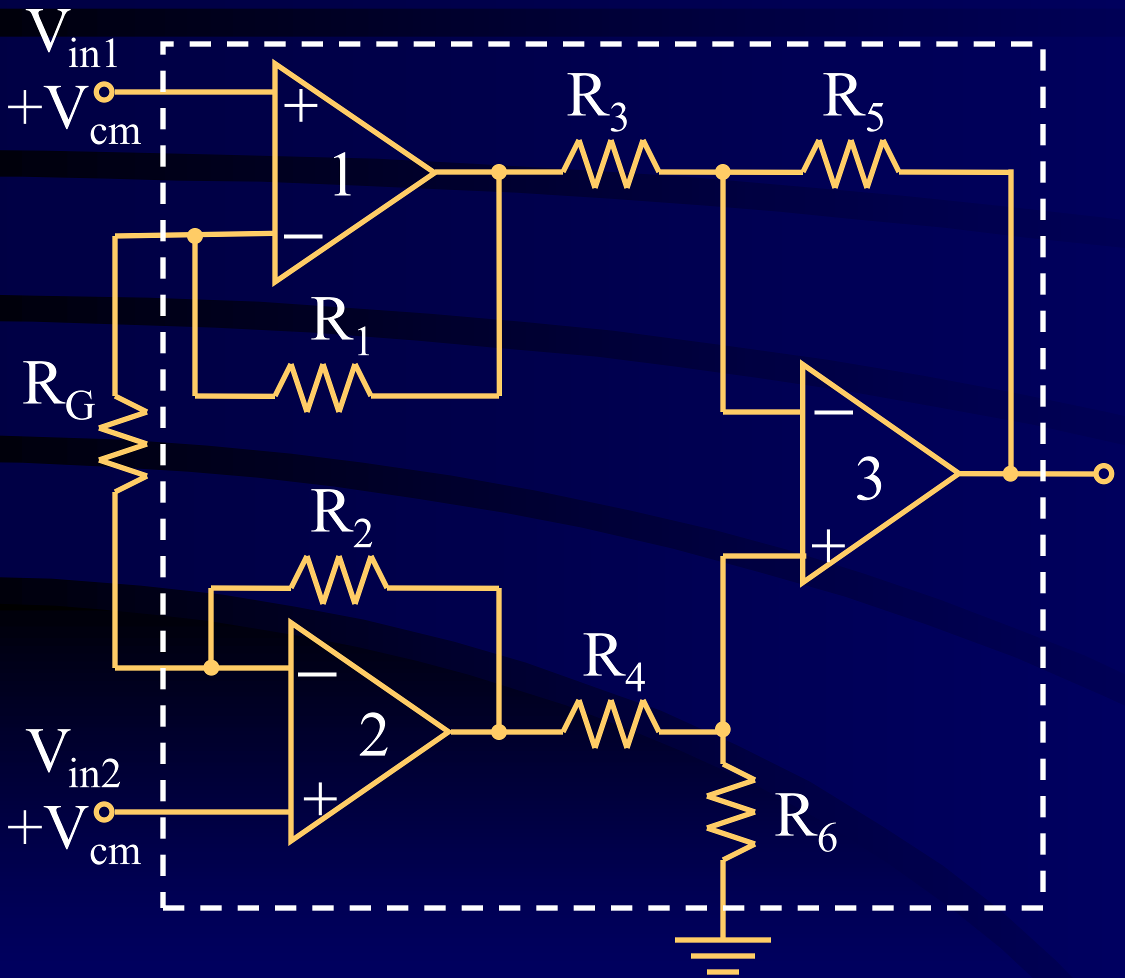
Op-Amp Differentiator





$$V_{out} = -\left(\frac{\Delta V_{in}}{\Delta t}\right) R_f C$$

Basic Instrumentation Amplifier



R_G is an external gain-setting resistor.

$V_{out} = A_{cl}(V_{in2} - V_{in1})$

For $R_1 = R_2 = R$, and $R_3 = R_4 = R_5 = R_6$,

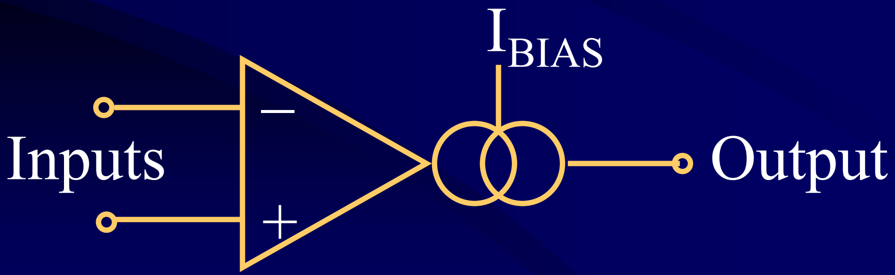
$$A_{cl} = 1 + \frac{2R}{R_G}$$

Notes on Instrumentation Amplifier

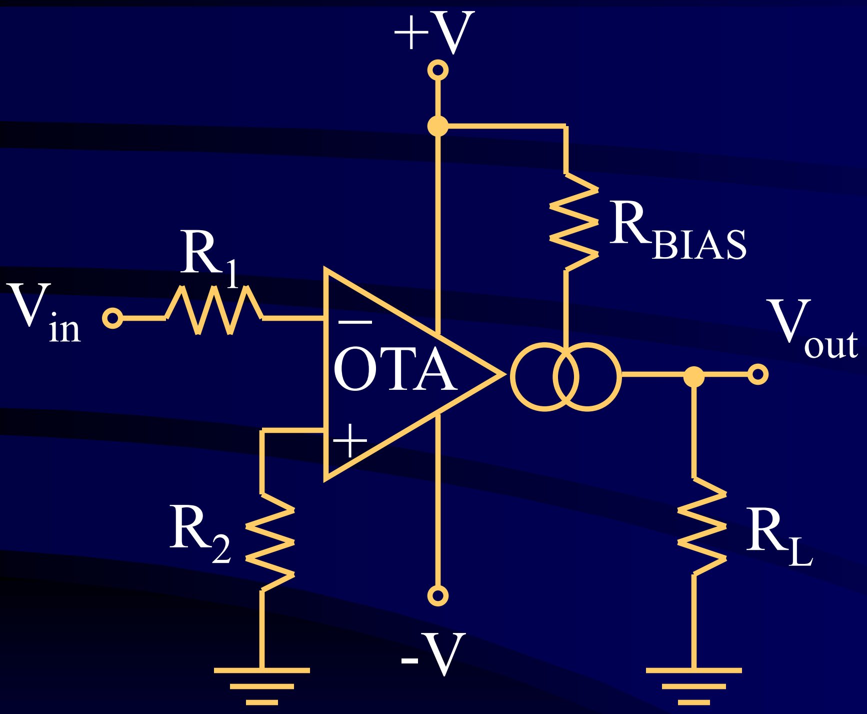
- The main purpose of an instrumentation amplifier is to amplify small signals that are riding on large common-mode voltages.
- Commonly used in environments with high common-mode noise, e.g., remote temperature- or pressure sensing over a long transmission line.
- Its main characteristics are: high Z_{in}, high CMRR, low output offset, and low Z_{out}
- A typical IC instrumentation amplifier : AD521

Operational Transconductance Amplifiers

- The OTA is primarily a voltage-to-current amplifier where $I_{out} = g_m V_{in}$.
- The voltage-to-current gain of an OTA is the transconductance, $g_m = KI_{BIAS}$ where K is dependent on the internal circuit design.



Basic OTA Circuit

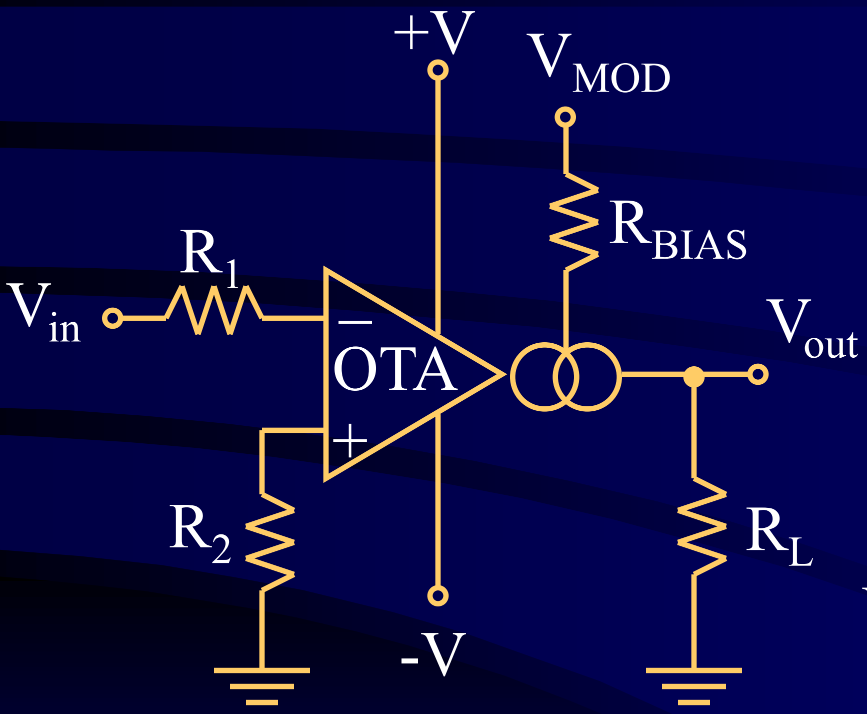


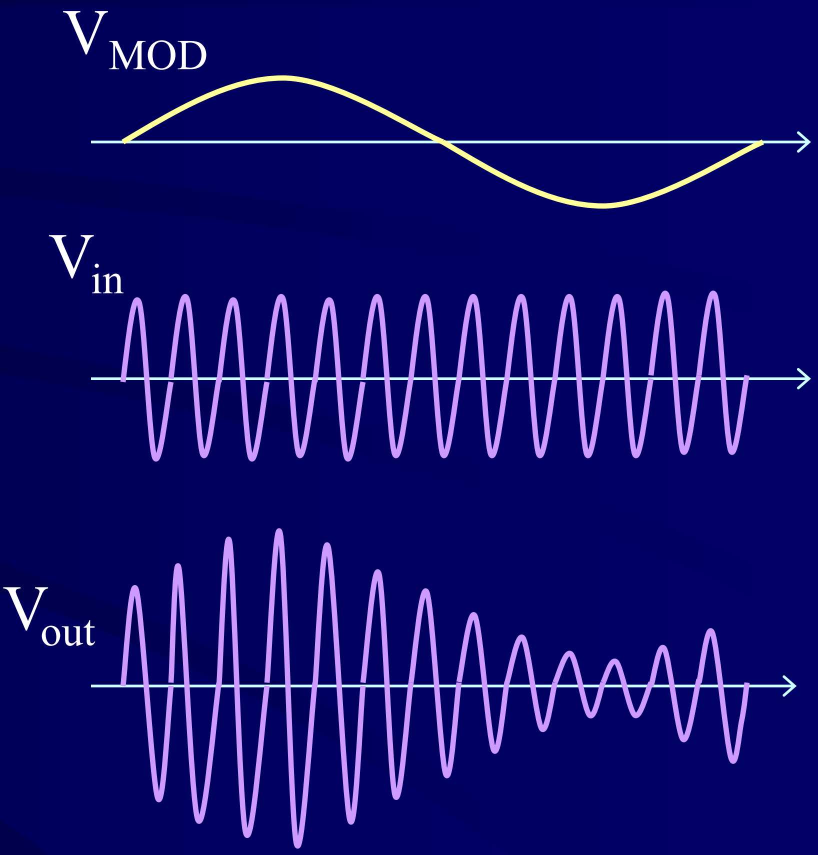
Inverting amp with fixed voltage gain

- The voltage gain of the amp., $|A_V| = g_m R_L$
- For variable gain, connect a pot. to R_{BIAS}
- If R_{BIAS} is connected to a separate bias voltage:

$$I_{BIAS} = \frac{+V_{BIAS} + V - 0.7}{R_{BIAS}}$$

OTA Amplitude Modulator



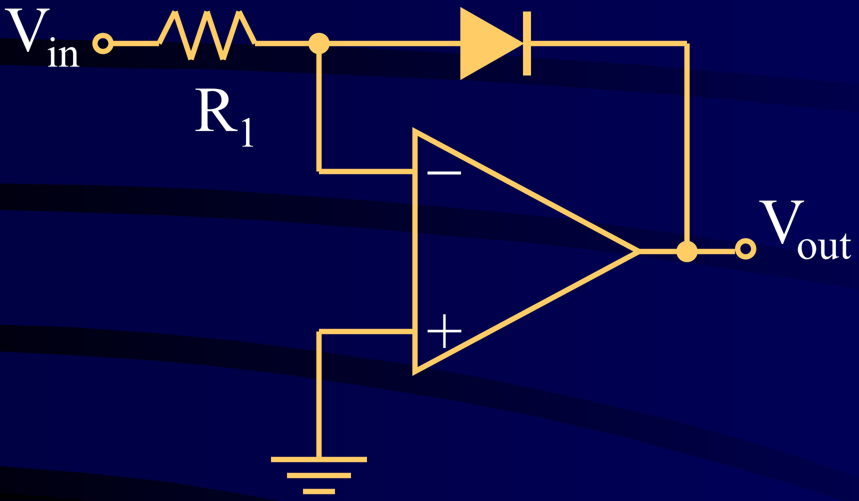


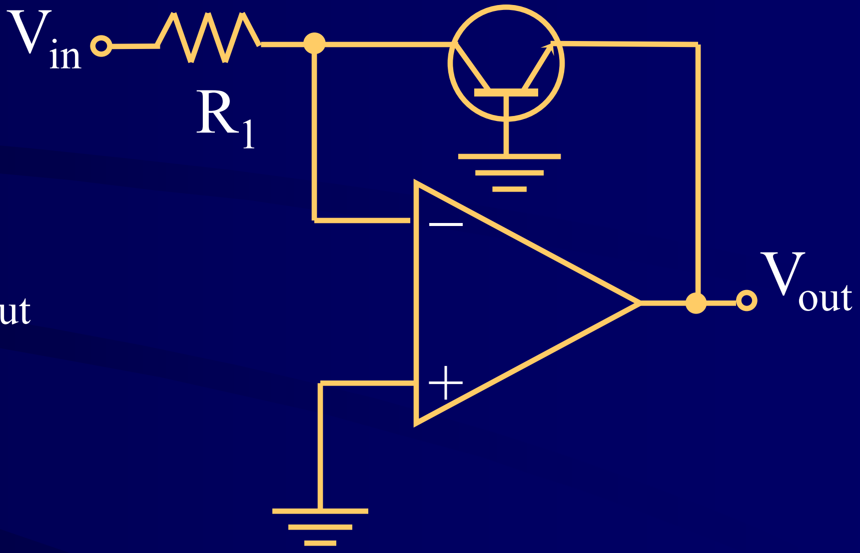
$$I_{BIAS} = \frac{V_{MOD} + V - 0.7}{R_{BIAS}}$$

Log Amplifiers

- The basic log amplifier produces an output voltage as a function of the logarithm of the input voltage; i.e., $V_{out} = -K \ln(V_{in})$, where K is a constant.
- Recall that the a diode has an exponential characteristic up to a forward voltage of approximately 0.7 V.
- Hence, the semiconductor pn junction in the form of a diode or the base-emitter junction of a BJT can be used to provide a logarithm characteristic.

Diode & BJT Log Amplifiers





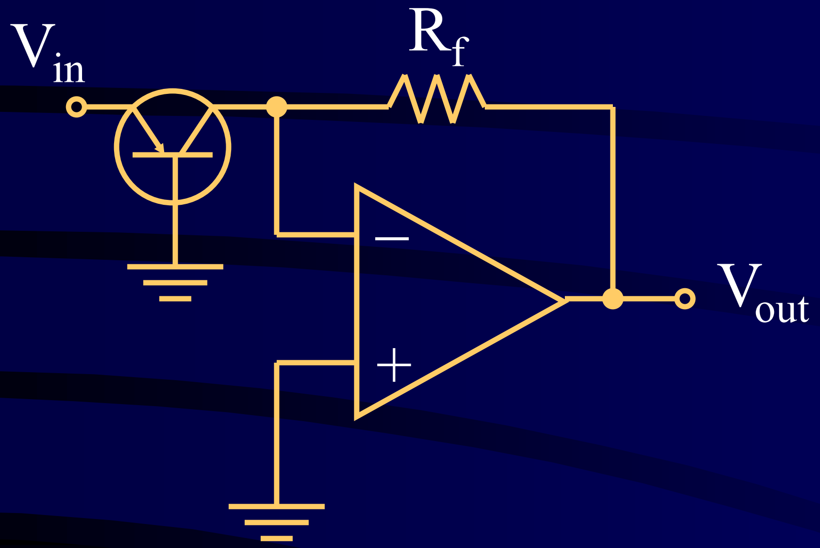
$$V_{out} \cong -0.025 \ln\left(\frac{V_{in}}{I_R R_1}\right) \text{ V}$$

$$V_{out} \cong -0.025 \ln\left(\frac{V_{in}}{I_{EBO} R_1}\right) \text{ V}$$

I_R = reverse leakage current

I_{EBO} = emitter-to-base leakage current

Basic Antilog Amplifier



$$V_{out} \cong -R_f I_{EBO} anti\ln\left(\frac{V_{in}}{0.025}\right)$$

- A transistor or a diode can be used as the input element.
- The operation of the circuit is based on the fact that $V_{out} = -R_f I_C$, and $I_C = I_{EBO} e^{Vin/K}$ where $K \cong 0.025$ V

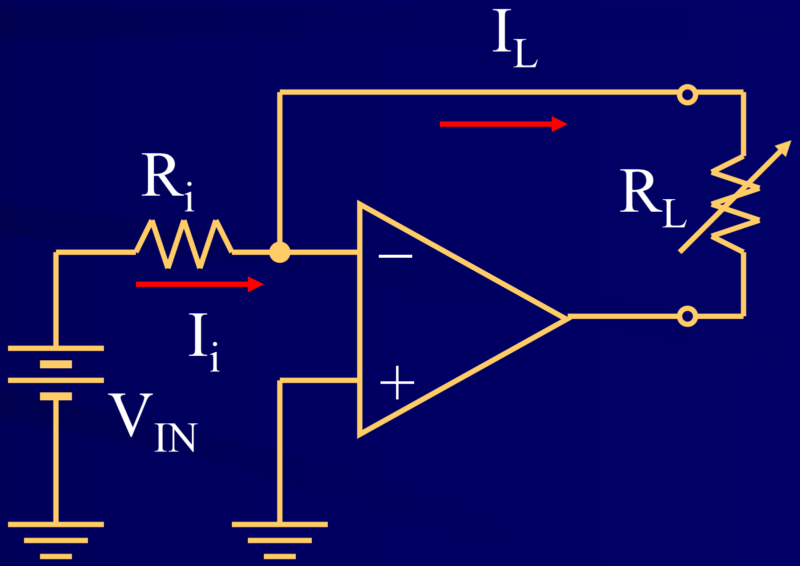
Signal Compression With Log Amp.

