Rectifiers, Filters and Regulator Transistor Configurations and Op AMP

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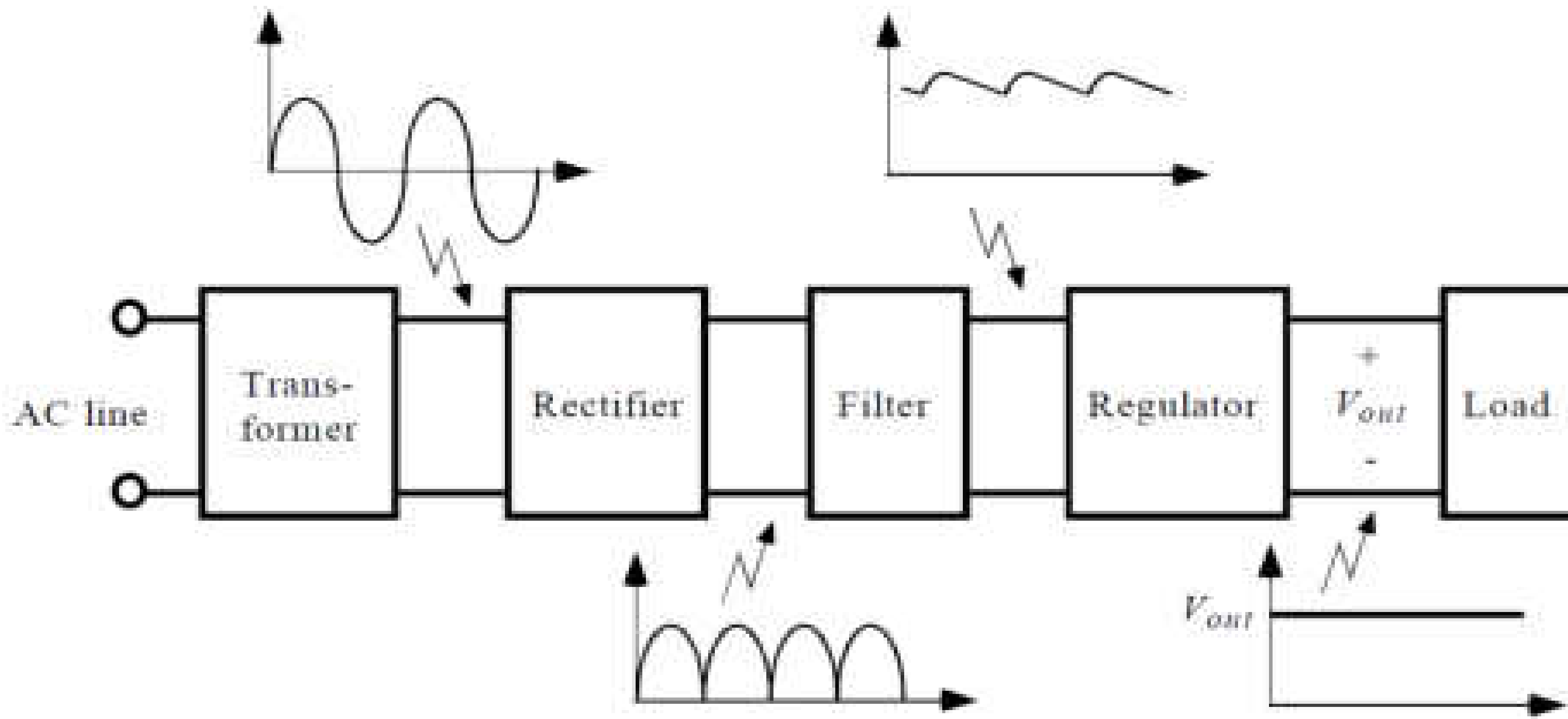
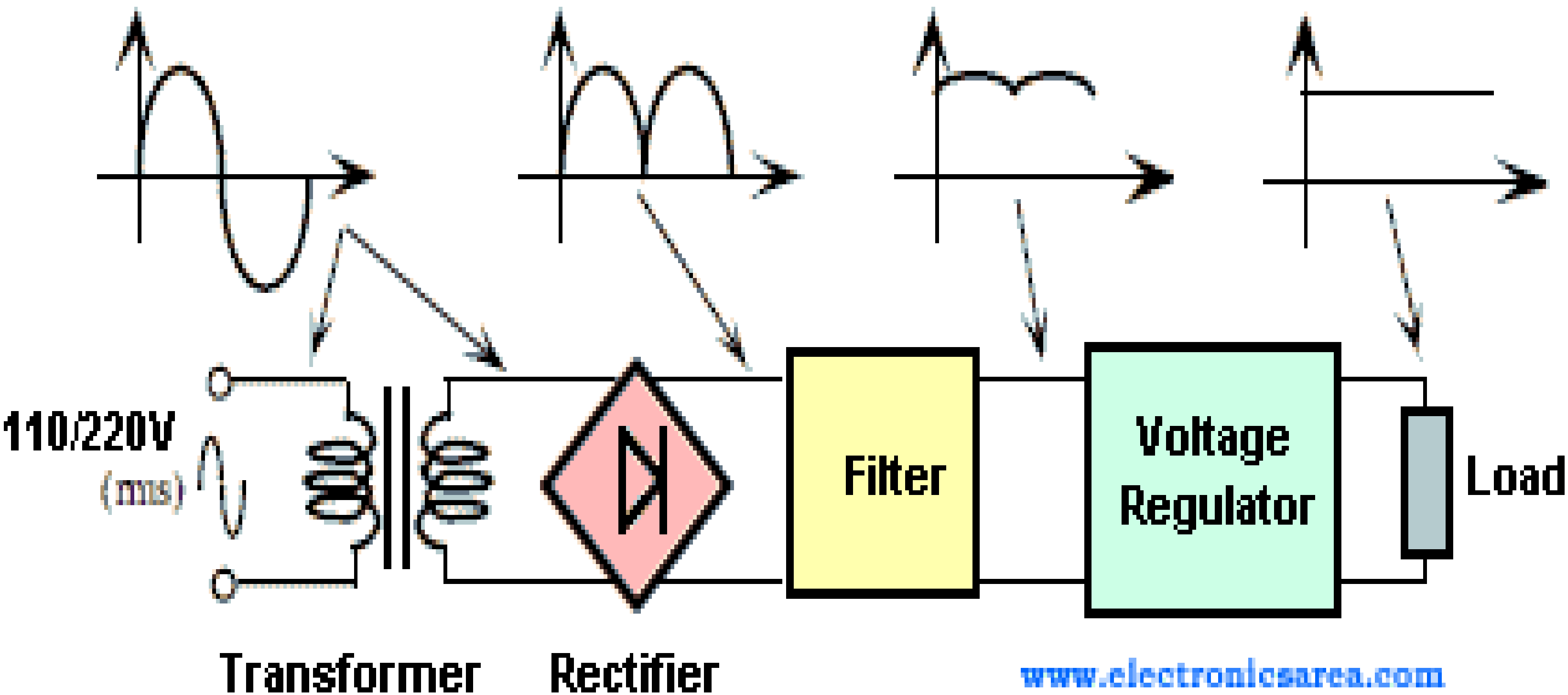
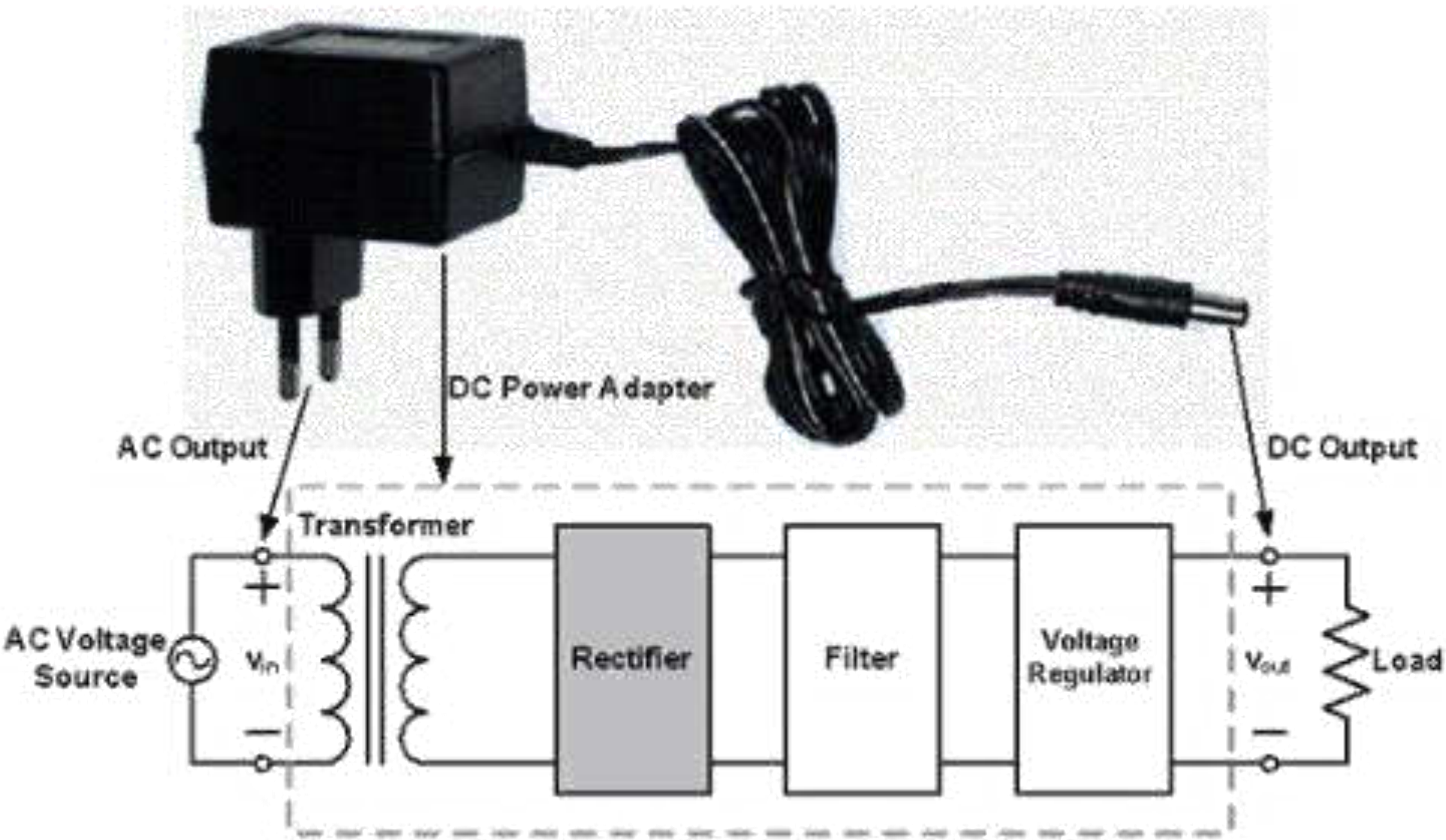
Basic Block Diagram of Regulated power Supply