Logarithmic
signal compression

- When a signal with a large dynamic range is compressed with a logarithmic amplifier, the higher voltages are reduced by a greater percentage than the lower voltages, thus keeping the lower signals from being lost in noise.

Constant-Current Source

- For the basic constant-current circuit, the op-amp has a very high Z_{in}, thus, $I_L = I_i$.
- If R_L changes, I_L remains constant as long as V_{IN} and R_i are held constant.



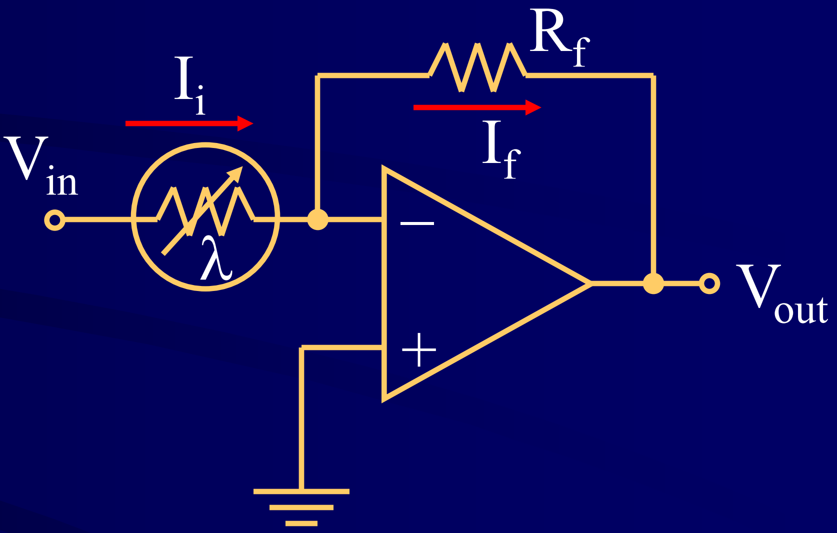
$$I_L = I_i = \frac{V_{IN}}{R_i}$$

Current-to-Voltage Converter

- Since the inverting terminal is at virtual ground,

  $V_{out} = -I_f R_f = -I_i R_f$
- As the amount of light changes, the current through the photocell changes; thus

  $\Delta V_{out} = |\Delta I_i| R_f$

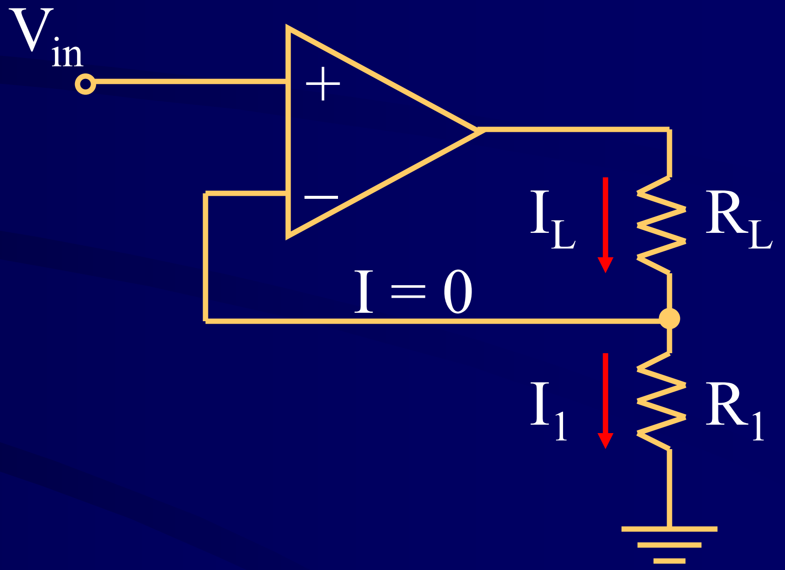


Circuit for sensing light level and converting it to a proportional output voltage

Voltage-to-Current Converter

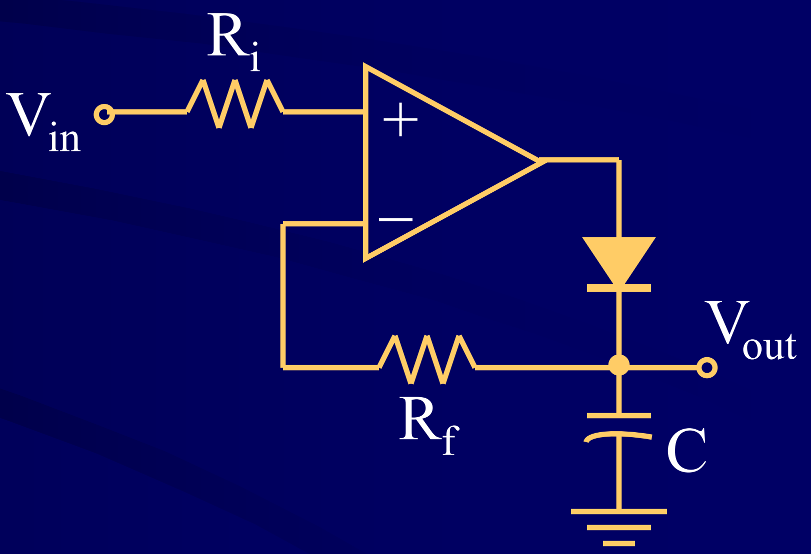
- Neglecting V_{IO}, the (-) and (+) terminals are at the same voltage, V_{in}. Therefore, V_{R1} = V_{in}.
- Since I = 0,

$I_L = I_1 = V_{in}/R_1$

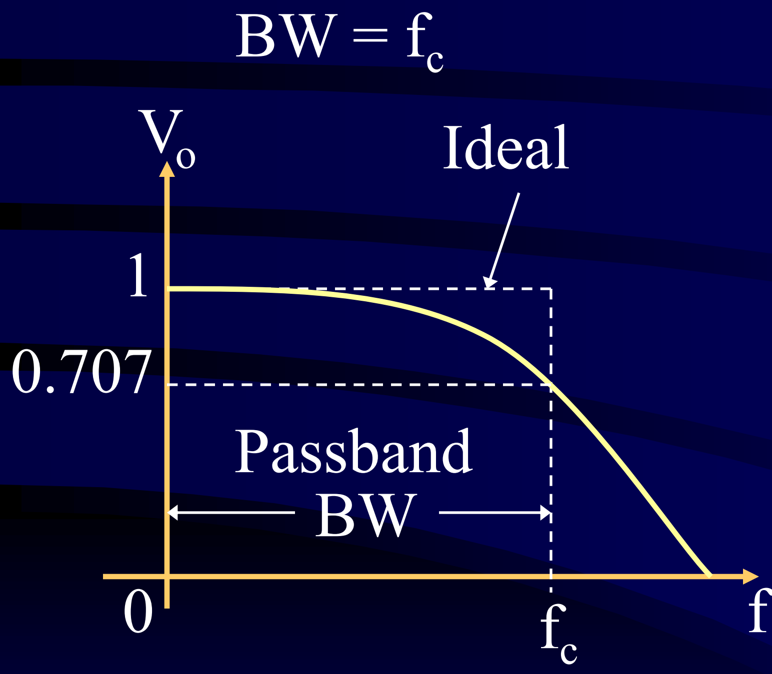


Peak Detector

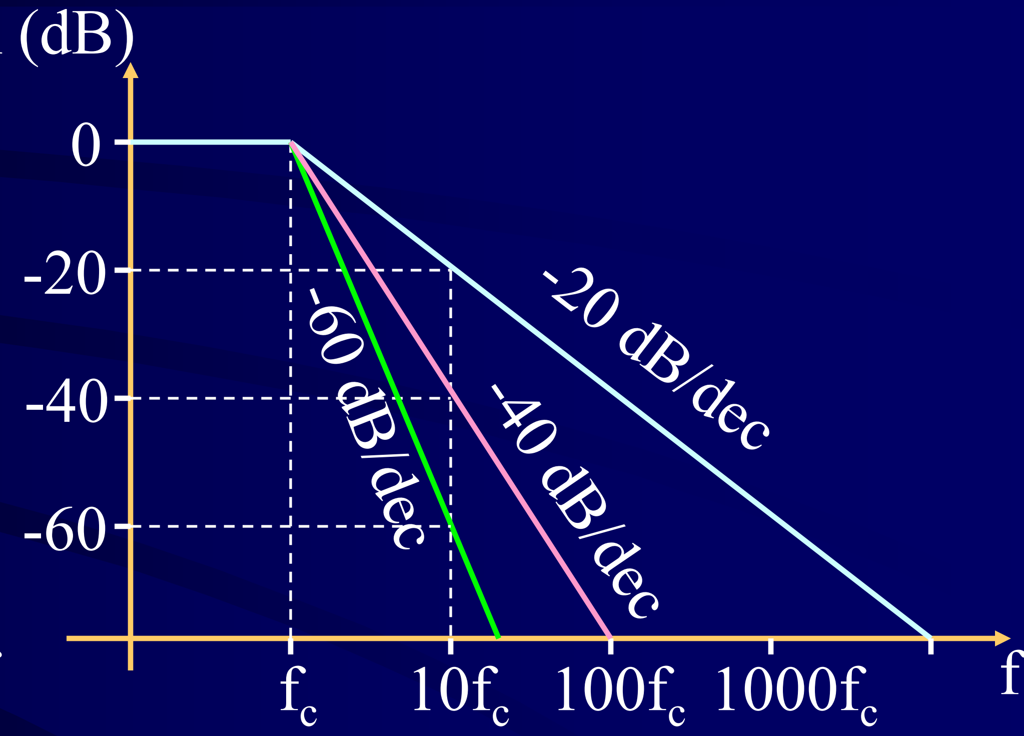
- When a positive voltage is applied, the output charges the capacitor until $V_C = V_{in(max)}$.
- If a greater input peak occurs, the capacitor charges to the new peak.



Low-Pass Filter Response

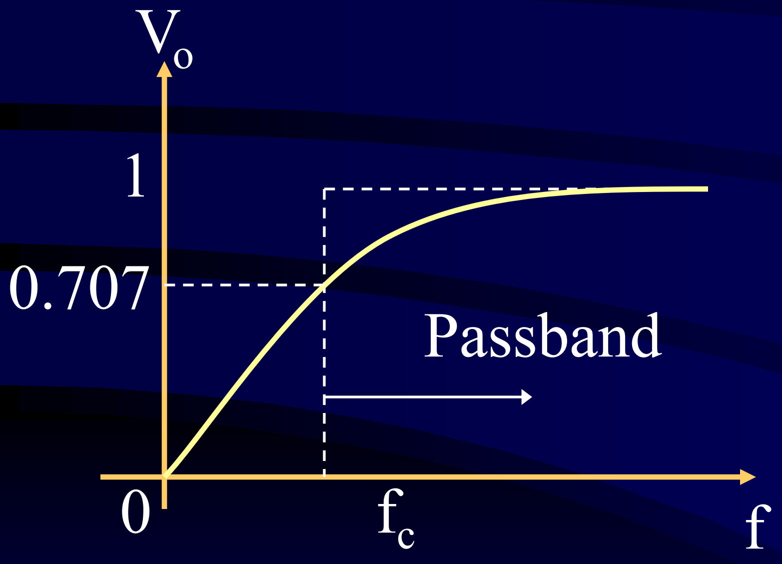


Basic LPF response

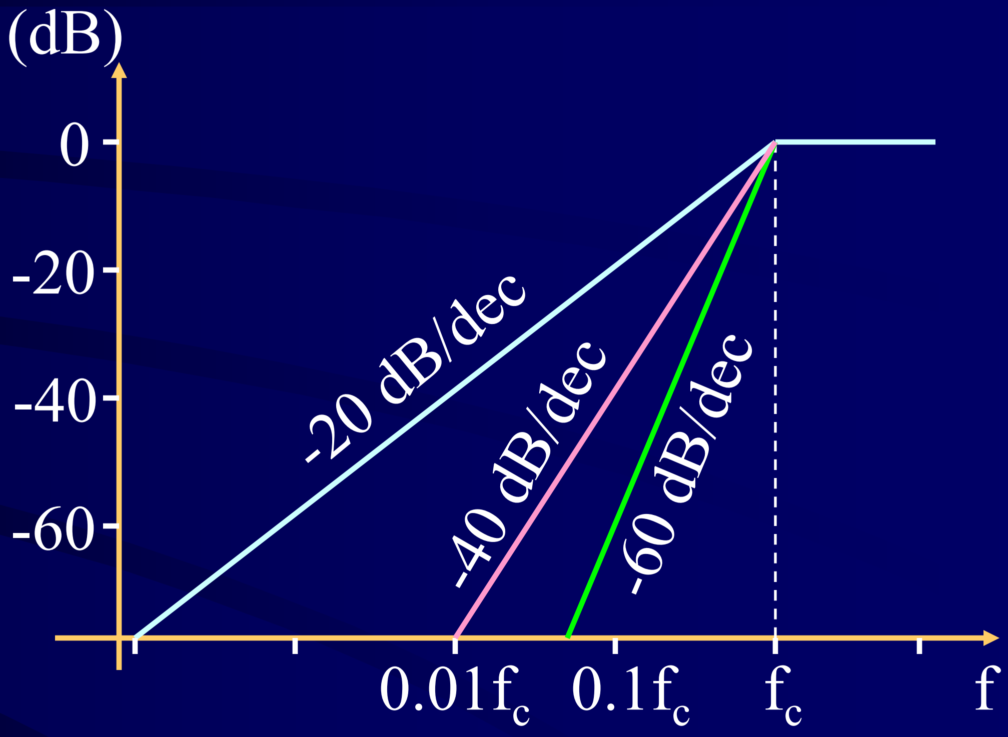


LPF with different roll-off rates

High-Pass Filter Response

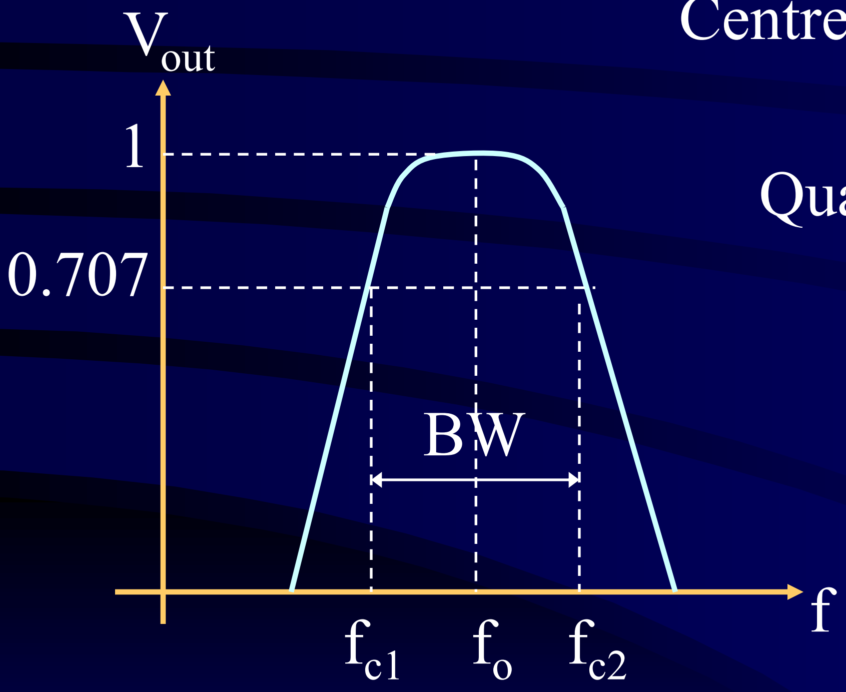


Basic HPF response



HPF with different roll-off rates

Band-Pass Filter Response



$BW = f_{c2} - f_{c1}$

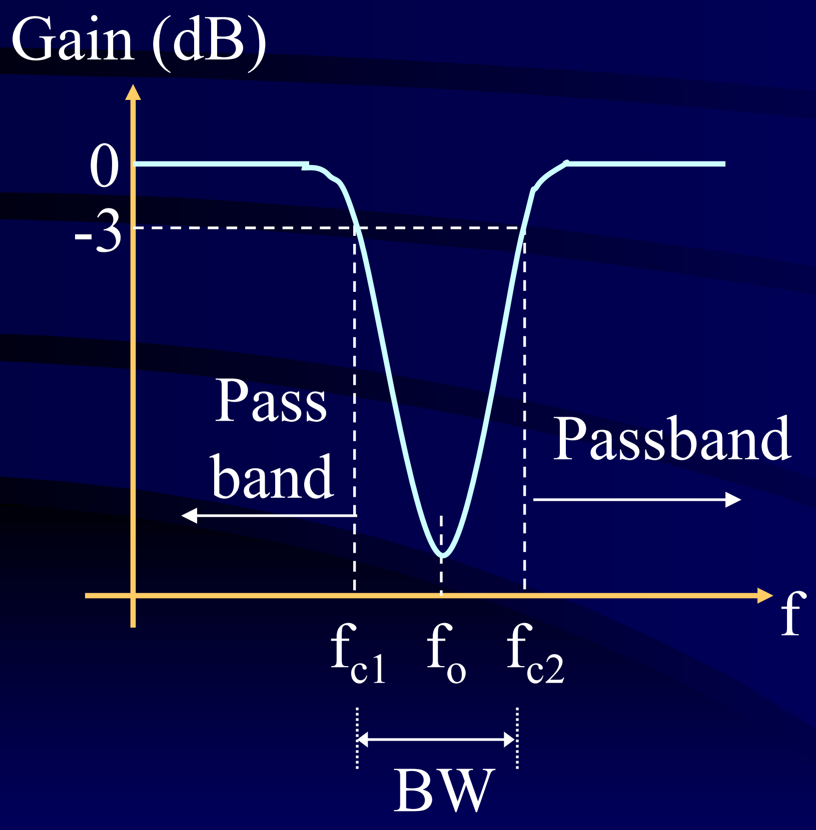
Centre frequency: $f_o = \sqrt{f_{c1} f_{c2}}$

Quality factor: $Q = \dfrac{f_o}{BW}$

Q is an indication of the selectivity of a BPF.
Narrow BPF: $Q > 10$.
Wide-band BPF: $Q < 10$.

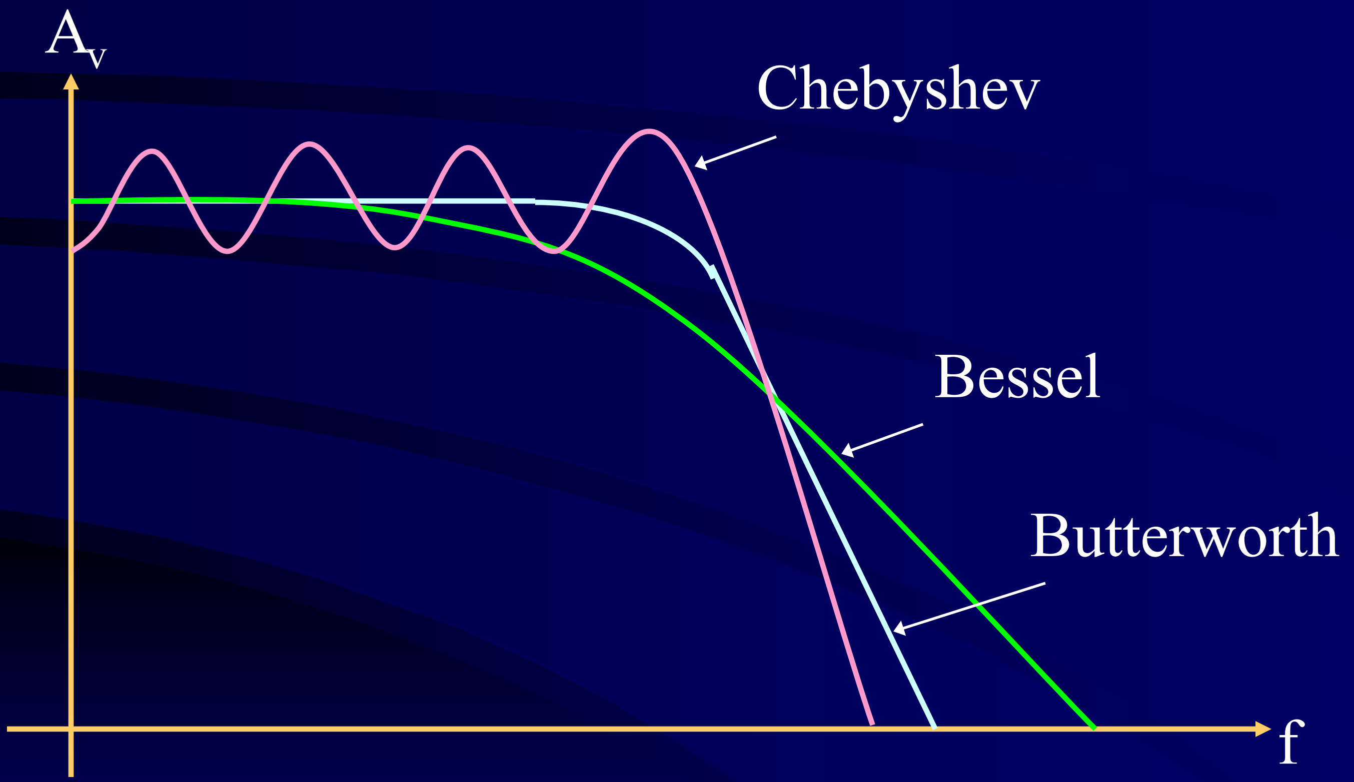
Damping Factor: $DF = {}^{1}\!/_{Q}$

Band-Stop Filter Response



- Also known as band-reject, or notch filter.
- Frequencies within a certain BW are rejected.
- Useful for filtering interfering signals.

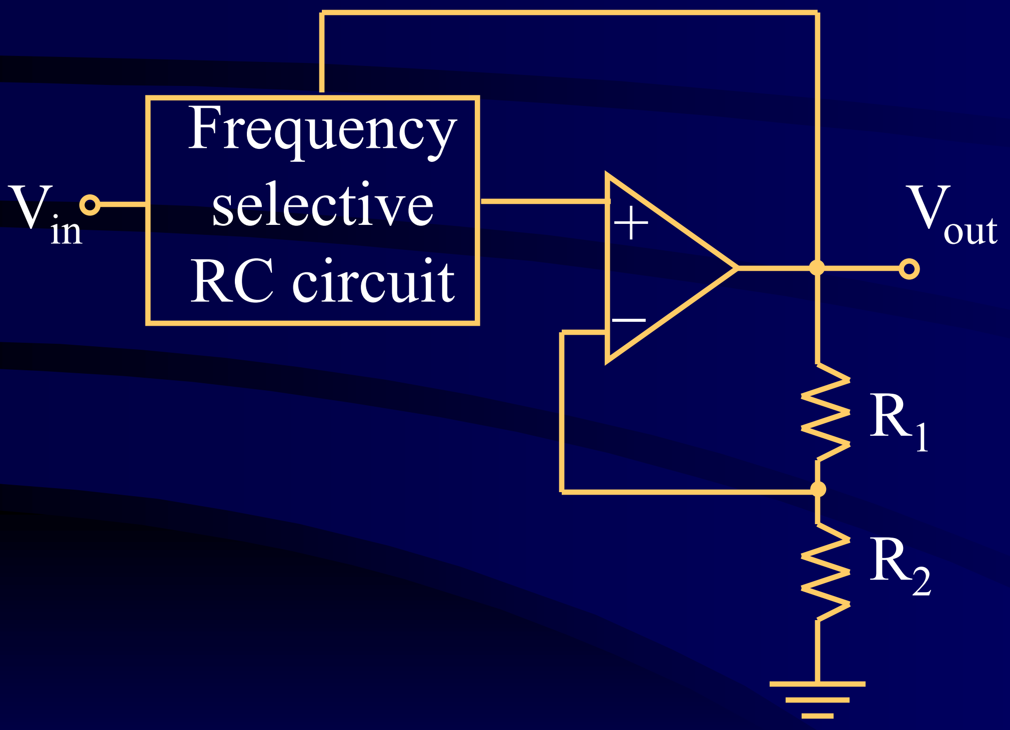
Filter Response Characteristics



Notes On Filter Characteristics

- Butterworth: very flat amplitude response in the passband and a roll-off rate of -20 dB/dec/pole; phase response however is not linear. (A *pole* is simply a circuit with one R and one C).
- Chebyshev: roll-off rate > -20 dB/dec/pole; ripples in passband; very nonlinear phase response.
- Bessel: linear phase response, therefore no overshoot on the output with a pulse input; roll-off rate is < -20 dB/dec/pole.

Damping Factor



General diagram of active filter

The damping factor (DF) of an active filter sets the response characteristic of the filter.

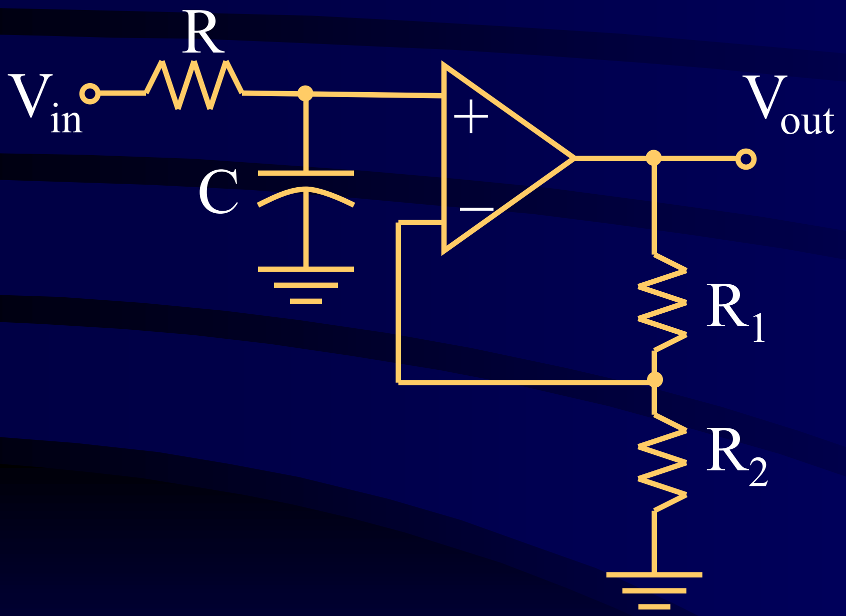
$$DF = 2 - \frac{R_1}{R_2}$$

Its value depends on the order (# of poles) of the filter. (See Table in text for DF values.)

Active Filters

- Advantages over passive LC filters:
  - Op-amp provides gain
  - high Z_{in} and low Z_{out} mean good isolation from source or load effects
  - less bulky and less expensive than inductors when dealing with low frequency
  - easy to adjust over a wide frequency range without altering desired response
- Disadvantage: requires dc power supply, and could be limited by frequency response of op-amp.

Single-pole Active LPF



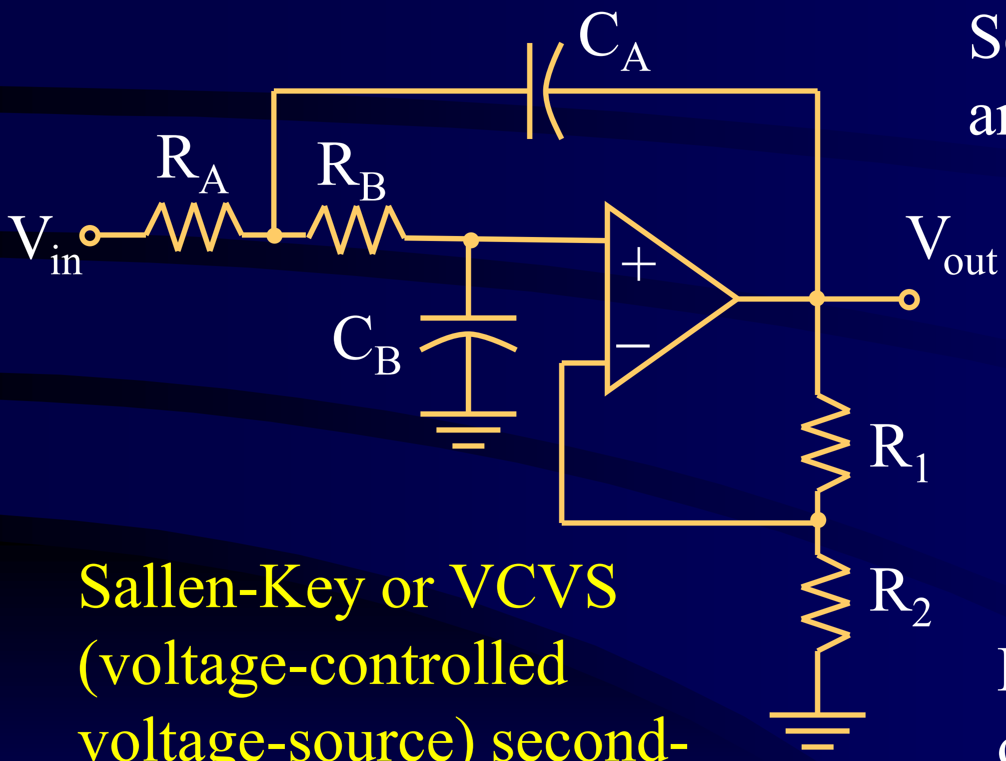
$$f_c = \frac{1}{2\pi RC}$$

$$A_{cl} = 1 + \frac{R_1}{R_2}$$

Roll-off rate for a single-pole filter is -20 dB/decade.

A_{cl} is selectable since DF is optional for single-pole LPF

Sallen-Key Low-Pass Filter



Sallen-Key or VCVS (voltage-controlled voltage-source) second-order low-pass filter

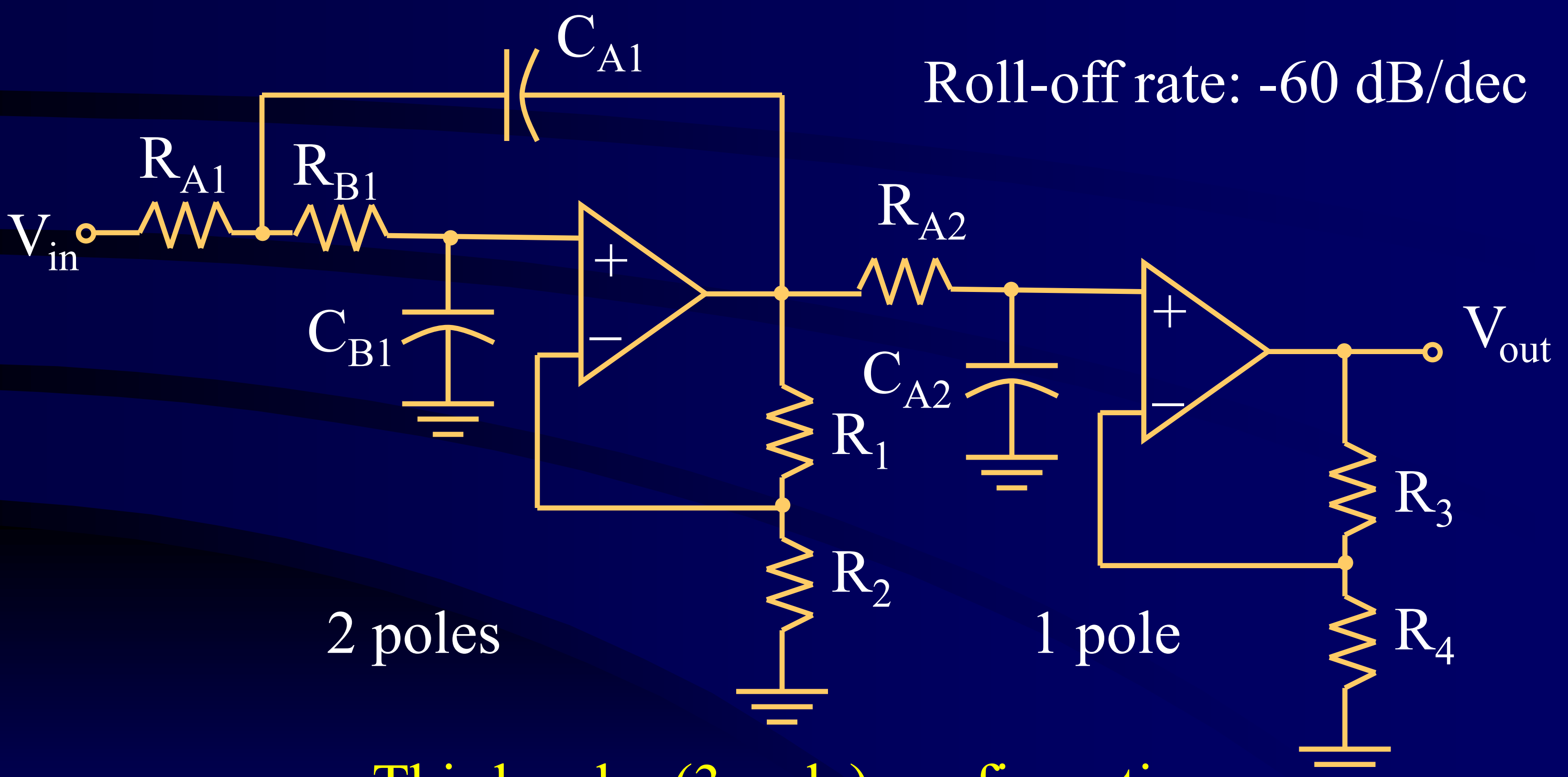
Selecting $R_A = R_B = R$, and $C_A = C_B = C$:

$$f_c = \frac{1}{2\pi RC}$$

The roll-off rate for a two-pole filter is -40 dB/decade.

For a Butterworth 2nd-order response, DF = 1.414; therefore, $R_1/R_2 = 0.586$.

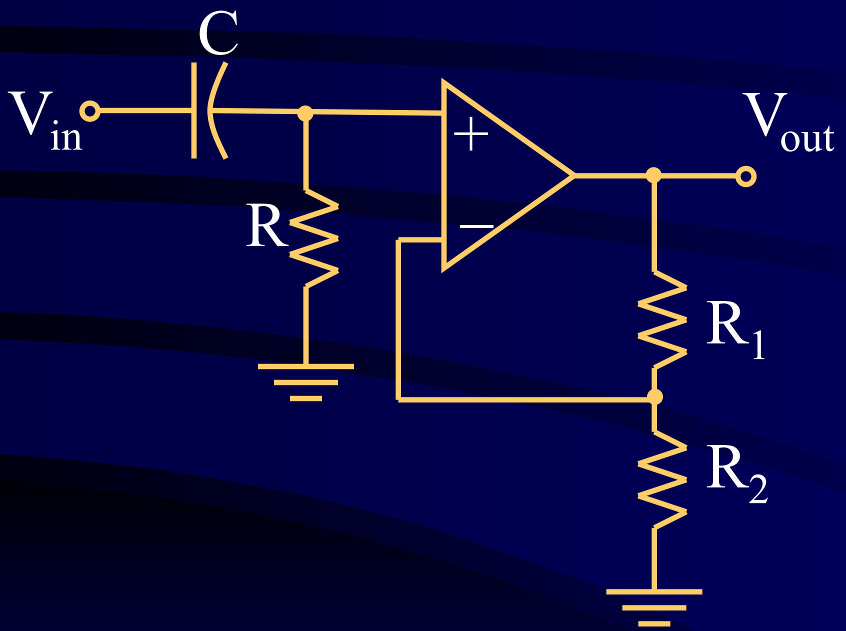
Cascaded Low-Pass Filter



Roll-off rate: -60 dB/dec

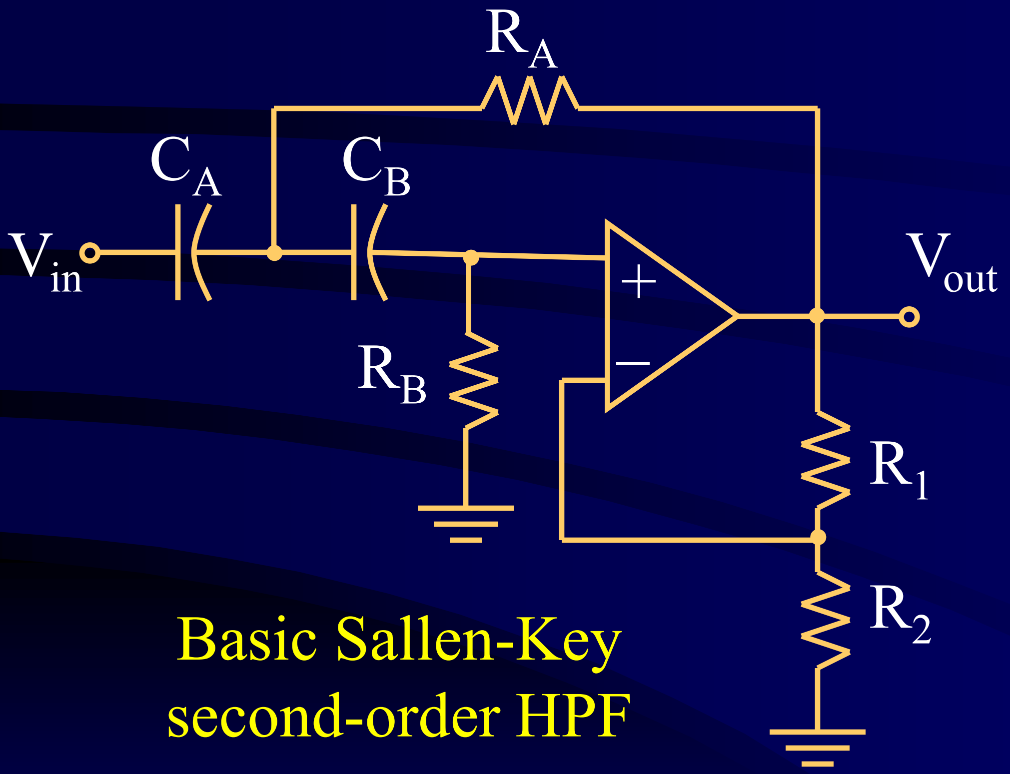
Third-order (3-pole) configuration

Single-Pole High-Pass Filter



- Roll-off rate, and formulas for f_c , and A_{cl} are similar to those for LPF.
- Ideally, a HPF passes all frequencies above f_c. However, the op-amp has an upper-frequency limit.