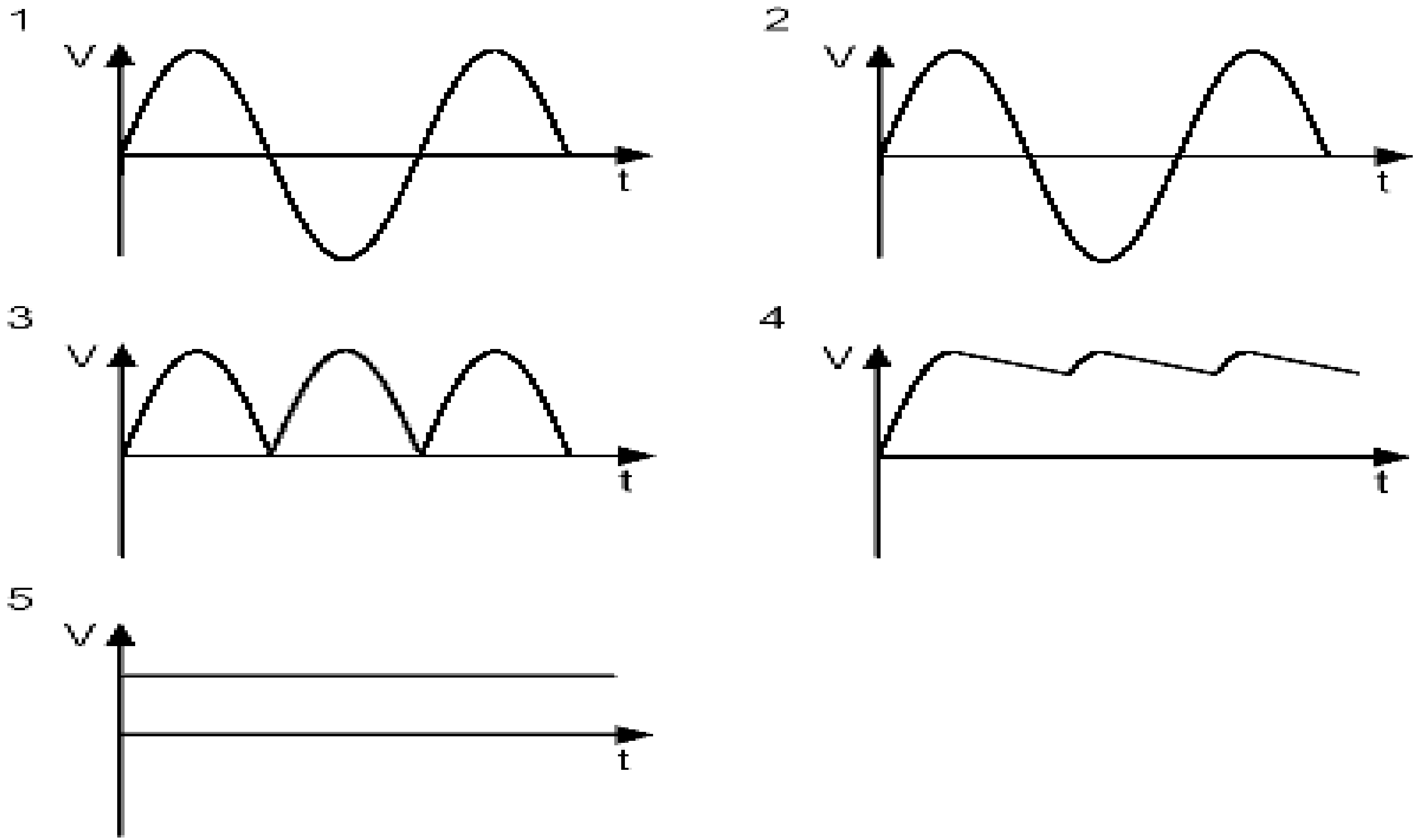




Picture 1. Regulated power source Block Diagram


DC Power Adapter
AC Output
DC Output
Transformer
AC Voltage
Source
V_{in}
Rectifier
Filter
Voltage
Regulator
V_{out}
Load

Wave forms at various points in a Regulated power supply



Rectification

- Rectification is a process of converting the alternating quantity (voltage or current) into a corresponding direct quantity(voltage or current).

- The **input to a rectifier is AC** whereas its **output is unidirectional or DC.**

Rectifiers

- Rectifier is an electronic device which is used for converting an alternating quantity (Voltage or current) into unidirectional i.e. DC quantity (Voltage or current).
- **Block diagram of Rectifier:**

Need of Rectification

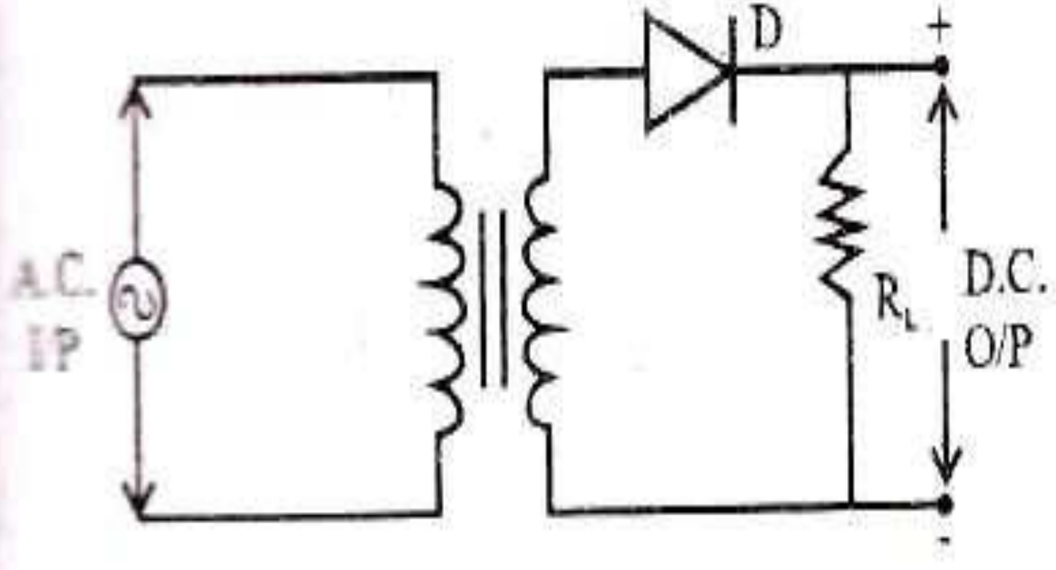
- Every electronic circuit such as amplifiers, needs a DC power source for its operation.
- This DC voltage has to be obtained from AC supply.
- For this the AC supply has to be reduced () Stepped down first using a Step down transformer and then converted to dc by using rectifier.