Sallen-Key High-Pass Filter

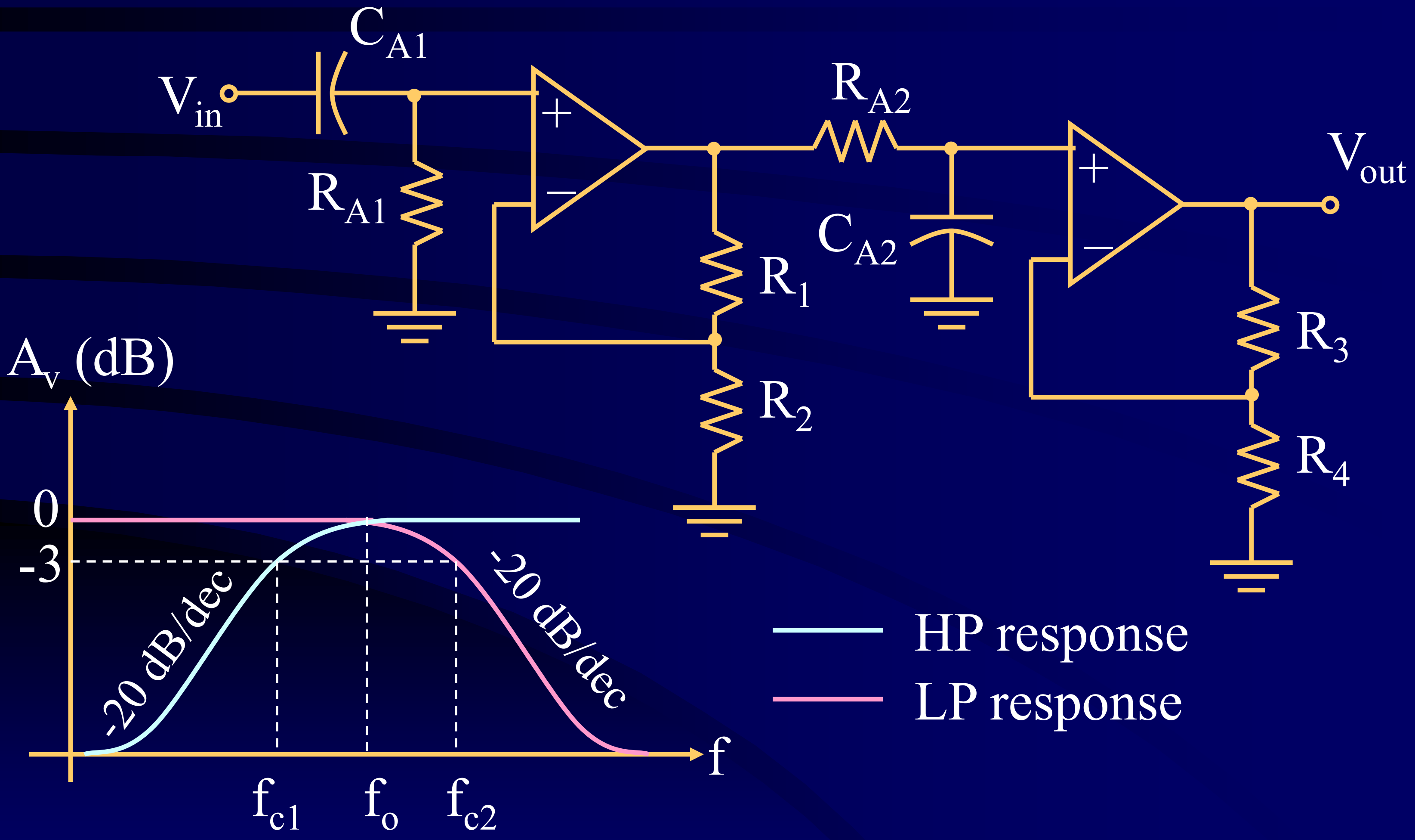


Basic Sallen-Key second-order HPF

Again, formulas and roll-off rate are similar to those for 2nd-order LPF.

To obtain higher roll-off rates, HPF filters can be cascaded.

BPF Using HPF and LPF



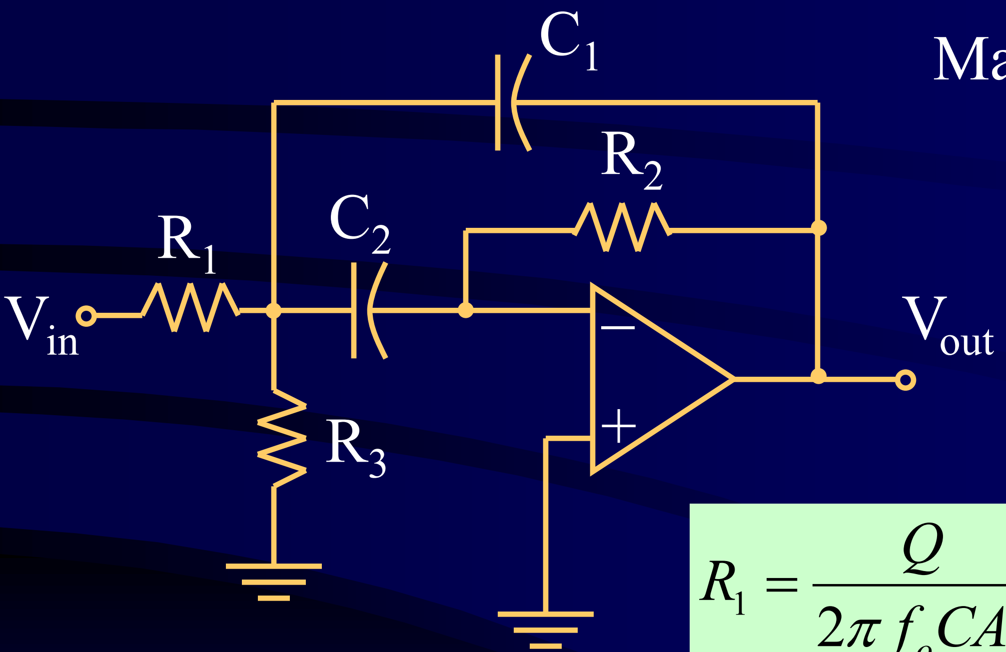
HP response

LP response

Notes On Cascading HPF & LPF

- Cascading a HPF and a LPF to yield a band-pass filter can be done as long as f_{c1} and f_{c2} are sufficiently separated. Hence the resulting bandwidth is relatively wide.
- Note that f_{c1} is the critical frequency for the HPF and f_{c2} is for the LPF.
- Another BPF configuration is the multiple-feedback BPF which has a narrower bandwidth and needing fewer components

Multiple-Feedback BPF



R1, C1 - LP section
R2, C2 - HP section

Making $C_1 = C_2 = C$,

$$f_o = \frac{1}{2\pi C}\sqrt{\frac{R_1 + R_3}{R_1 R_2 R_3}}$$

$Q = f_o/BW$

$$R_1 = \frac{Q}{2\pi f_o C A_o}; R_2 = \frac{Q}{\pi f_o C}$$

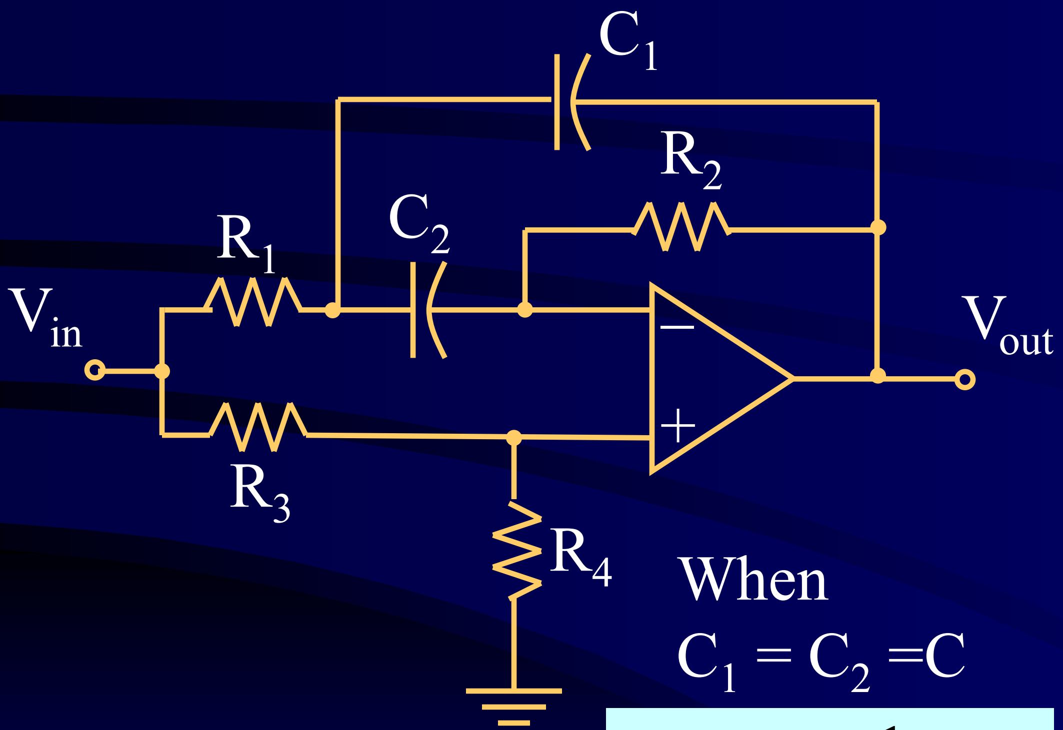
$$R_3 = \frac{Q}{2\pi f_o C(2Q^2 - A_o)}$$

Max. gain:

$$A_o = \frac{R_2}{2R_1}$$

$A_o < 2Q^2$

Multiple-Feedback Band-Stop Filter



When

$C_1 = C_2 = C$

$$f_o = \frac{1}{2\pi C\sqrt{R_1 R_2}}$$

The multiple-feedback BSF is very similar to its BP counterpart. For frequencies between f_{c1} and f_{c2} the op-amp will treat V_{in} as a pair of common-mode signals thus rejecting them accordingly.

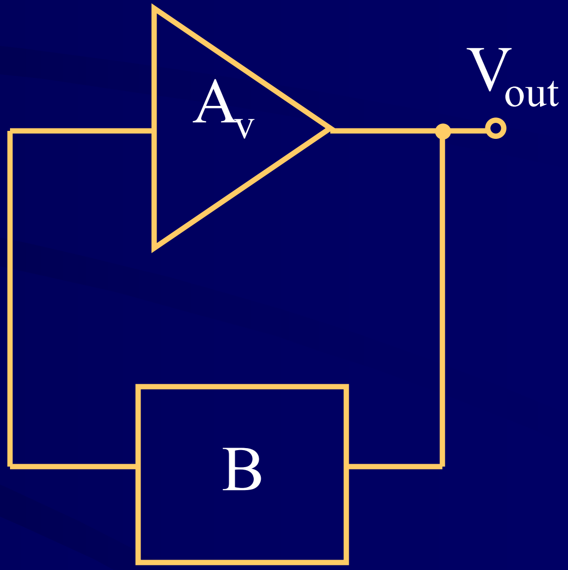
Filter Response Measurements

- Discrete Point Measurement: Feed a sine wave to the filter input with a varying frequency but a constant voltage and measure the output voltage at each frequency point.
- A faster way is to use the swept frequency method:

The sweep generator outputs a sine wave whose frequency increases linearly between two preset limits.

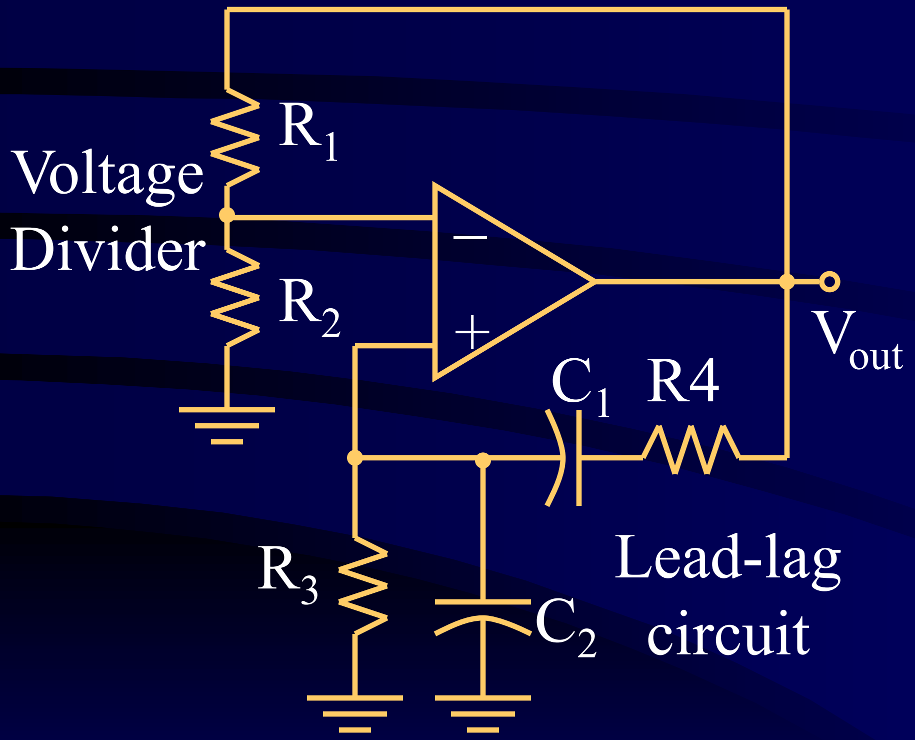
Oscillator Principles

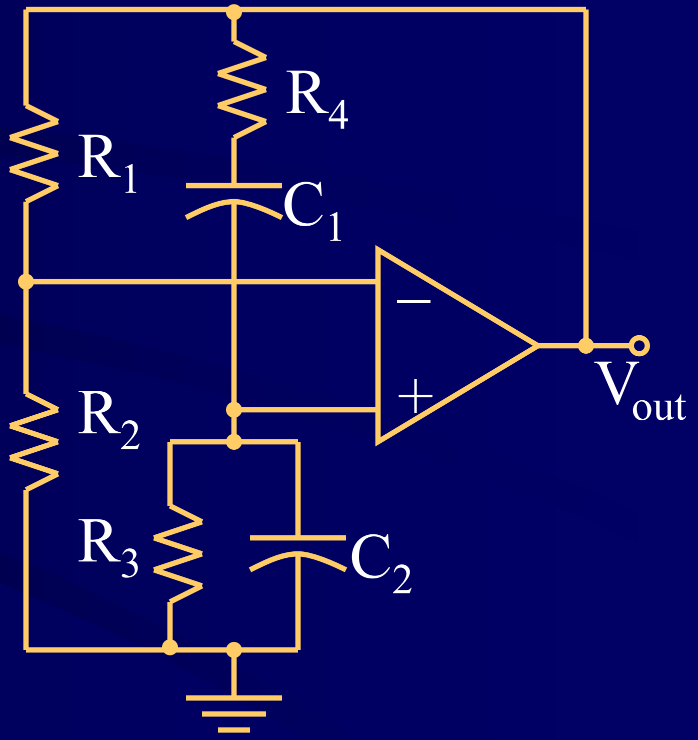
- Conditions for sustained oscillation:
  - the phase shift around the feedback loop must be 0^o or 360^o (i.e. positive feedback)
  - the loop gain $|BA_v| = 1$, where B = attenuation of feedback circuit, and A_v = amplifier's gain.