Types of Rectifier

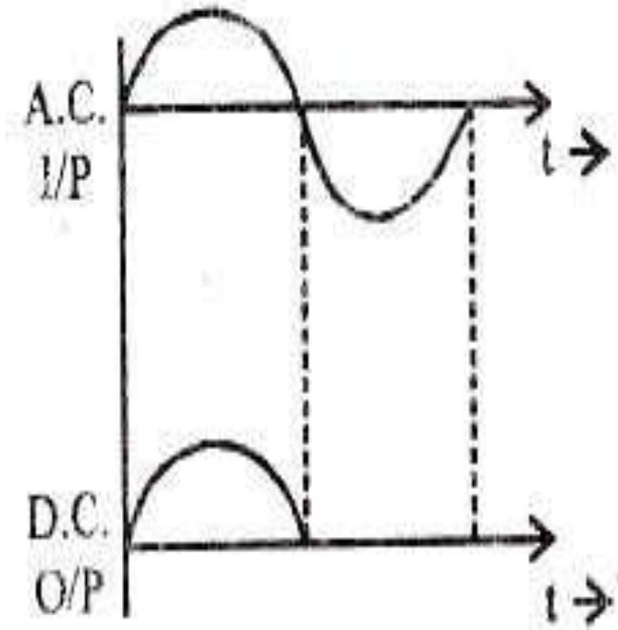
Rectifier Circuits

- **Half wave Rectifier (HWR)**
- **Full wave Rectifier**
  1. FWR with centre tapped xmer
  2. Full wave bridge rectifier