Basic elements of an oscillator

Basic Wien-Bridge Oscillator





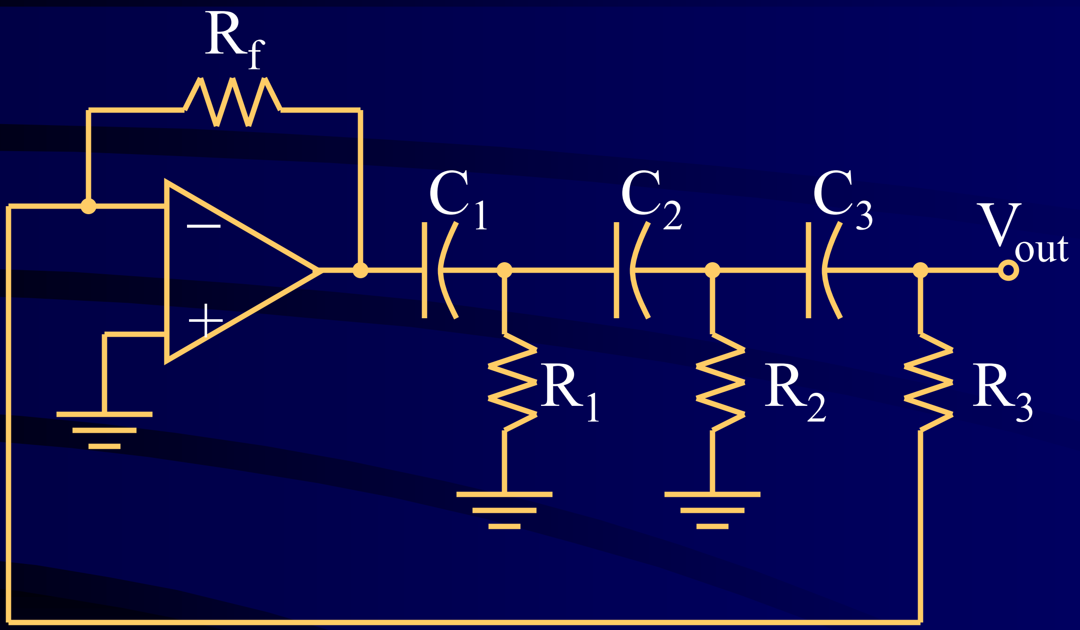
Two forms of the same circuit

Notes on Wien-Bridge Oscillator

- At the resonant frequency the lead-lag circuit provides a positive feedback (purely resistive) with an attenuation of 1/3 when $R_3=R_4=X_{C1}=X_{C2}$.
- In order to oscillate, the non-inverting amplifier must have a closed-loop gain of 3, which can be achieved by making $R_1 = 2R_2$
- When $R_3 = R_4 = R$, and $C_1 = C_2 = C$, the resonant frequency is:

$$\boxed{f_r = \frac{1}{2\pi RC}}$$

Phase-Shift Oscillator



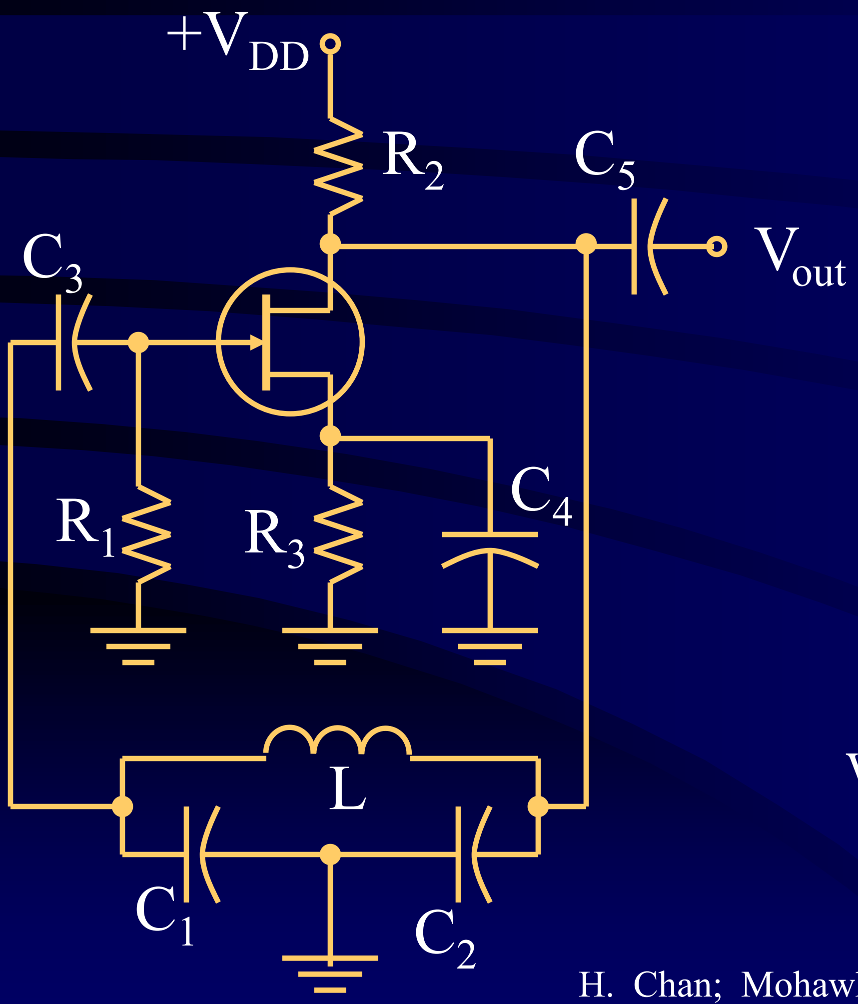
$$A_{cl} = \frac{R_f}{R_3} = 29$$

Choosing
$R_1 = R_2 = R_3 = R$,
$C_1 = C_2 = C_3 = C$,
the resonant
frequency is:

$$f_r = \frac{1}{2\pi\sqrt{6}RC}$$

Each RC section provides 60° of phase shift. Total attenuation of the three-section RC feedback, $B = 1/29$.

Colpitts Oscillator



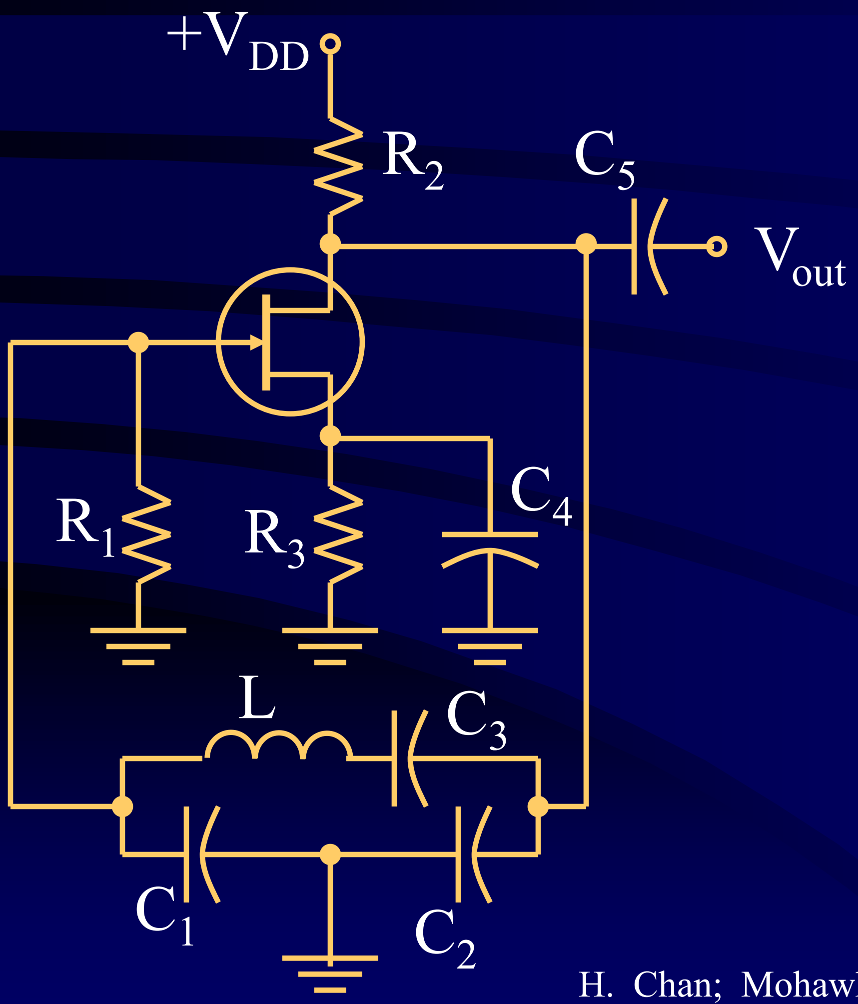
$$B = \frac{C_2}{C_1} = \frac{1}{A_V}$$

Neglecting loading effect,

$$f_r = \frac{1}{2\pi\sqrt{LC_T}}$$

where $$C_T = \frac{C_1 C_2}{C_1 + C_2}$$

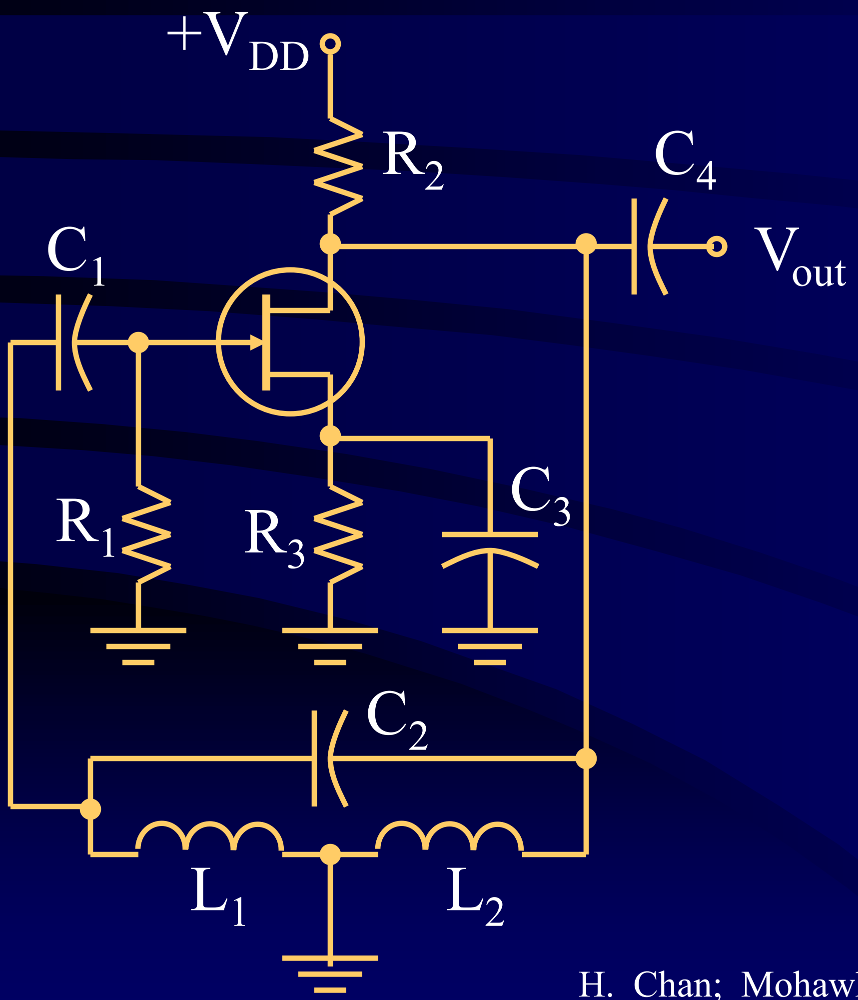
Clapp Oscillator



The Clapp oscillator is a variation of the Colpitts. It has a capacitor, C_3 in series with L in the resonant circuit. Formulas are similar to those for Colpitts except

$$C_T = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}$$

Hartley Oscillator



$$A_V = \frac{L_2}{L_1} = \frac{1}{B}$$

Neglecting loading effect

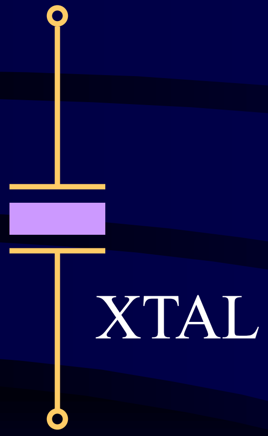
$$f_r = \frac{1}{2\pi\sqrt{L_T C_2}}$$

where $L_T = L_1 + L_2$

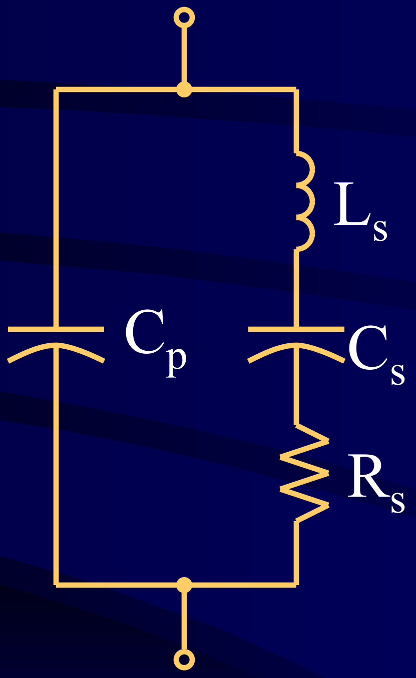
Crystal-Controlled Oscillators

- For stable and accurate oscillations, a piezoelectric crystal (e.g. quartz) is used in the feedback loop.
- Piezoelectric effect: When a changing mechanical stress is applied to the crystal, a voltage develops at the frequency of mechanical vibrations. Conversely, when an ac voltage is applied across the crystal, it vibrates at the frequency of the applied voltage. The greatest vibration occurs at the crystal's natural resonant frequency.

Symbol & Electrical Equivalent of Crystals



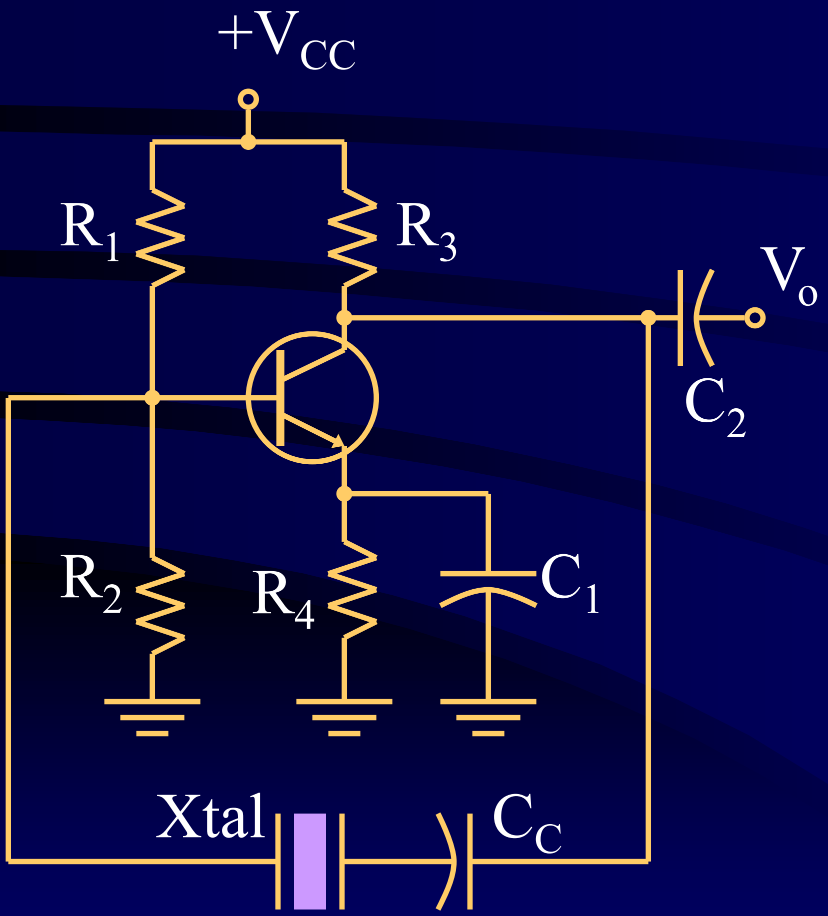
Symbol

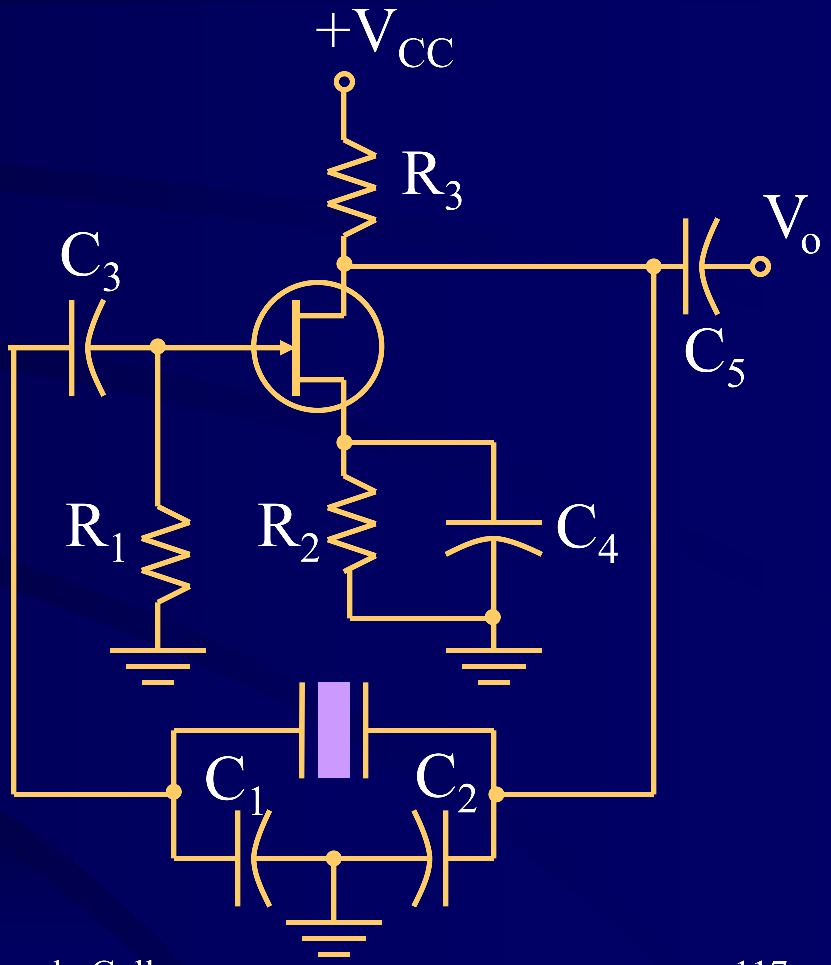


Electrical equivalent

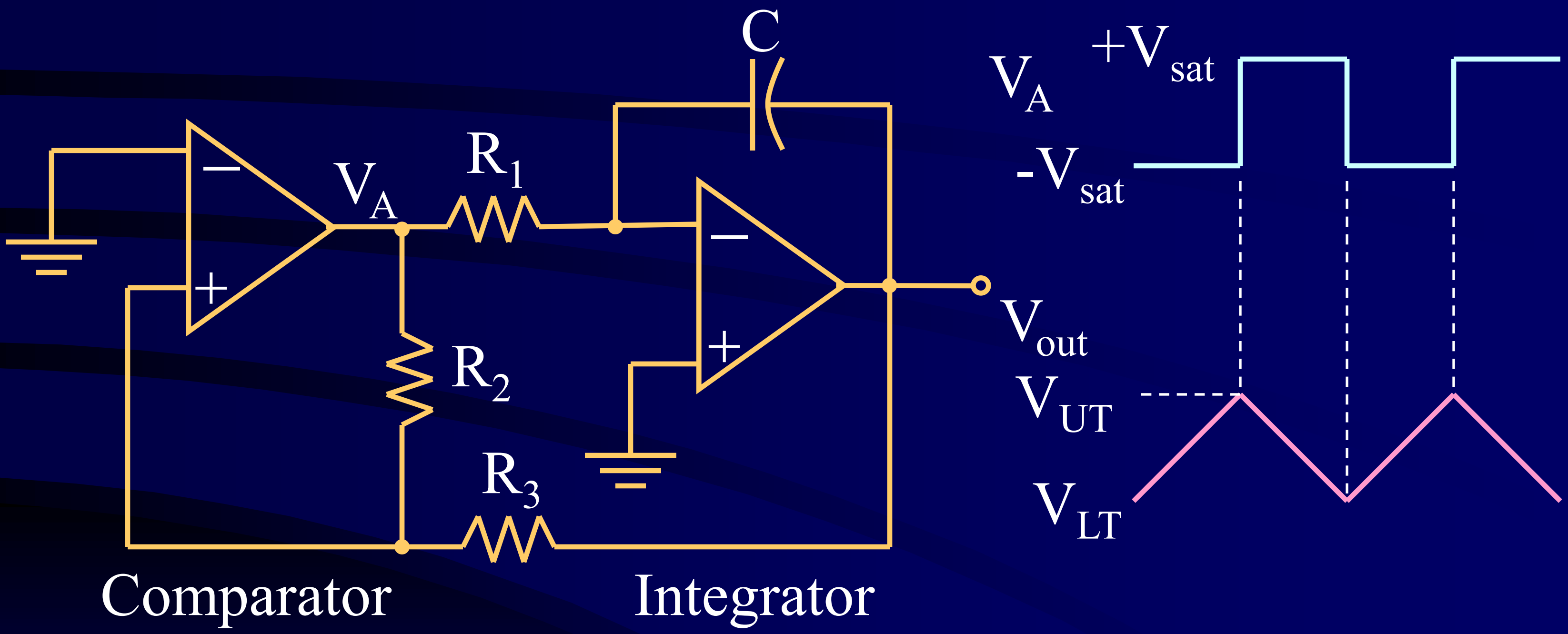
- A crystal can operate either in series or parallel resonance.
- Crystals have very high Q.
- Resonant frequency depends on dimension, type of cut, thickness, temperature, etc.

Basic Crystal Oscillators





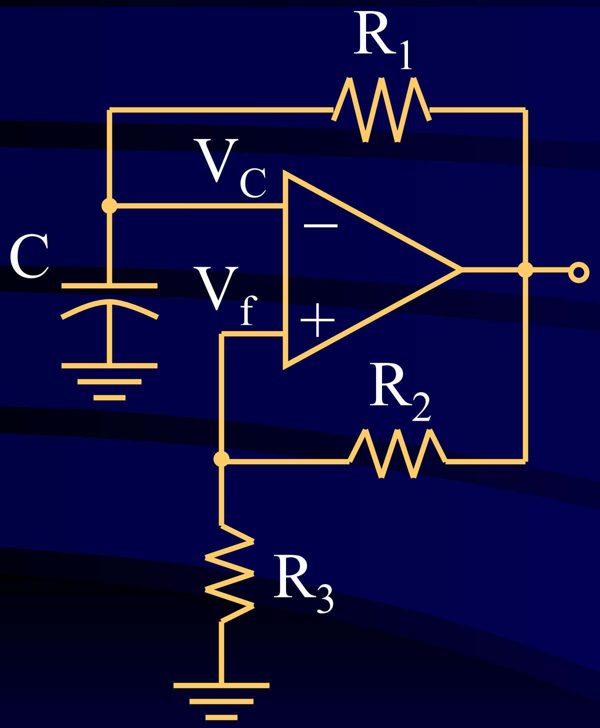
Triangular-Wave Oscillator



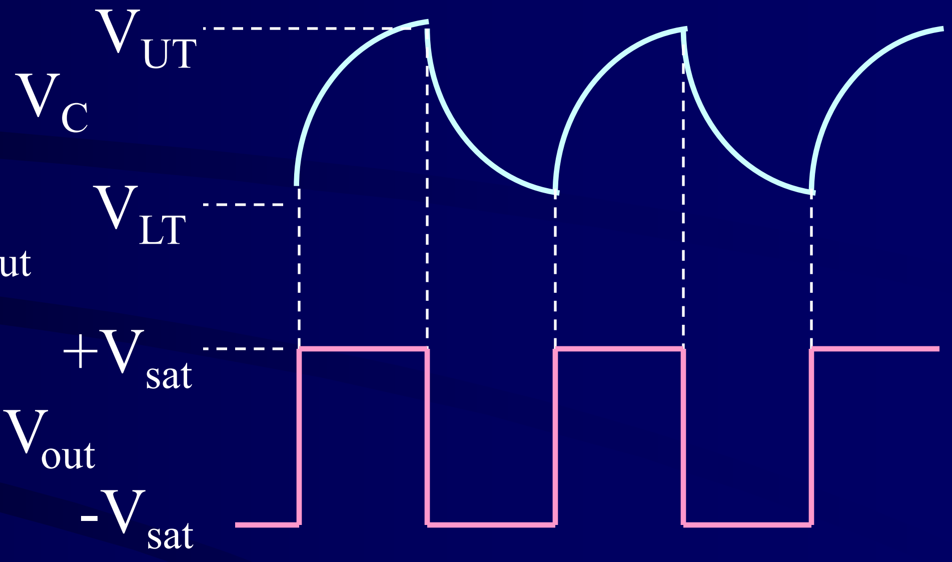
$$f = \frac{1}{4R_1C}\left(\frac{R_2}{R_3}\right)$$

$$V_{UT} = +V_{sat}\left(\frac{R_3}{R_2}\right); V_{LT} = -V_{sat}\left(\frac{R_3}{R_2}\right)$$

Square-Wave Oscillator

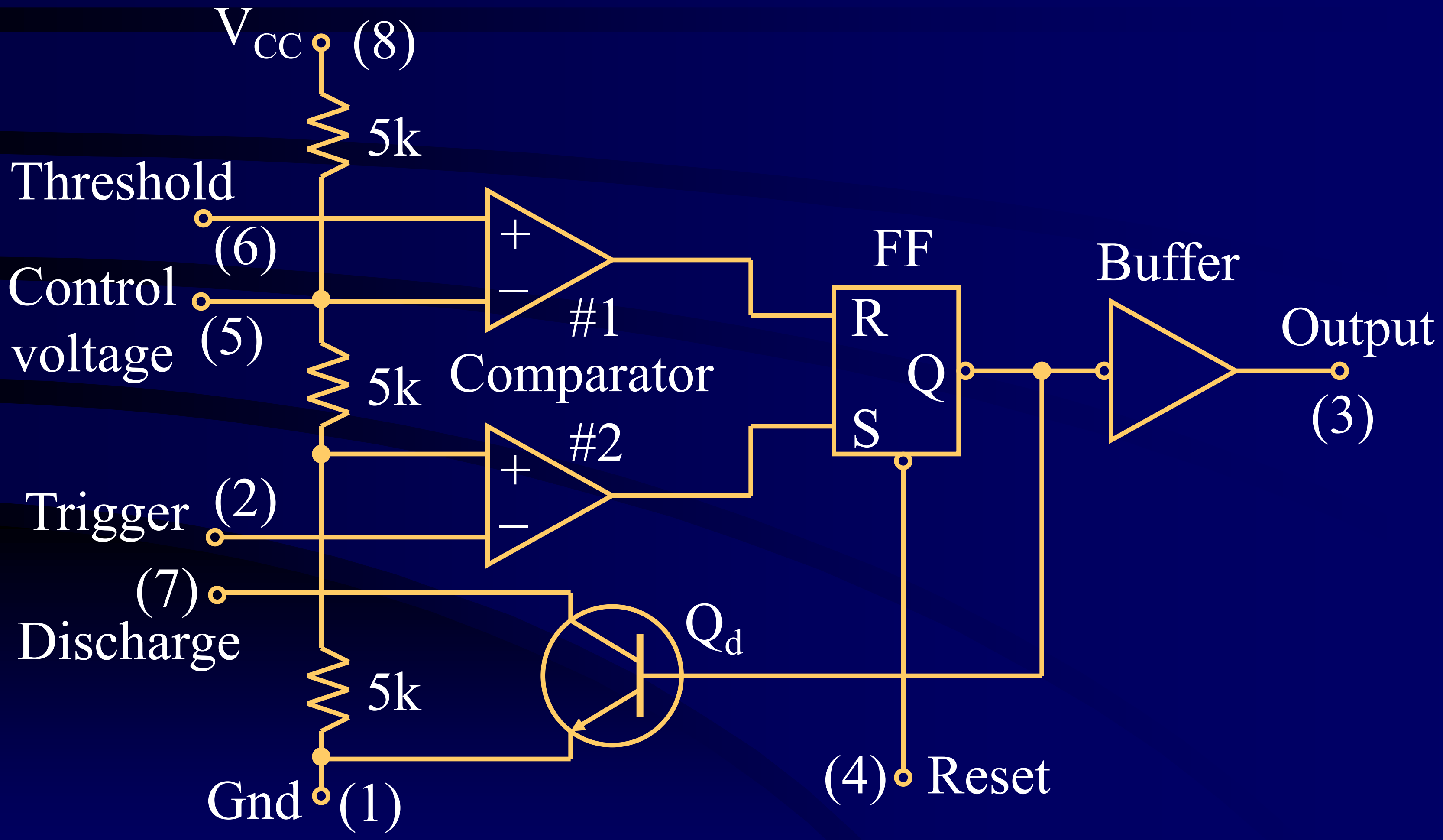


Relaxation oscillator



If $R_3 = 0.859R_2$, then: $\boxed{f = \dfrac{1}{2R_1C}}$

Functional Block Diagram of LM555



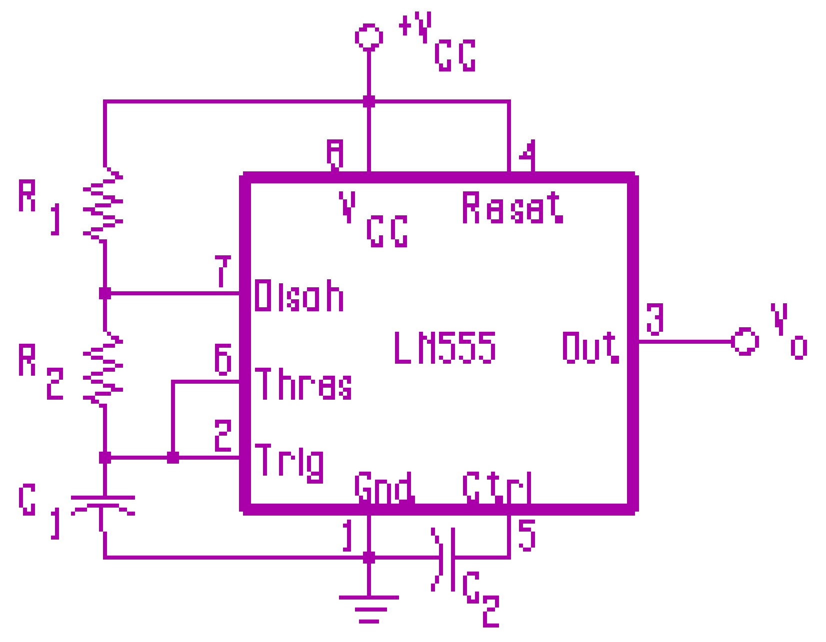
Operation of 555

- Voltage divider sets reference of ☎ V_{CC} for comparator #1 and ✂ V_{CC} for comparator #2.
- When trigger voltage (pin 2) is < ✂ V_{CC}, FF output is LO, output at pin 3 is HI, and Q_d is OFF. This allows capacitor connected to pin 6 to charge up.
- When threshold voltage (pin 6) is > ☎ V_{CC}, FF output turns HI, output at pin 3 is LO, and Q_d is ON, thereby discharging capacitor.
- The cycle then repeats once V_C < ✂ V_{CC}.

Notes on 555 Timer/Oscillator IC

- Widely used as a monostable or astable multivibrator.
- Can operate between 4.5 and 16 V.
- Output voltage is approximately V_{CC} - 2 V.
- Max. output frequency is about 10 kHz.
- f_o varies somewhat with V_{CC}.
- *Threshold* input (pin 6) and *trigger* input (pin 2) are normally tied together to external timing RC.

555 as a Simple Oscillator



Duty cycle is:

$$D = \frac{t_{ch}}{T} = \frac{R_1 + R_2}{R_1 + 2R_2}$$

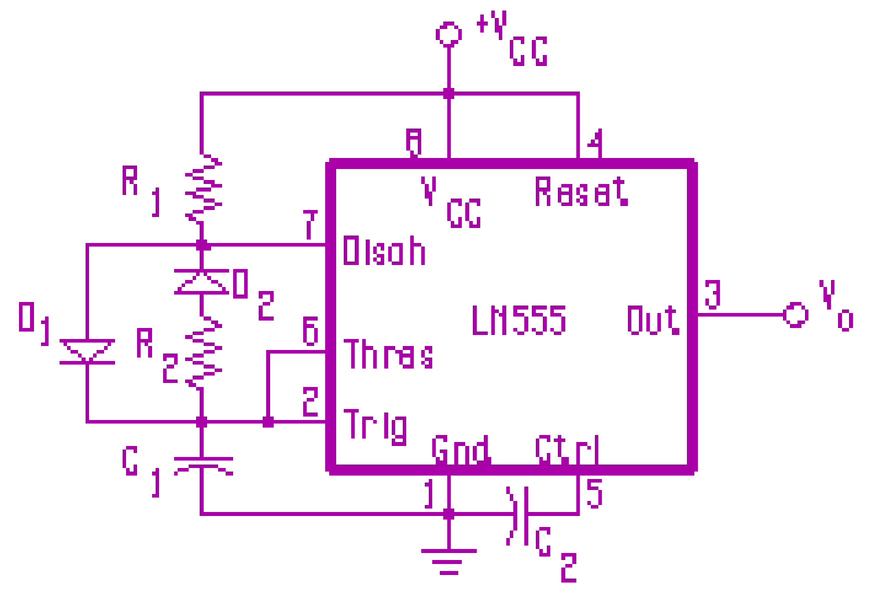
Given f_o and D,

$$R_1 = \frac{2D - 1}{0.693 f_o C_1}\ ;\ R_2 = \frac{1 - D}{0.693 f_o C_1}$$

$t_{ch} = 0.693(R_1 + R_2)C_1$
$t_{disch} = 0.693\ R_2C_1$
$T = 0.693(R_1 + 2R_2)C_1$

Note that D must always be > 0.5. To get 50% duty cycle, $R_1 = 0$, which would short out V_{CC}.

555 Square-Wave Oscillator



$$D = \frac{R_1}{R_1 + R_2}$$

$$R_1 = \frac{D}{0.693 f_o C_1} \; ; \; R_2 = \frac{1 - D}{0.693 f_o C_1}$$

$t_{ch} = 0.693\ R_1C_1$; $t_{disch} = 0.693\ R_2C_1$

For 50% duty cycle,

$$R_1 = R_2 = \frac{1}{1.386 f_o C_1}$$

$$f_o = \frac{1}{0.693(R_1 + R_2)C_1}$$

Line Regulation

is a measure of the effectiveness of a voltage regulator to maintain the output dc voltage constant despite changes in the supply voltage.

$$Line\ regulation = \frac{\Delta V_{out}}{\Delta V_{in}} x100\%$$

OR

$$Line\ regulation = \frac{\Delta V_{out}}{\Delta V_{in}} x \frac{100}{V_{out}} \% / V$$

Load Regulation

is a measure of the ability of a regulator to maintain a constant dc output despite changes in the load current.

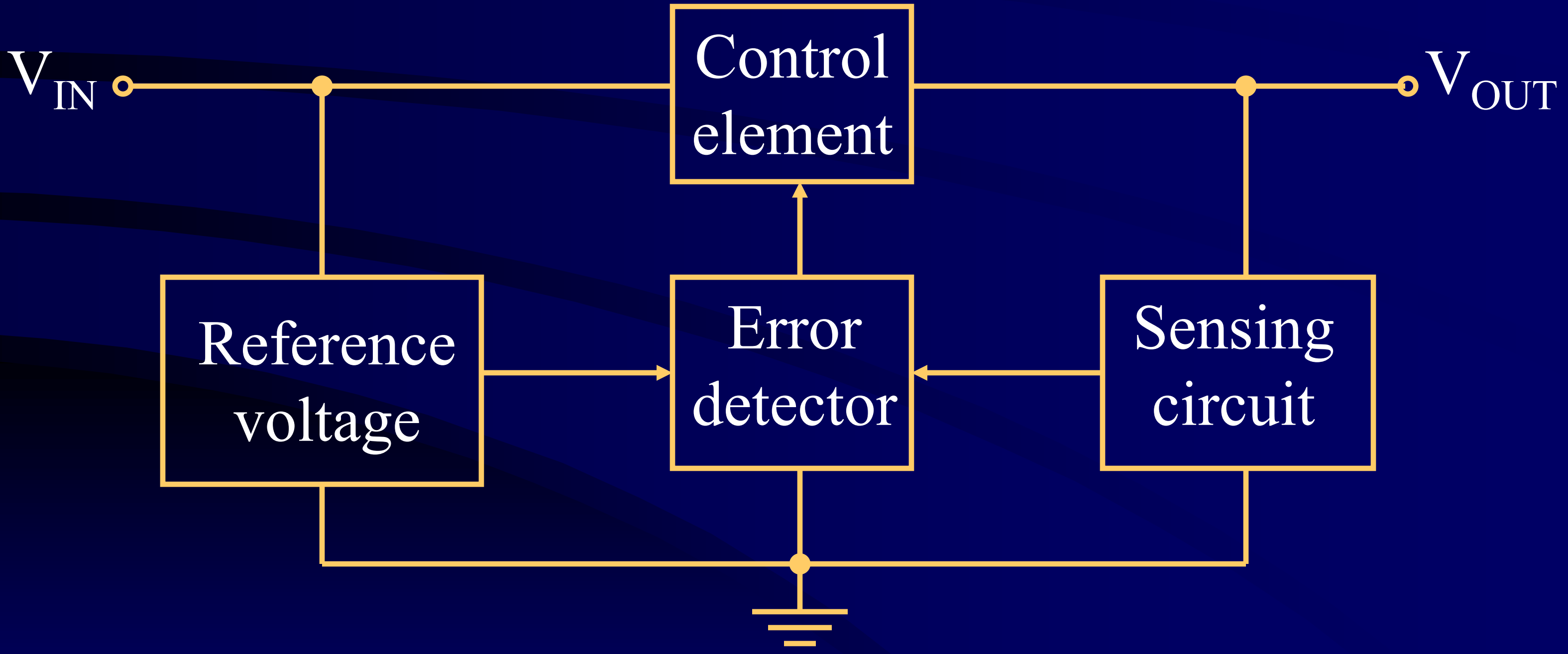
$$Load\ regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} x100\%$$