Half Wave Rectifier

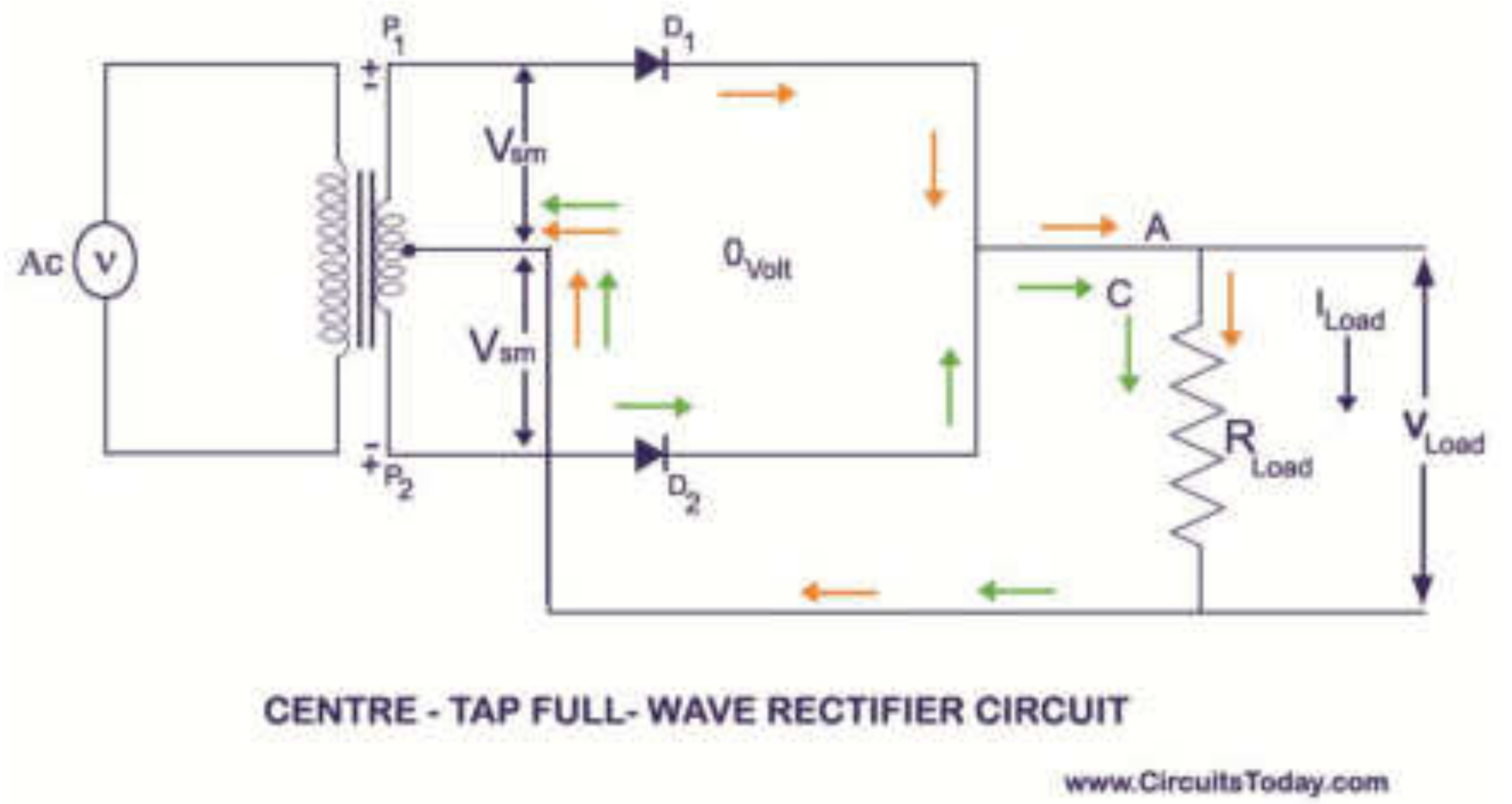


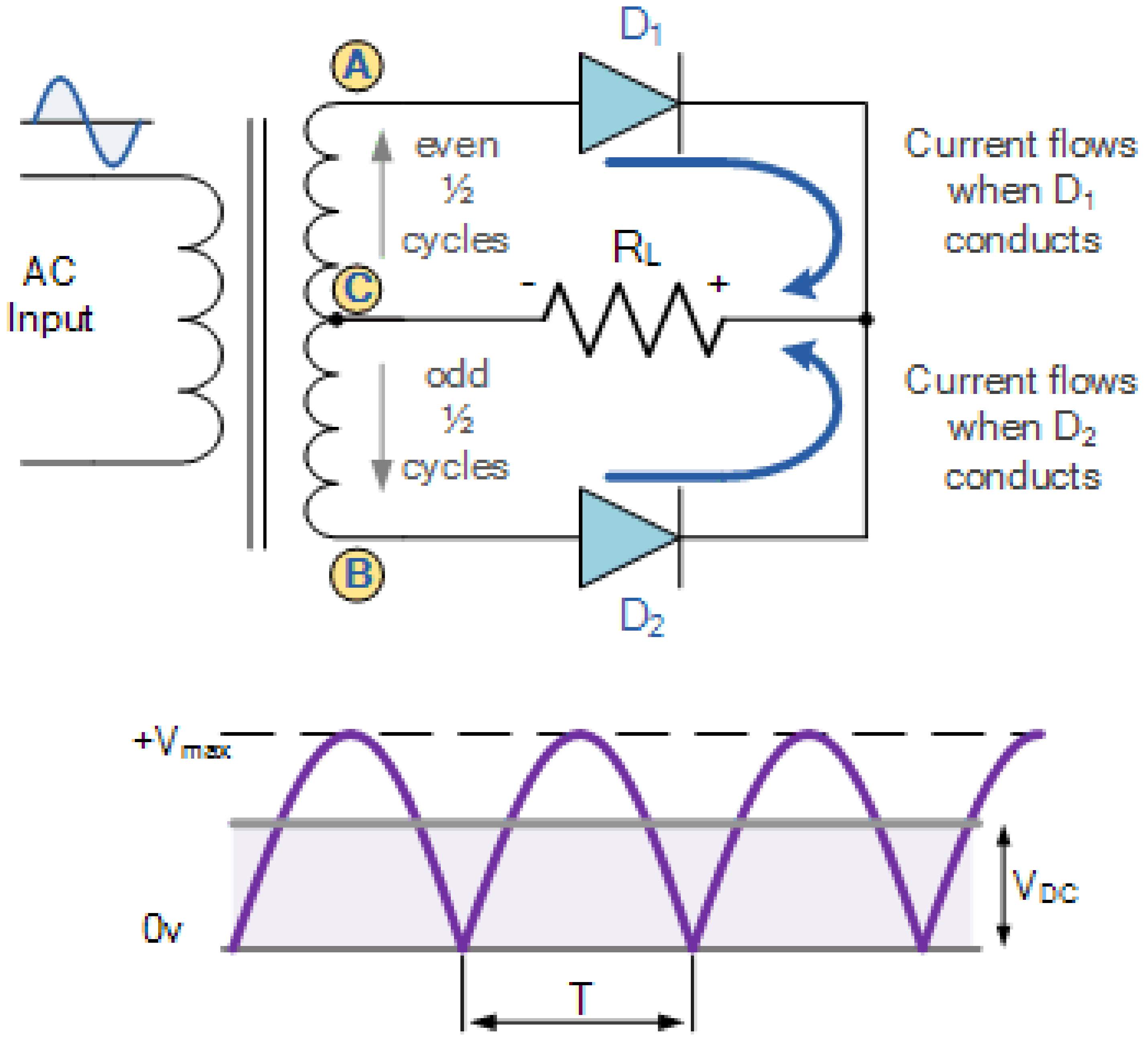
a) Half wave Rectifier



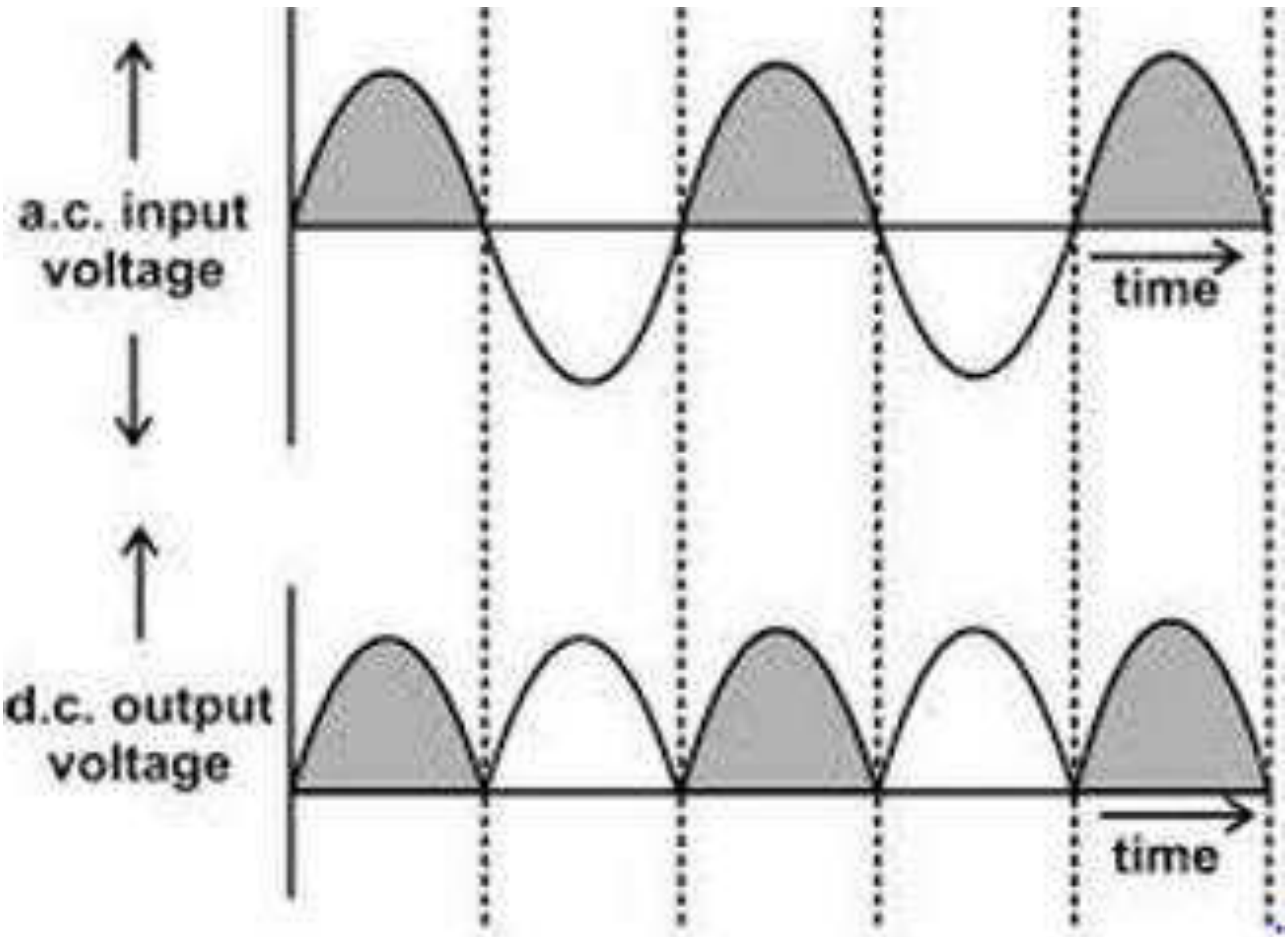
b) Wave forms

Full Wave Rectifier (Center Tapped Transformer)