OR

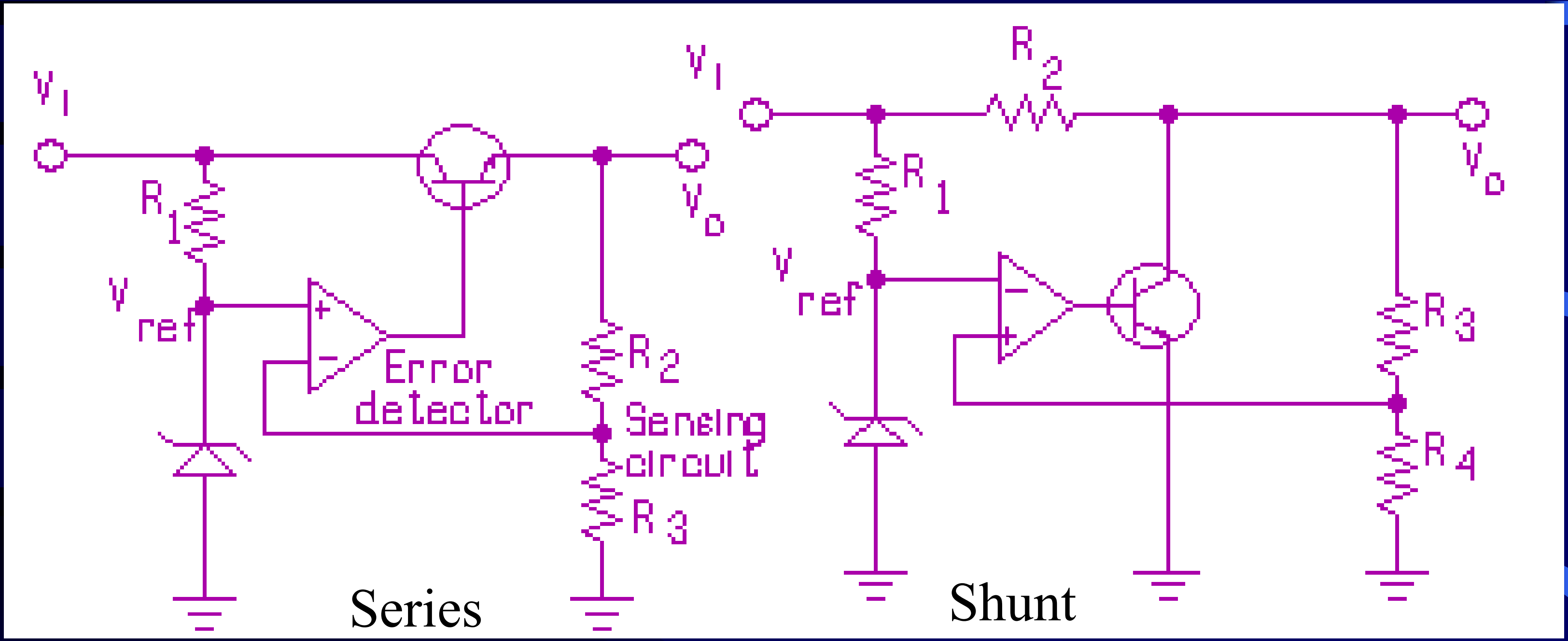
$$Load\ regulation = \frac{V_{NL} - V_{FL}}{V_{FL}} x \frac{100}{I_{FL}} \% / mA$$

Regulator Block Diagram

The essential elements in a series voltage regulator is shown in the block diagram below:



Op-Amp Voltage Regulators



$$V_o \cong \left(1+\frac{R_2}{R_3}\right)V_Z$$

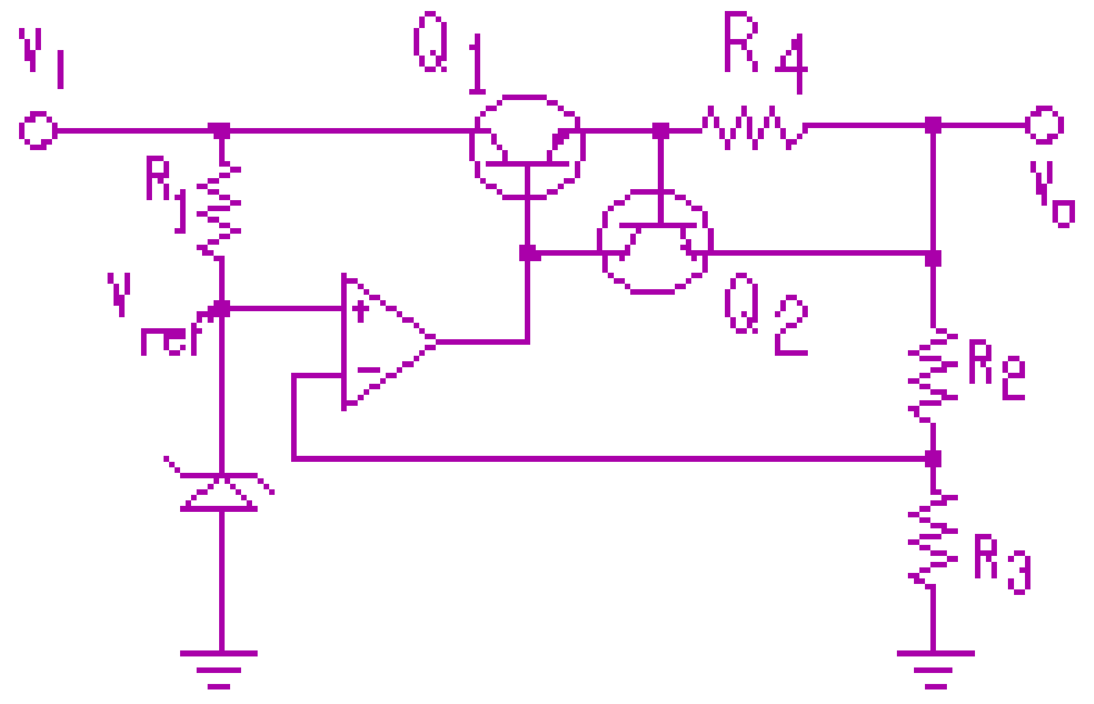
$$V_o \cong \left(1+\frac{R_3}{R_4}\right)V_Z$$

Notes on Op-Amp Voltage Regulator

- More flexibility possible in design of voltage output than IC voltage regulator packages.
- The essential circuit elements are: a zener reference, a pass or shunt transistor, a sensing circuit, and an error/amplifier circuit.
- Equation indicates that V_o depends on R_2, R_3, and V_Z. However, V_i must be greater than V_o.
- The shunt configuration is less efficient but R_2 offers short-circuit current limiting.

Constant Current Limiting

can be used for short-circuit or overload protection of the series voltage regulator.



Q_2 and R_4 form the current limiter.

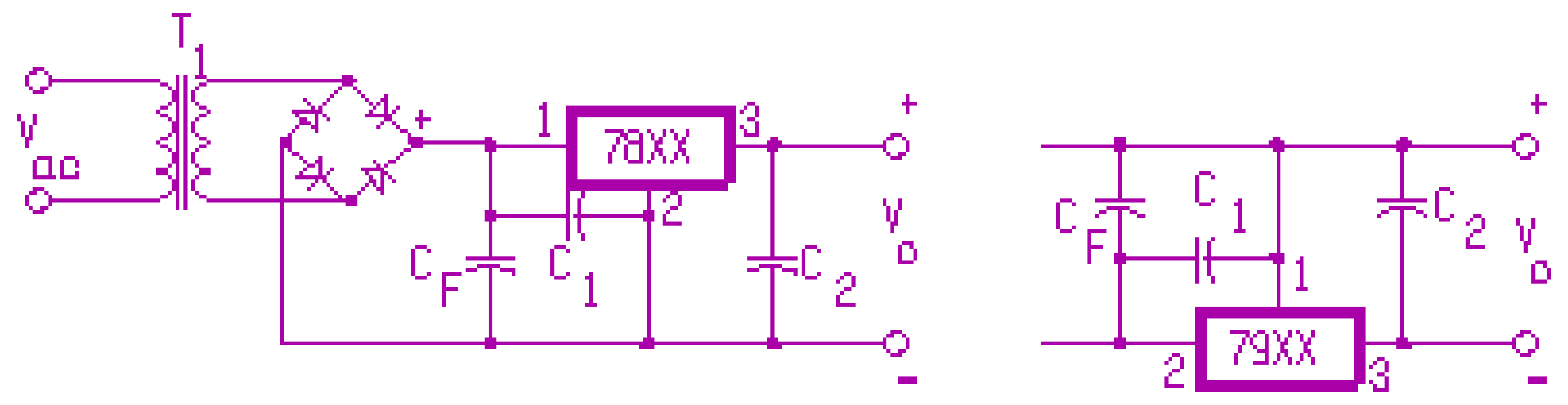
Output current is limited to:

$$I_{L(\max)} = \frac{0.7}{R_4}$$

Three-Terminal Fixed Voltage Regulators

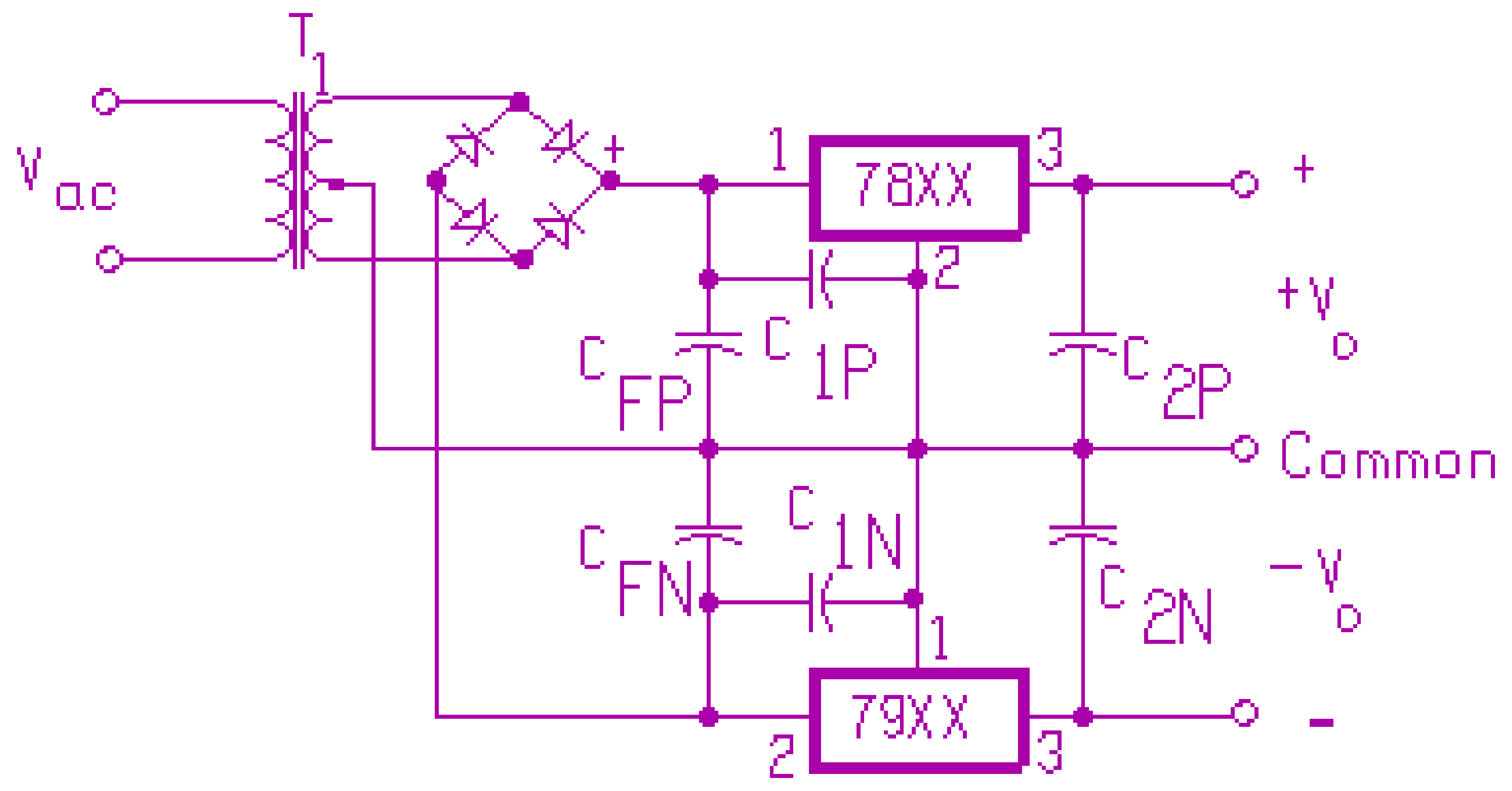
- Less flexible, but simple to use
- Come in standard TO-3 (20 W) or TO-220 (15 W) transistor packages
- 78/79XX series regulators are commonly available with 5, 6, 8, 12, 15, 18, or 24 V output
- Max. output current with heat sink is 1 A
- Built-in thermal shutdown protection
- 3-V dropout voltage; max. input of 37 V

Basic Circuits With 78/79XX Regulators

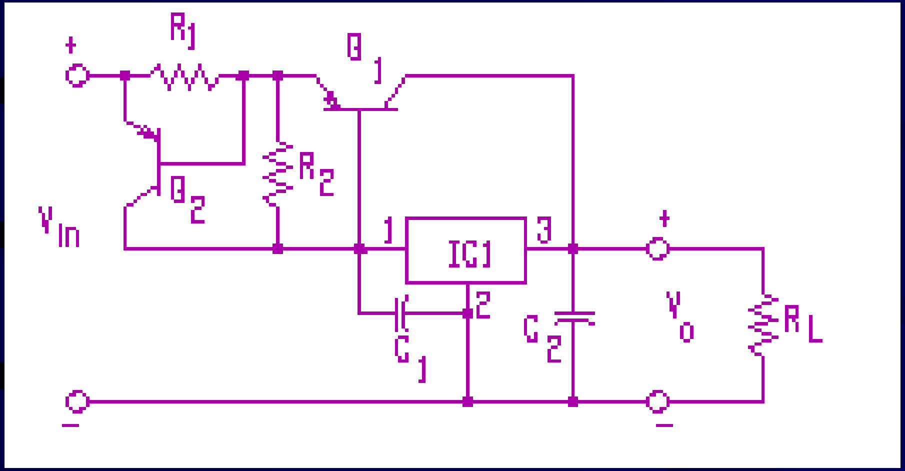


- Both the 78XX and 79XX regulators can be used to provide +ve or -ve output voltages
- C_1 and C_2 are generally optional. C_1 is used to cancel any inductance present, and C_2 improves the transient response.

Dual-Polarity Output with 78/79XX Regulators



78XX Regulator with Pass Transistor

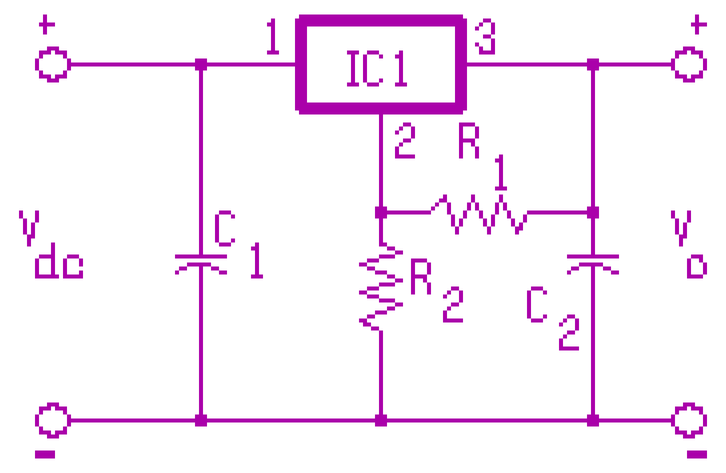


$$R_1 = \frac{0.7}{I_{\max}}$$

$$R_2 = \frac{0.7}{I_{R2}}$$

- Q_1 starts to conduct when V_{R2} = 0.7 V.
- R2 is typically chosen so that max. I_{R2} is 0.1 A.
- Power dissipation of Q_1 is P = $(V_i - V_o)I_L$.
- Q_2 is for current limiting protection. It conducts when V_{R1} = 0.7 V.
- Q_2 must be able to pass max. 1 A; but note that max. V_{CE2} is only 1.4 V.

78XX Floating Regulator



- It is used to obtain an output > the V_{reg} value up to a max.of 37 V.
- R_1 is chosen so that R_1 ✂ $0.1\ V_{reg}/I_Q$, where I_Q is the *quiescent current* of the regulator.

$$V_o = V_{reg} + \left(\frac{V_{reg}}{R_1} + I_Q \right) R_2$$

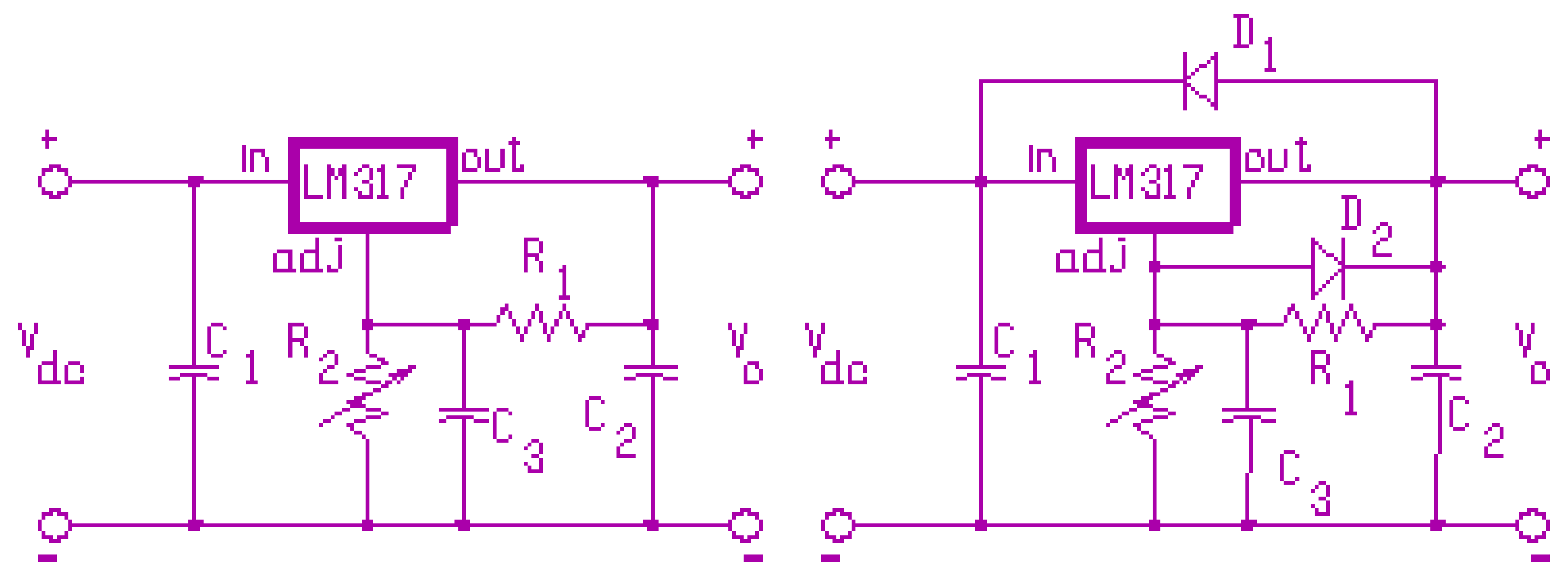
or

$$R_2 = \frac{R_1 (V_o - V_{reg})}{V_{reg} + I_Q R_1}$$

3-Terminal Variable Regulator

- The floating regulator could be made into a variable regulator by replacing R_2 with a pot. However, there are several disadvantages:
  - Minimum output voltage is V_{reg} instead of 0 V.
  - I_Q is relatively large and varies from chip to chip.
  - Power dissipation in R_2 can in some cases be quite large resulting in bulky and expensive equipment.
- A variety of 3-terminal variable regulators are available, e.g. LM317 (for +ve output) or LM 337 (for -ve output).