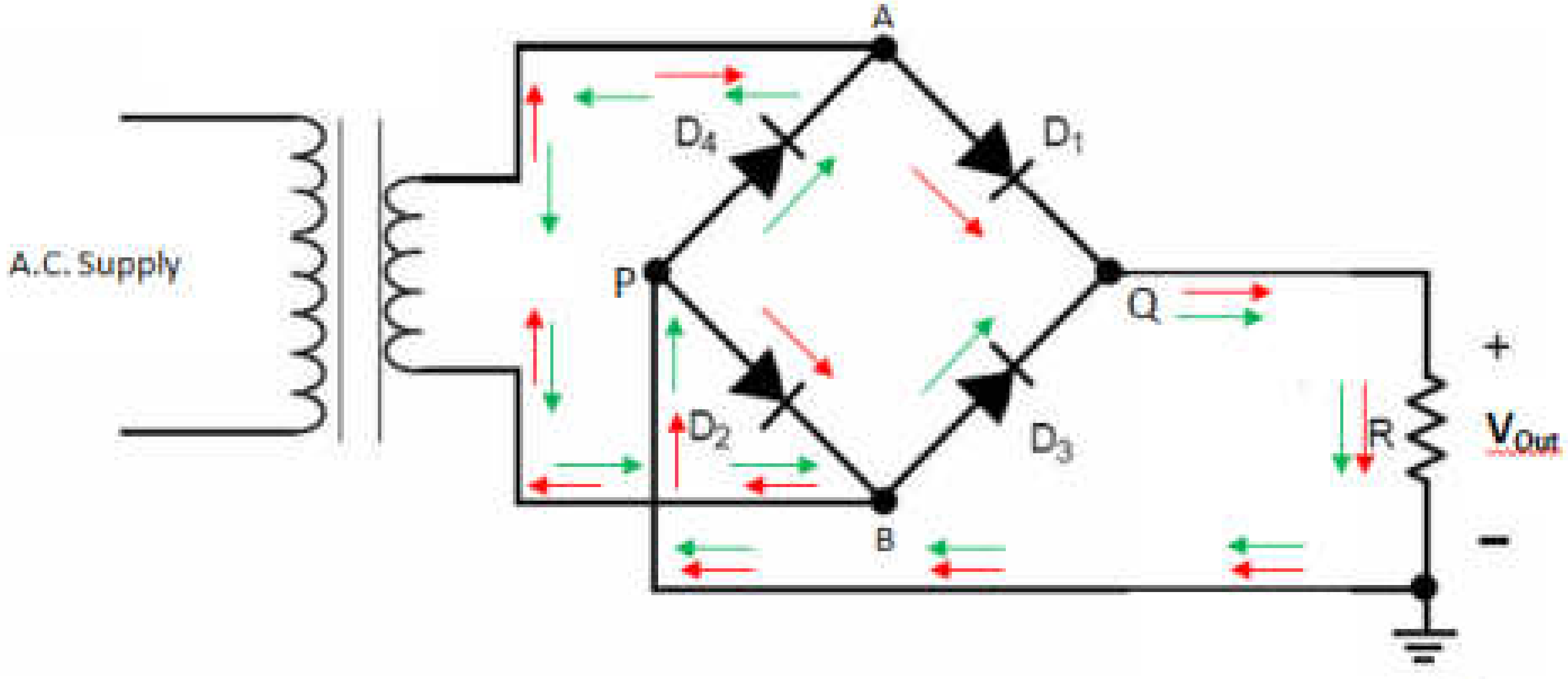


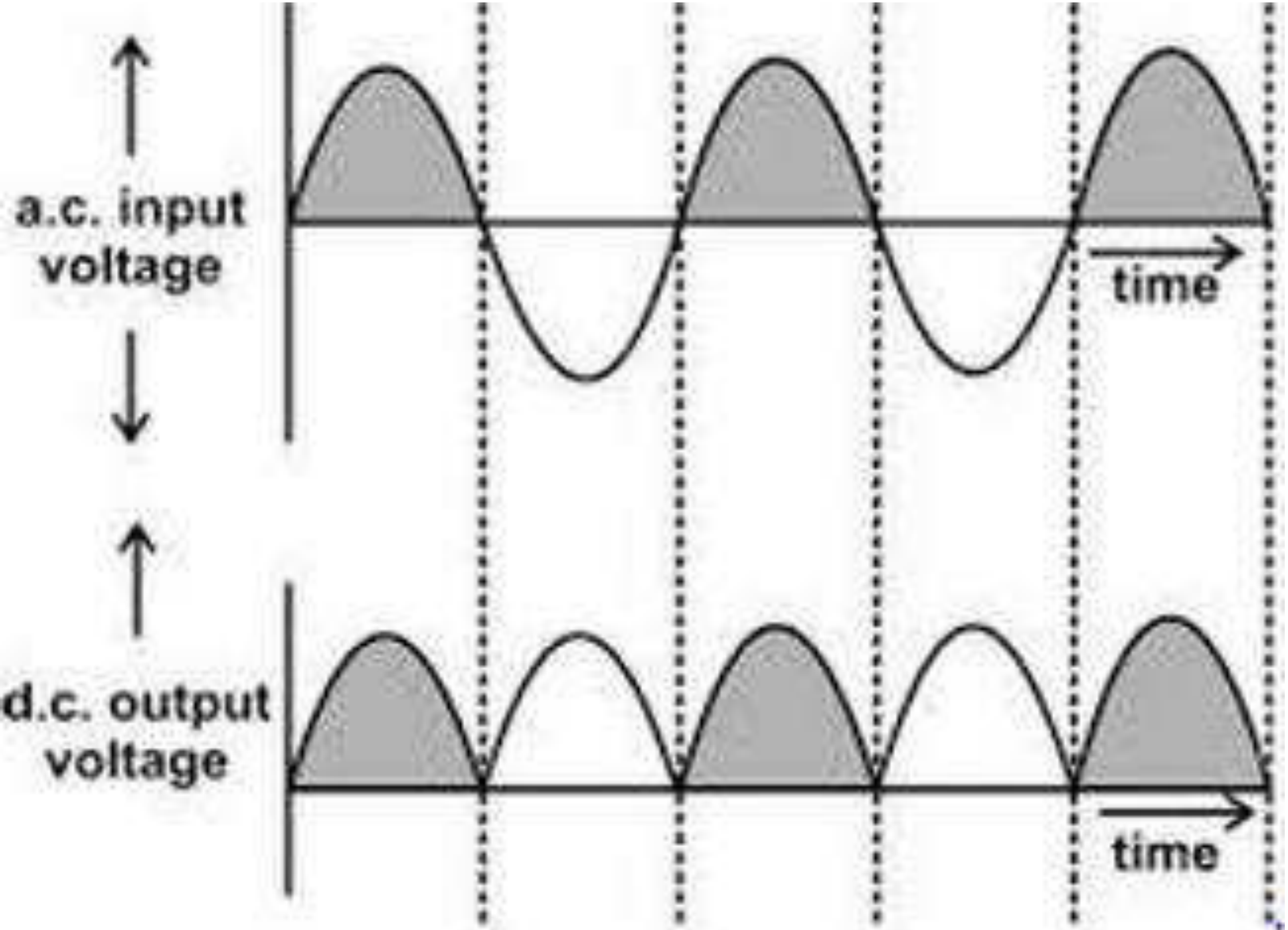


Resultant Output Waveform


a.c. input
voltage
time
d.c. output
voltage
time

Full Wave Rectifier (Bridge)

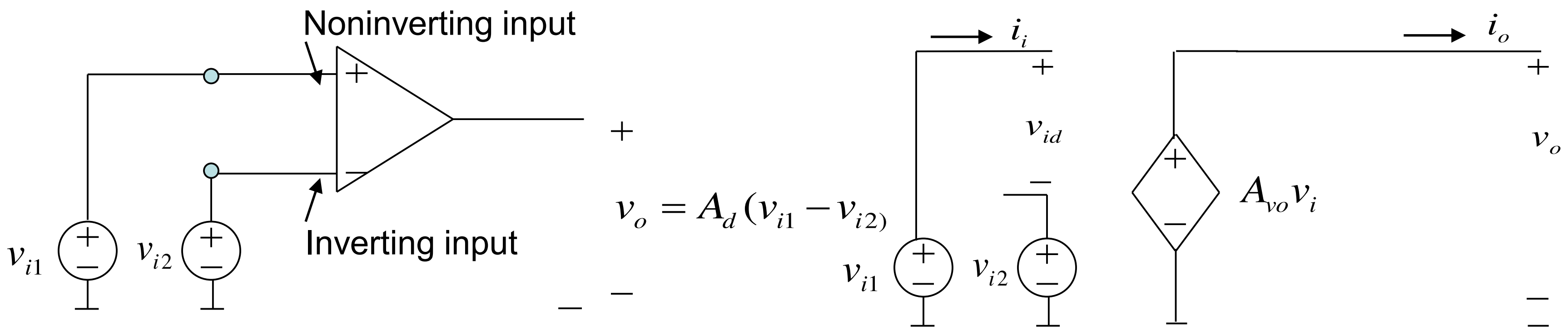




For more detail contact us

Operational amplifier

- Operational amplifier, or simply *OpAmp* refers to an integrated circuit that is employed in wide variety of applications (including voltage amplifiers)



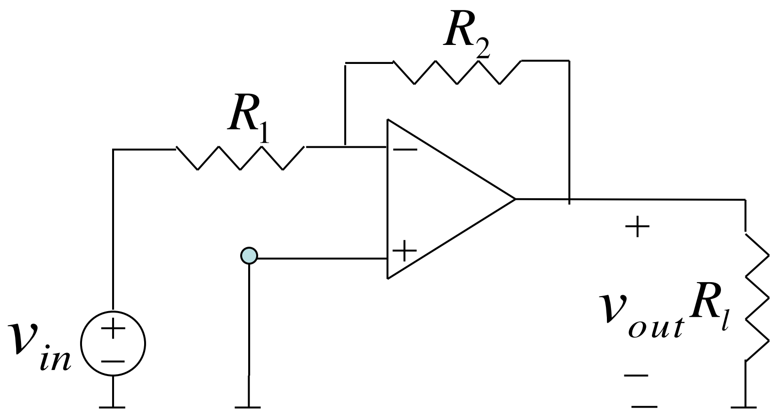
- OpAmp is a differential amplifier having both inverting and non-inverting terminals
- What makes an ideal OpAmp
  - infinite input impedance
  - Infinite open-loop gain for differential signal
  - zero gain for common-mode signal
  - zero output impedance
  - Infinite bandwidth

Summing point constraint

- In a *negative feedback* configuration, the feedback network returns a fraction fo the output to the *inverting input terminal*, forcing the differential input voltage toward zero. Thus, the input current is also zero.
- We refer to the fact that differential input voltage and the input current are forced to zero as the summing point constraint
- Steps to analyze ideal OpAmp-based amplifier circuits
  - Verify that negative feedback is present
  - Assume summing point constraints
  - Apply Kirchhoff’s law or Ohm’s law

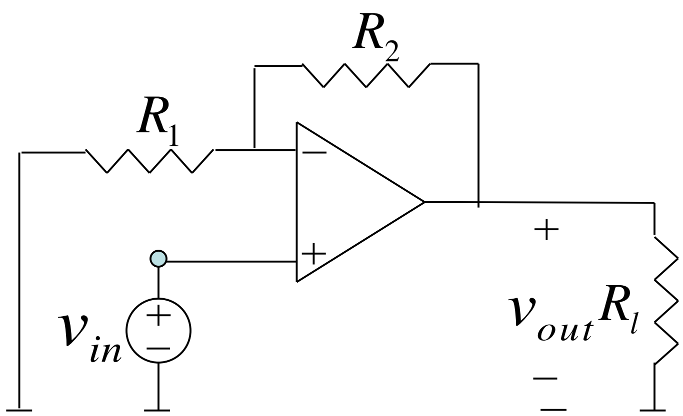
Some useful amplifier circuits

- Inverting amplifier



$$A_v = v_{out} / v_{in} = -R_2 / R_1$$
$$Z_{in} = R_1$$
$$Z_{out} = 0$$

- Noninverting amplifier



$$A_v = v_{out} / v_{in} = 1 + R_2 / R_1$$
$$Z_{in} = \infty$$
$$Z_{out} = 0$$

- Voltage follower if $R_2 = 0$ and R_1 open circuit (unity gain)

Amplifier design using OpAmp

- Resistance value of resistor used in amplifiers are preferred in the range of (1K,1M)ohm (this may change depending on the IC technology). Small resistance might induce too large current and large resistance consumes too much chip area.

OpAmp non-idealities I

- *Nonideal properties in the linear range of operation*
  - ➢ Finite input and output impedance
  - ➢ Finite gain and bandwidth limitation
    - ✓ Generally, the open-loop gain of OpAmp as a function of frequency is

$$A_{ol}(f) = \frac{A_{0ol}}{1 + j(f / f_{bol})}, A_{0ol} \ is \ open - loop \ gain \ at \ DC,$$

$$f_{bol} \ is \ open - loop \ break \ frequency, also \ called \ do\min at \ pole$$

    - ✓ Closed-loop gain versus frequency for non-inverting amplifier

$$A_{cl(f)=} \frac{A_{0cl}}{1 + j(f / f_{bcl})}, \ A_{0cl} = \frac{A_{0ol}}{1 + \beta A_{0ol}}, \ f_{bcl} = f_{bol}(1 + \beta A_{0ol}), \ \beta = \frac{R_1}{R_1 + R_2}$$

    - ✓ Gain-bandwidth product:

$$f_t = A_{0cl} f_{bcl} = A_{0ol} f_{bol}, where \ f_t \ is \ called \ unity - gain \ frequency$$

    - ✓ Closed-loop bandwidth for both non-inverting and inverting amplifier

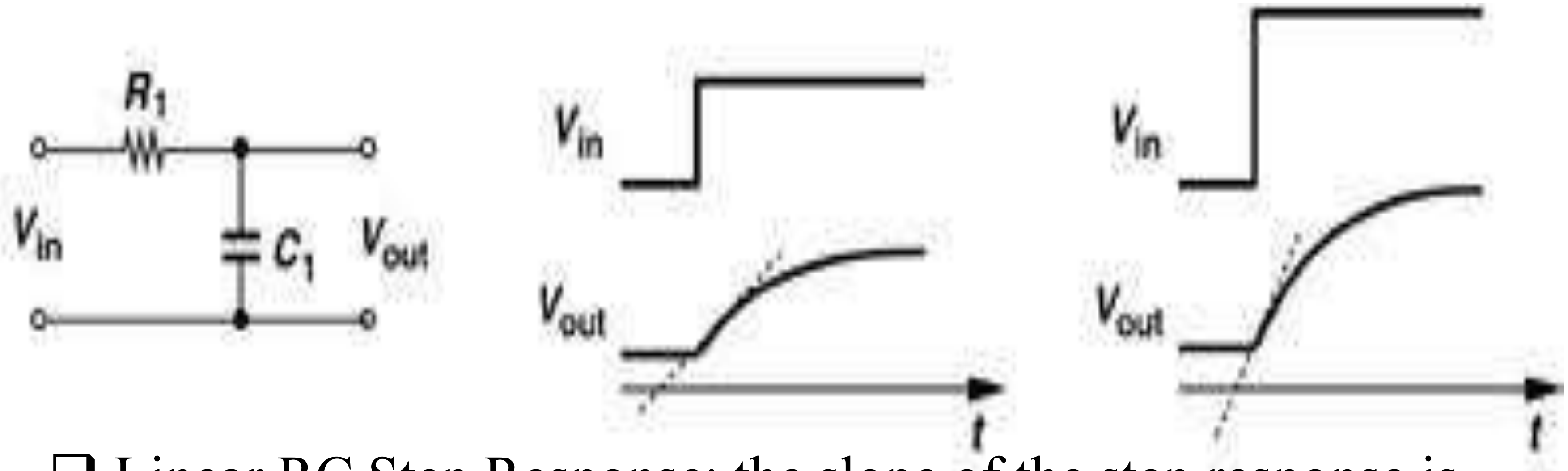
$$f_{bcl} = \frac{f_t}{1 + R_2 / R_1} = \frac{A_{0ol} f_{bol}}{1 + R_2 / R_1}$$