Basic LM317 Variable Regulator Circuits



(a)

Circuit with capacitors to improve performance

(b)

Circuit with protective diodes

Notes on Basic LM317 Circuits

- The function of C_1 and C_2 is similar to those used in the 78/79XX fixed regulators.
- C_3 is used to improve ripple rejection.
- Protective diodes in circuit (b) are required for high-current/high-voltage applications.

$$V_o = V_{ref} + \left(\frac{V_{ref}}{R_1} + I_{adj} \right) R_2$$

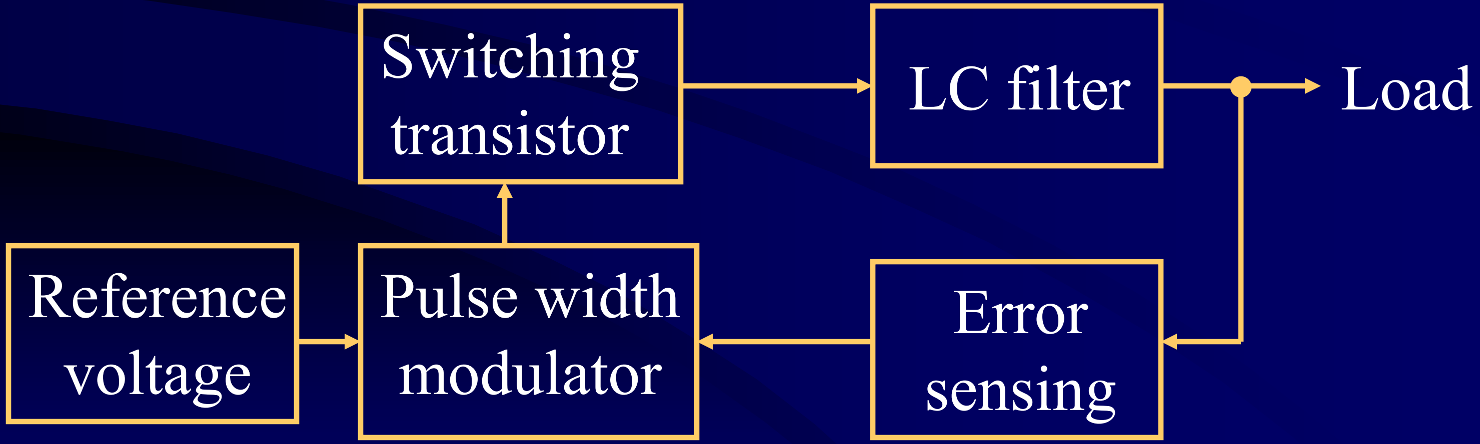
where $V_{ref} = 1.25$ V, and I_{adj} is the current flowing into the adj. terminal (typically 50 μA).

$$R_2 = \frac{R_1 (V_o - V_{ref})}{V_{ref} + I_{adj} R_1}$$

R_1 is typically 120 Ω or 240 Ω

Switching Regulators

- Instead of operating the pass transistor in a linear manner, switching regulators use a transistor switch to improve the power efficiency.
- A basic block diagram is shown below:



Comparing Switching to Linear Regulators

Advantages:

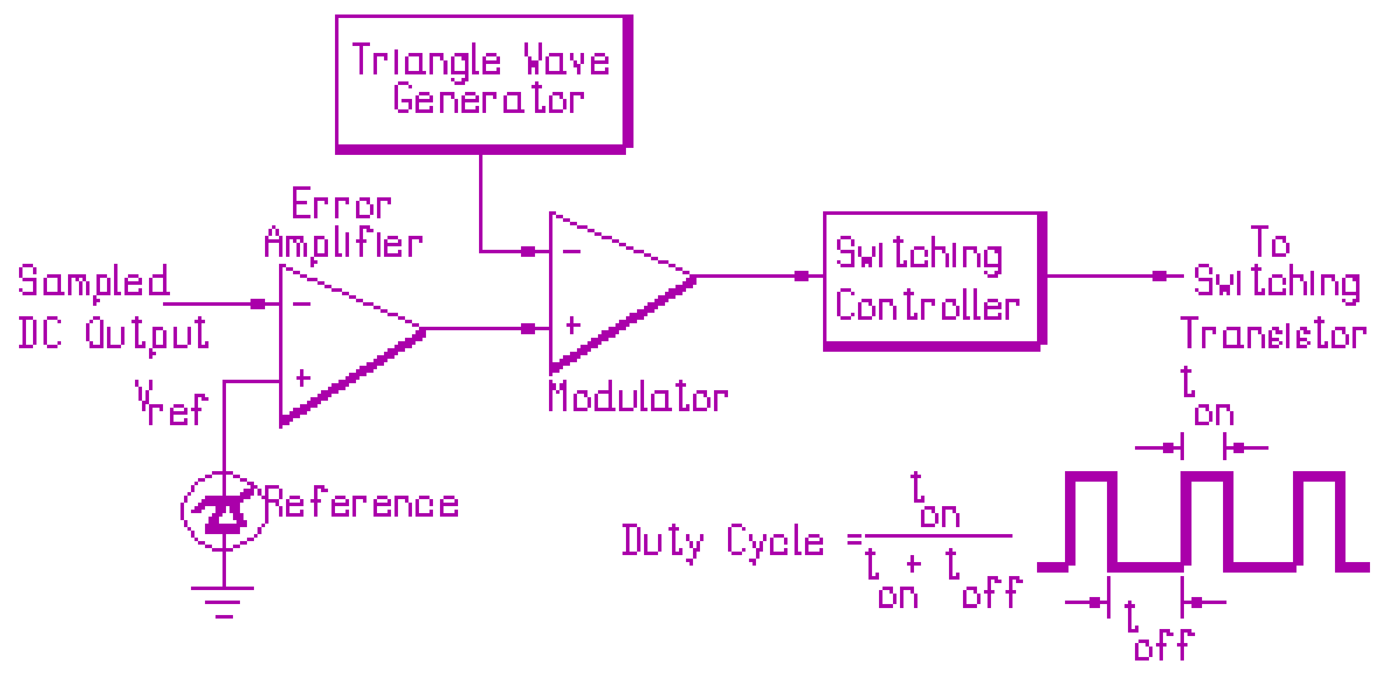
- 70-90% efficiency (about double that of linear ones)
- can make output voltage > input voltage, if desired
- can invert the input voltage
- can result in considerable weight and size reductions

Disadvantages:

- More complex circuitry
- Potential EMI problems unless good shielding, low-loss ferrite cores and chokes are used

Switch-Mode Operation

The duty cycle of the series transistor (power switch) determines the average dc output of the regulator. A circuit to control the duty cycle is shown in the schematic below:

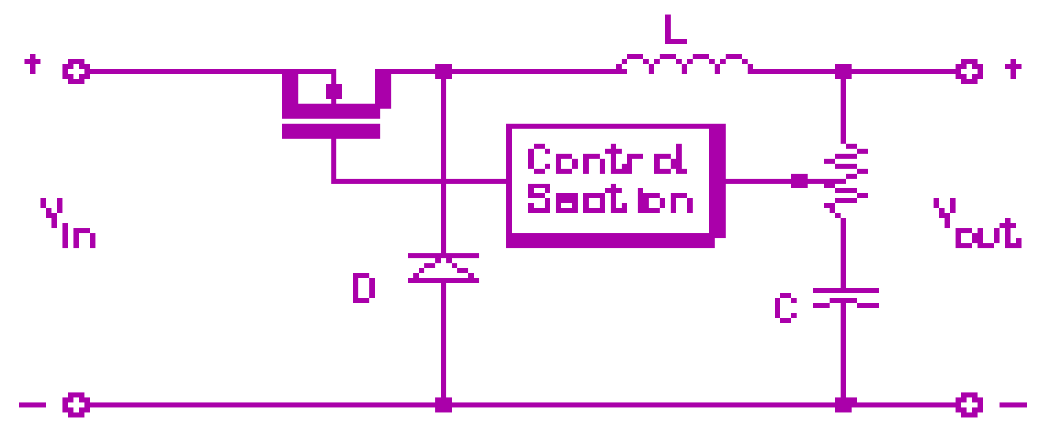


$$\text{Duty Cycle} = \frac{t_{on}}{t_{on} + t_{off}}$$

Notes On Switch-Mode Operation

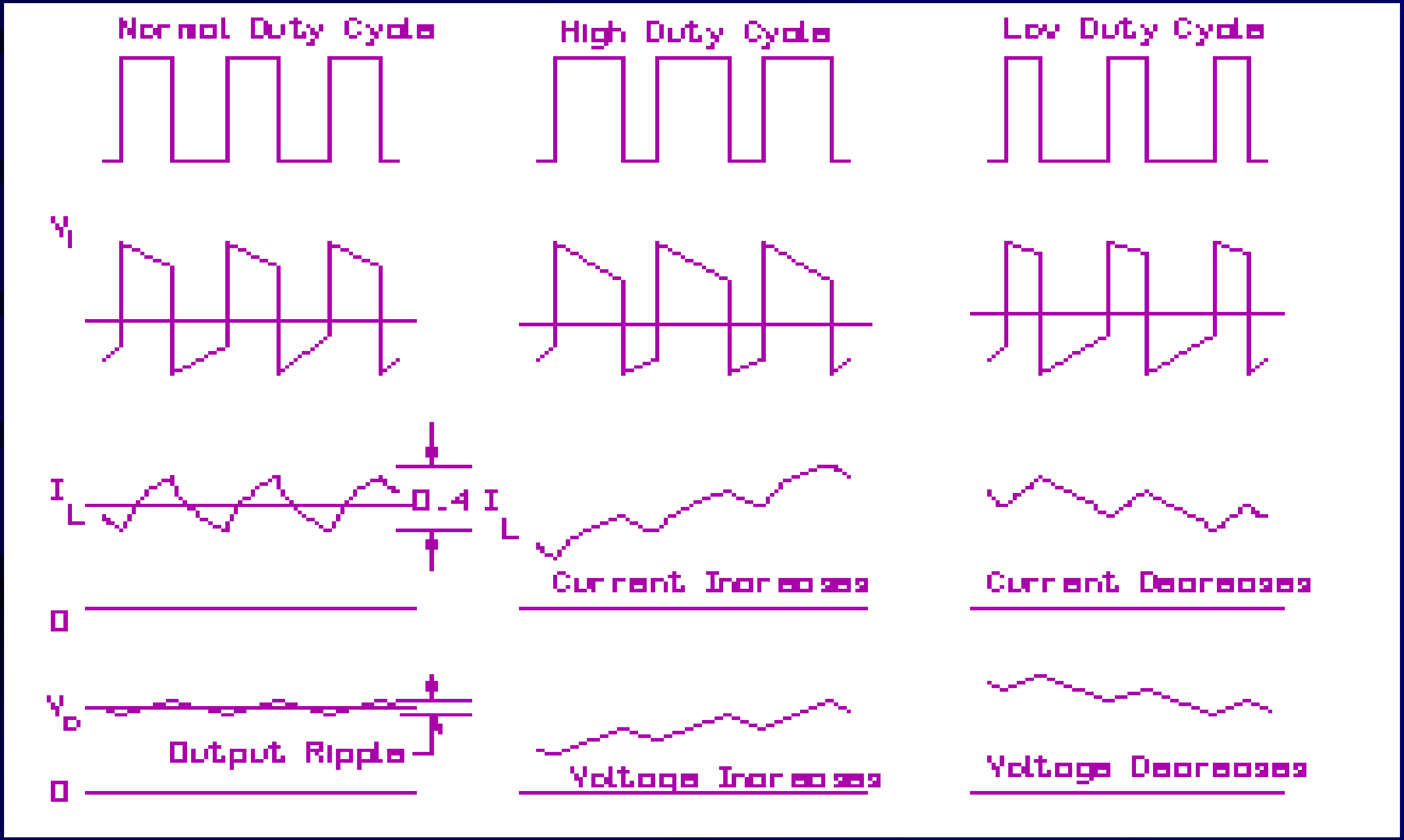
- The *error amplifier* compares a sample of the regulator V_o to an internal V_{ref}. The difference or error voltage is amplified and applied to a *modulator* where it is compared to a triangle wave. The result is an output pulse whose width is proportional to the error voltage.
- Darlington transistors and TMOS FETs with f_T of at least 4 MHz are often used. TMOS FETs are more efficient.
- A fast-recovery rectifier, or a Schottky barrier diode (sometimes referred to as a *catch diode*) is used to direct current into the inductor.
- For proper switch-mode operation, current must always be present in the inductor.

Step-Down or Buck Converter



- When the transistor is turned ON, V_L is initially high but falls exponentially while I_L increases to charge C. When the transistor turns OFF, V_L reverses in polarity to maintain the direction of current flow. I_L decreases but its path is now through the forward-biased diode, D. Duty cycle is adjusted according to the level of V_o.

V & I Waveforms for Buck Regulator



PWM output

V_L

I_L

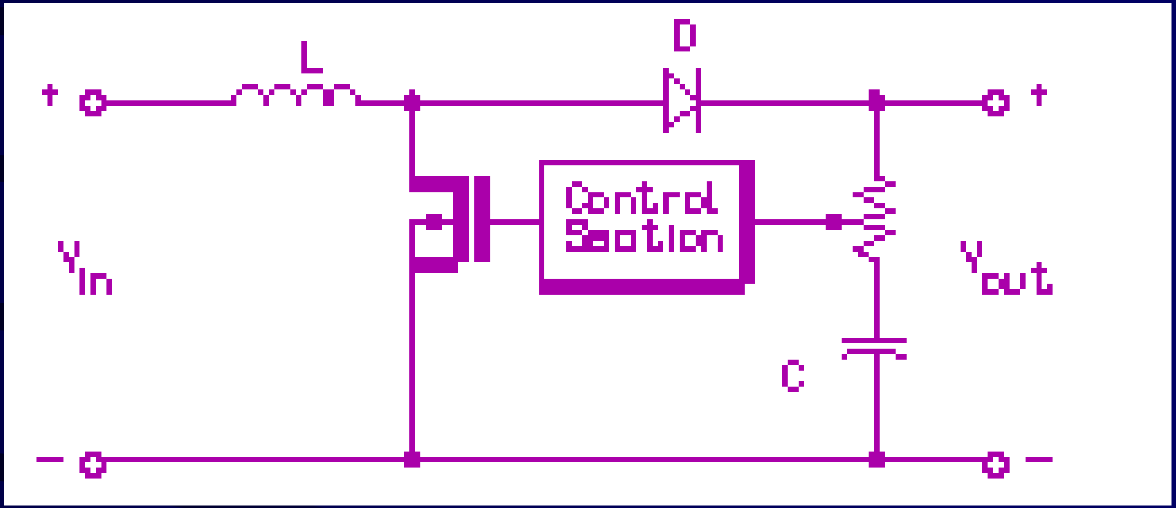
V_o

Normal

Low V_o

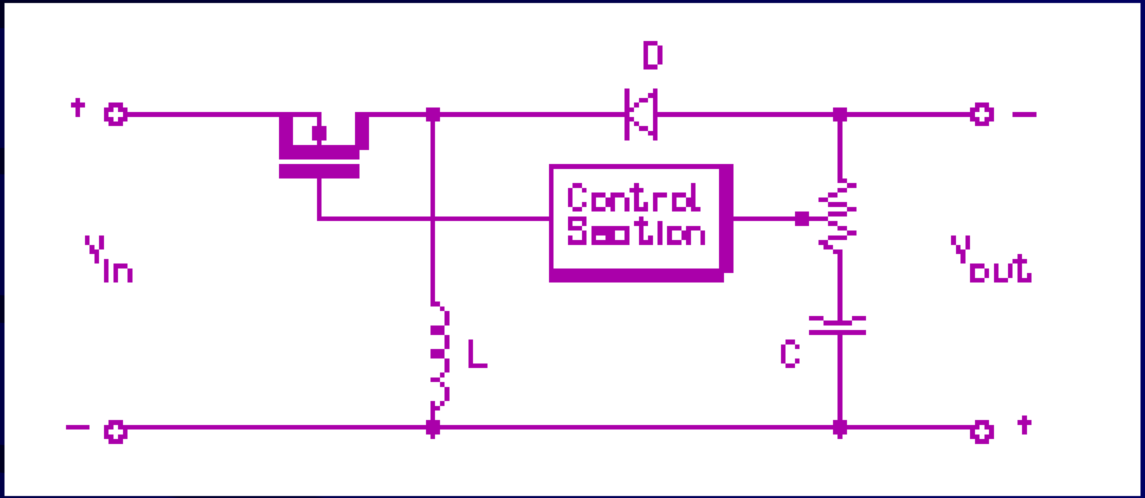
High V_o

Step-Up, Flyback, or Boost Regulator



- Assuming steady-state conditions, when the transistor is turned ON, L reacts against V_{in}. D is reverse-biased and C supplies the load current. When the transistor is OFF, V_L reverses polarity causing current to flow through D and charges C. Note that $V_{out} > V_{in}$ because V_L adds on to V_{in}.

Voltage-Inverting or Buck-Boost Regulator



- V_o can be either step-up or step-down and its polarity is opposite to input.
- During ON period, V_{in} is across L, and D is reverse-biased.
- During OFF period, V_L reverses polarity causing current to flow through C and D.

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