OpAmp non-idealities II

- Output voltage swing: real OpAmp has a maximum and minimum limit on the output voltages
  - OpAmp transfer characteristic is nonlinear, which causes clipping at output voltage if input signal goes out of linear range
  - The range of output voltages before clipping occurs depends on the type of OpAmp, the load resistance and power supply voltage.
- Output current limit: real OpAmp has a maximum limit on the output current to the load
  - The output would become clipped if a small-valued load resistance drew a current outside the limit
- Slew Rate (SR) limit: real OpAmp has a maximum rate of change of the output voltage magnitude
  - limit $\left|\frac{dv_o}{dt}\right| \leq SR$
  - SR can cause the output of real OpAmp very different from an ideal one if input signal frequency is too high
  - Full Power bandwidth: the range of frequencies for which the OpAmp can produce an undistorted sinusoidal output with peak amplitude equal to the maximum allowed voltage output

$$f_{FP} = \frac{SR}{2\pi\, v_{o\max}}$$

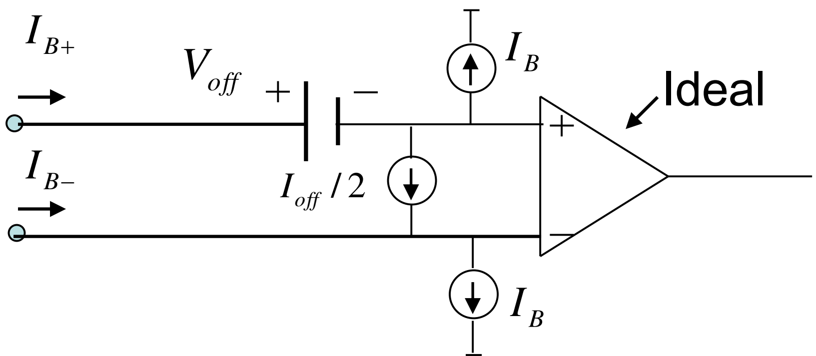
Slew Rate



- Linear RC Step Response: the slope of the step response is proportional to the final value of the output, that is, if we apply a larger input step, the output rises more rapidly.
- If Vin doubles, the output signal doubles at every point, therefore a twofold increase in the slope.
- But the problem in real OpAmp is that this slope can not exceed a certain limit.

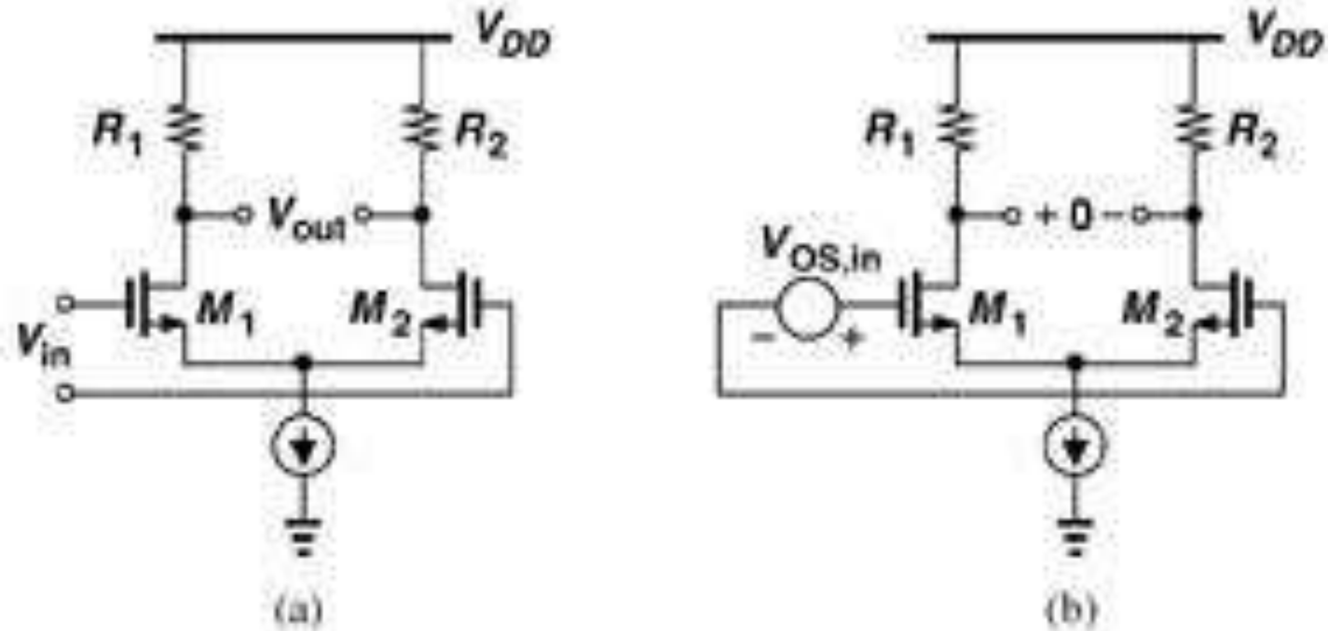
OpAmp non-idealities III

- DC imperfections: *bias current, offset current and offset voltage*
  - bias current I_B : the average of the dc currents flow into the noninverting terminal I_{B+} and inverting terminal I_{B-}, $I_B = 1/2(I_{B+} + I_{B-})$
  - offset current: the half of difference of the two currents, $I_{off} = 1/2(I_{B+} - I_{B-})$
  - offset voltage: the DC voltage needed to model the fact that the output is not zero with input zero, V_{off}
- The three DC imperfections can be modeled using DC current and voltage sources



- The effects of DC imperfections on both inverting and noninverting amplifier is to add a DC voltage to the output. It can be analyzed by considering the extra DC sources assuming an otherwise ideal OpAmp
- It is possible to cancel the bias current effects. For the inverting amplifier, we can add a resistor $R = R_1 // R_2$ to the non-inverting terminal

DC offset of an differential pair

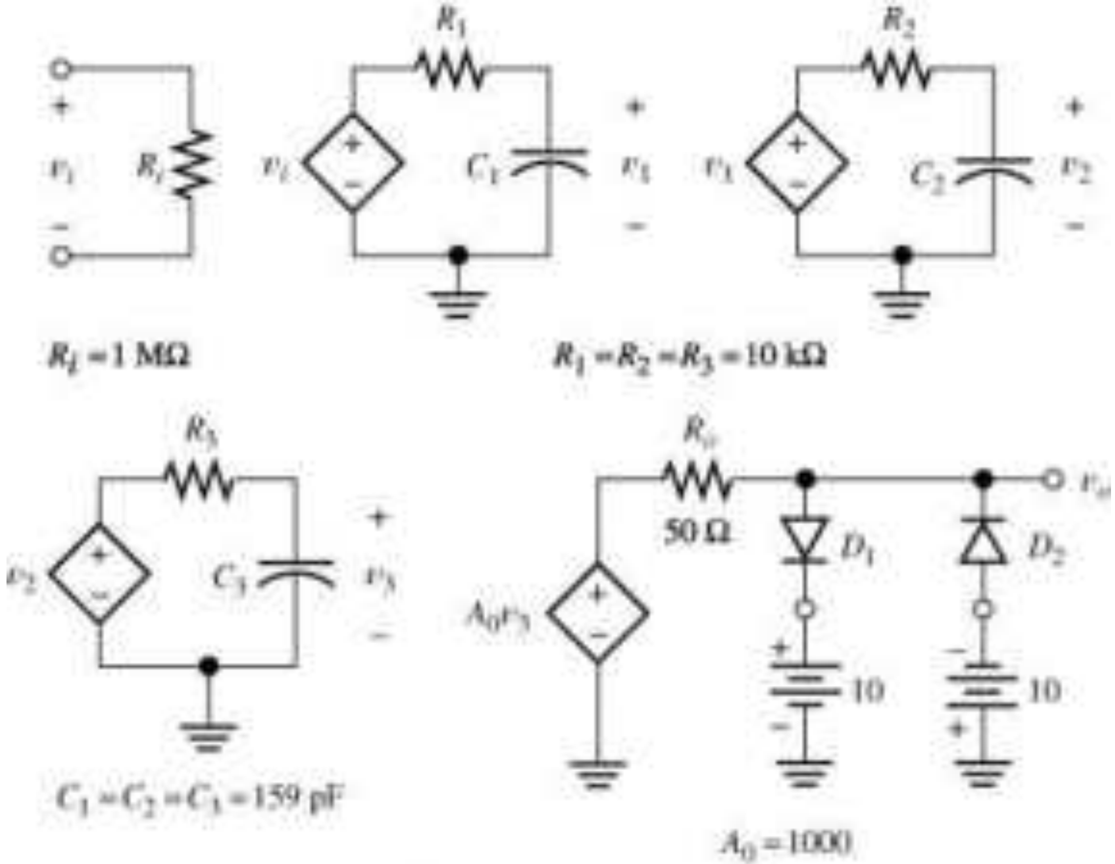


- ❑ When Vin=0, Vout is NOT 0 due to mismatch of transistors in real circuit design.
- ❑ It is more meaningful to specify input-referred offset voltage, defined as Vos,in=Vos,out / A.
- ❑ Offset voltage may causes a DC shift of later stages, also causes limited precision in signal comparison.

Behavioral modeling of OpAmp

❑ Behavioral models is preferred to include as many non-idealities of OpAmp as possible.

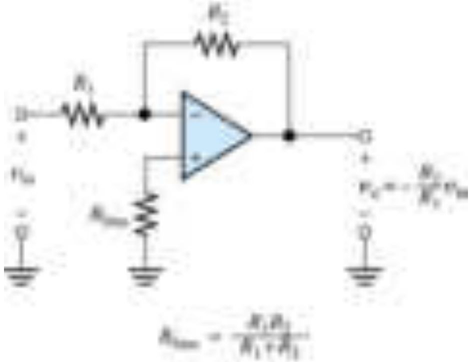
❑ They are used to replace actual physical OpAmp for analysis and fast simulation.



(a) Circuit model of amplifier

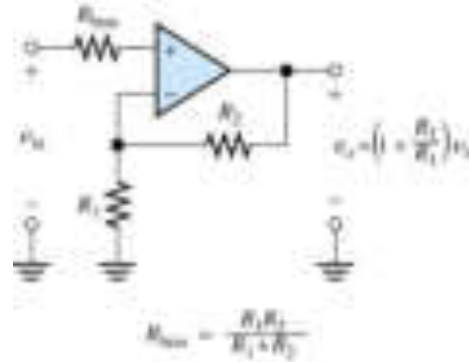
Important amplifier circuits I

- Inverting amplifer



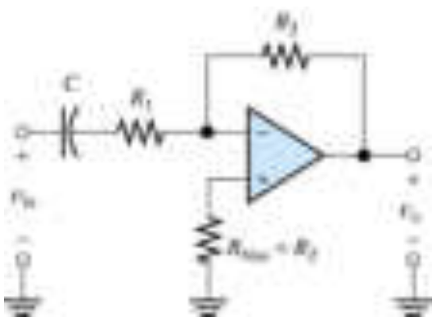
$$A_v = -R_2 / R_1$$
$$Z_{in} = R_1$$
$$Z_{out} = 0$$

- Noninverting amplifier



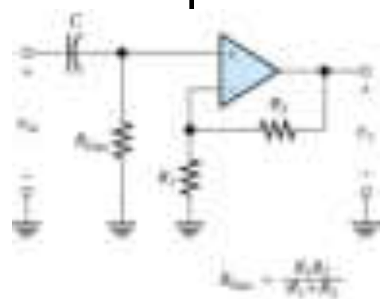
$$A_v = 1 + R_2 / R_1$$
$$Z_{in} = \infty$$
$$Z_{out} = 0$$

- AC-coupled inverting amplifier



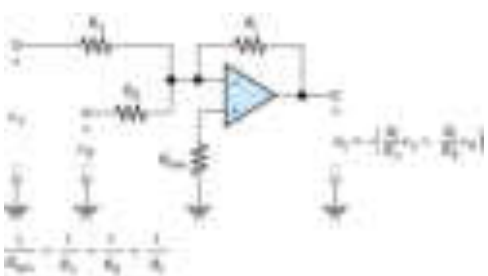
$$A_v = -R_2 / R_1$$
$$Z_{in} = R_1$$
$$Z_{out} = 0$$

- AC-coupled noninverting amplifier



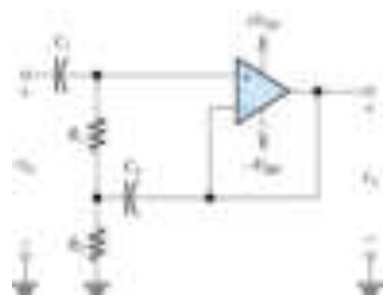
$$A_v = 1 + R_2 / R_1$$
$$Z_{in} = R_{bias}$$
$$Z_{out} = 0$$

- Summing amplifier



$$A_v = -R_f / R_{A/B}$$
$$Z_{in1} = R_A \text{ for } v_A$$
$$Z_{in2} = R_B \text{ for } v_B$$
$$Z_{out} = 0$$

- Bootstrap AC-coupled voltage follower

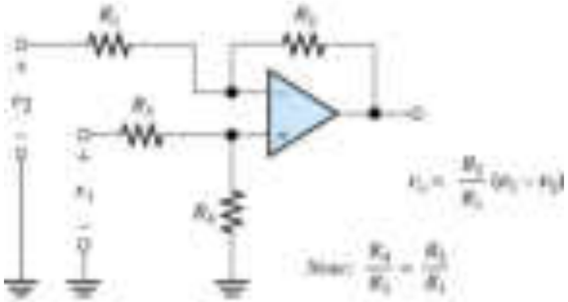


$$A_v = 1$$
$$Z_{in} = \infty$$
$$Z_{out} = 0$$

Graphs from Prentice Hall

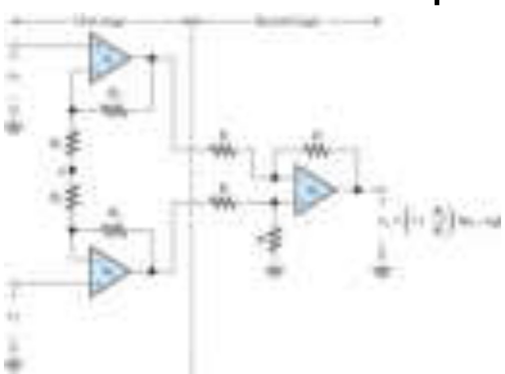
Important amplifier circuits II

- Differential amplifier



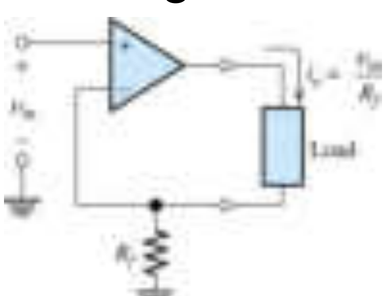
$Z_{in} = R_3 + R_4 \text{ for } v_1$
$Z_{out} = 0$

- Instrumentation qualify Diff Amp



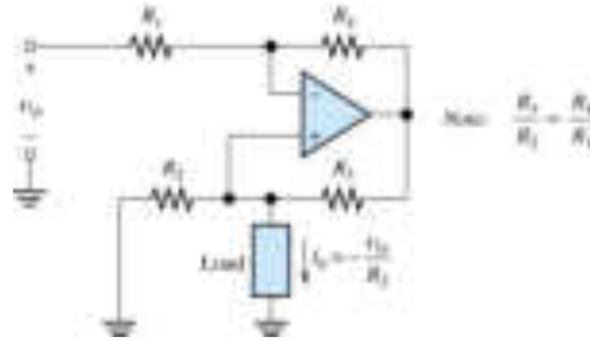
$Z_{in} = \infty$
$Z_{out} = 0$

- Voltage-to-current converter



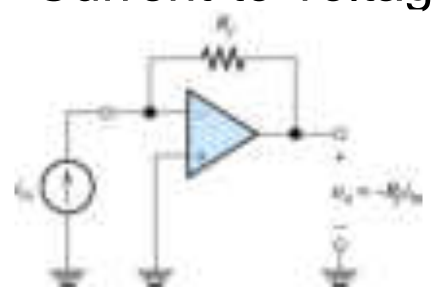
$G_m = i_o / v_{in} = -1/R_f$
$Z_{in} = \infty$
$Z_{out} = \infty$

- Howland voltage-to-current converter for grounded load



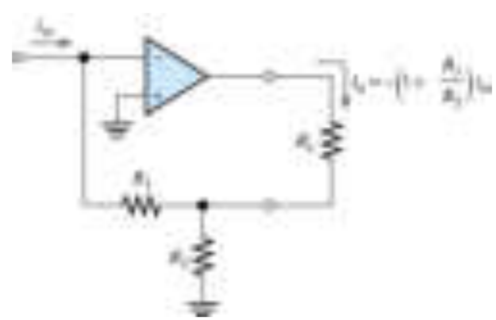
$G_m = -1/R_2$
$Z_{in} = R_1 R_2 /(R_2 + R_L)$
$Z_{out} = \infty$

- Current-to-voltage amplifier



$R_m = -R_f$
$Z_{in} = 0$
$Z_{out} = 0$

- Current amplifier

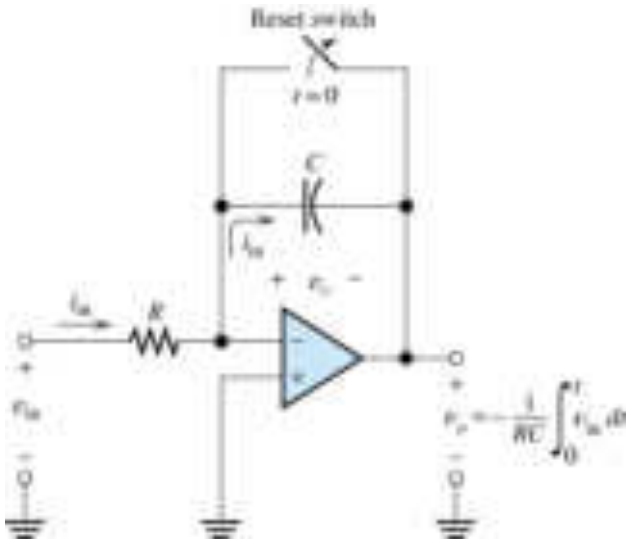


$A_{vi} = -(1 + R_2 / R_1)$
$Z_{in} = 0$
$Z_{out} = \infty$

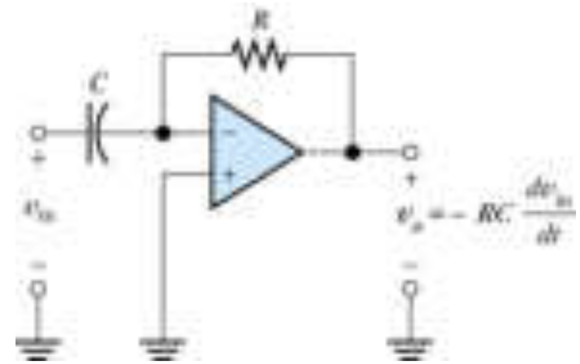
Graphs from Prentice Hall

Important amplifier circuits III

- Integrator circuit: produces an output voltage proportional to the running time integral of the input signal



- Differentiator circuit: produces an output proportional to the time derivative of the input voltage



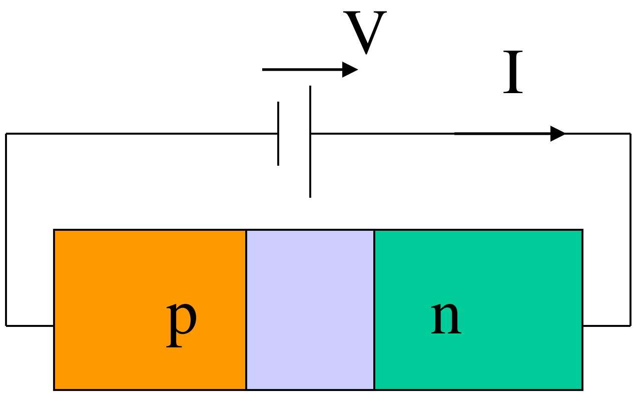
Graphs from Prentice Hall

Bipolar Junction transistor

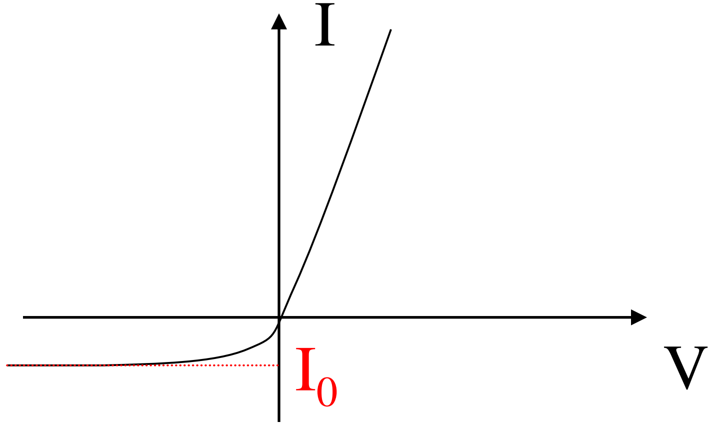
Holes and electrons
determine device characteristics

Three terminal device
⇒
Control of two terminal currents

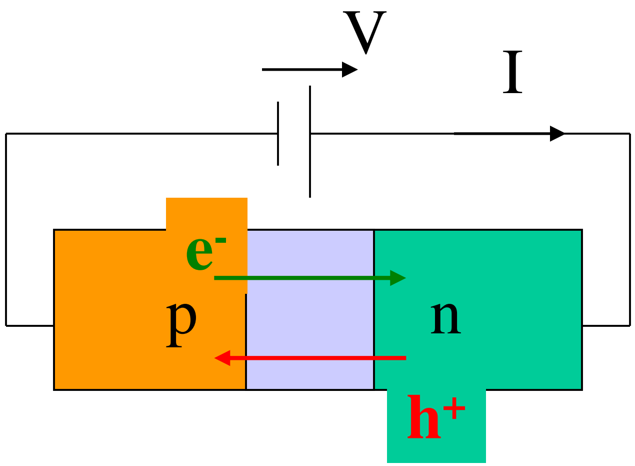
How can we make a BJT from a pn diode?

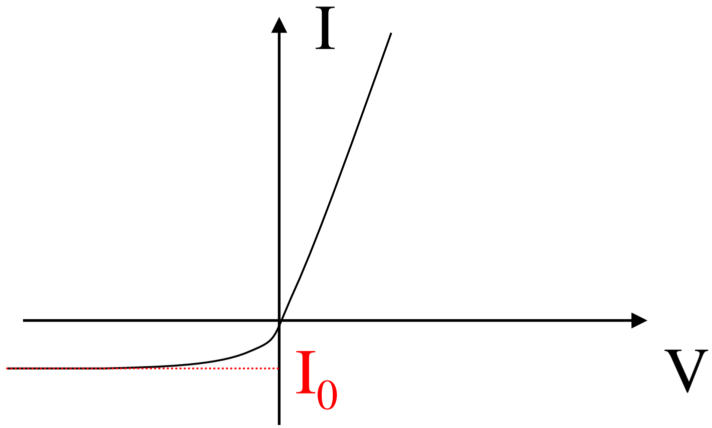


- Take pn diode
- Remember reverse bias characteristics
- Reverse saturation current: I_0



How can we make a BJT from a pn diode?





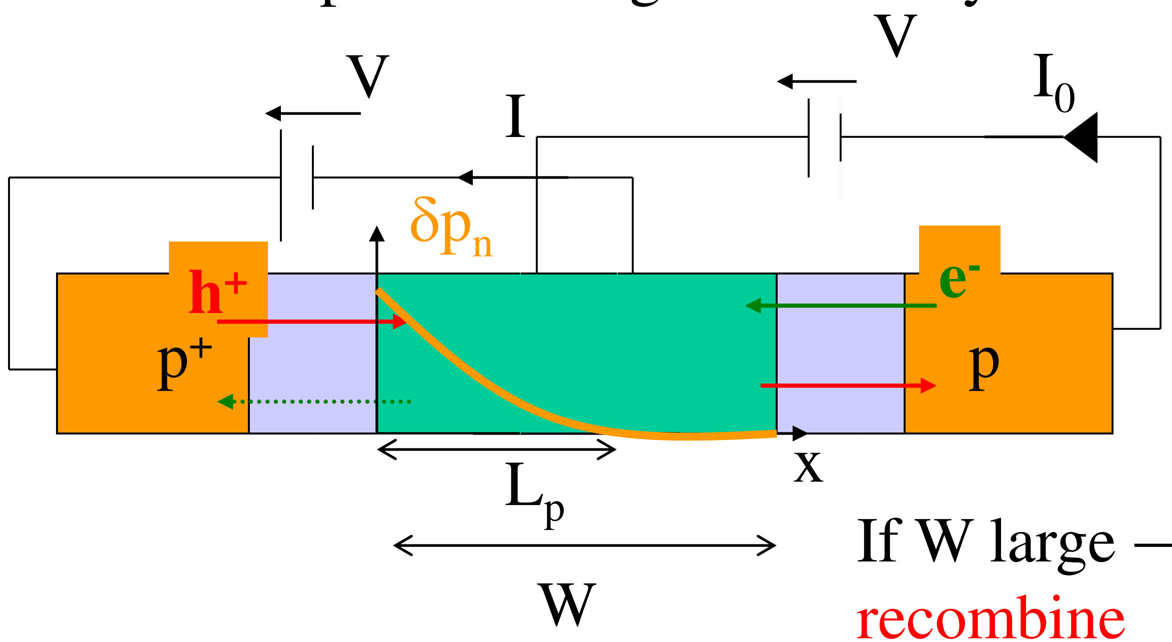
- Take pn diode
- Remember reverse bias characteristics
- Reverse saturation current: I_0
  Caused by minority carriers swept across the junction
- n_p and p_n low

  → I_0 small

Thus:

A forward biased p^+n diode is a good hole injector

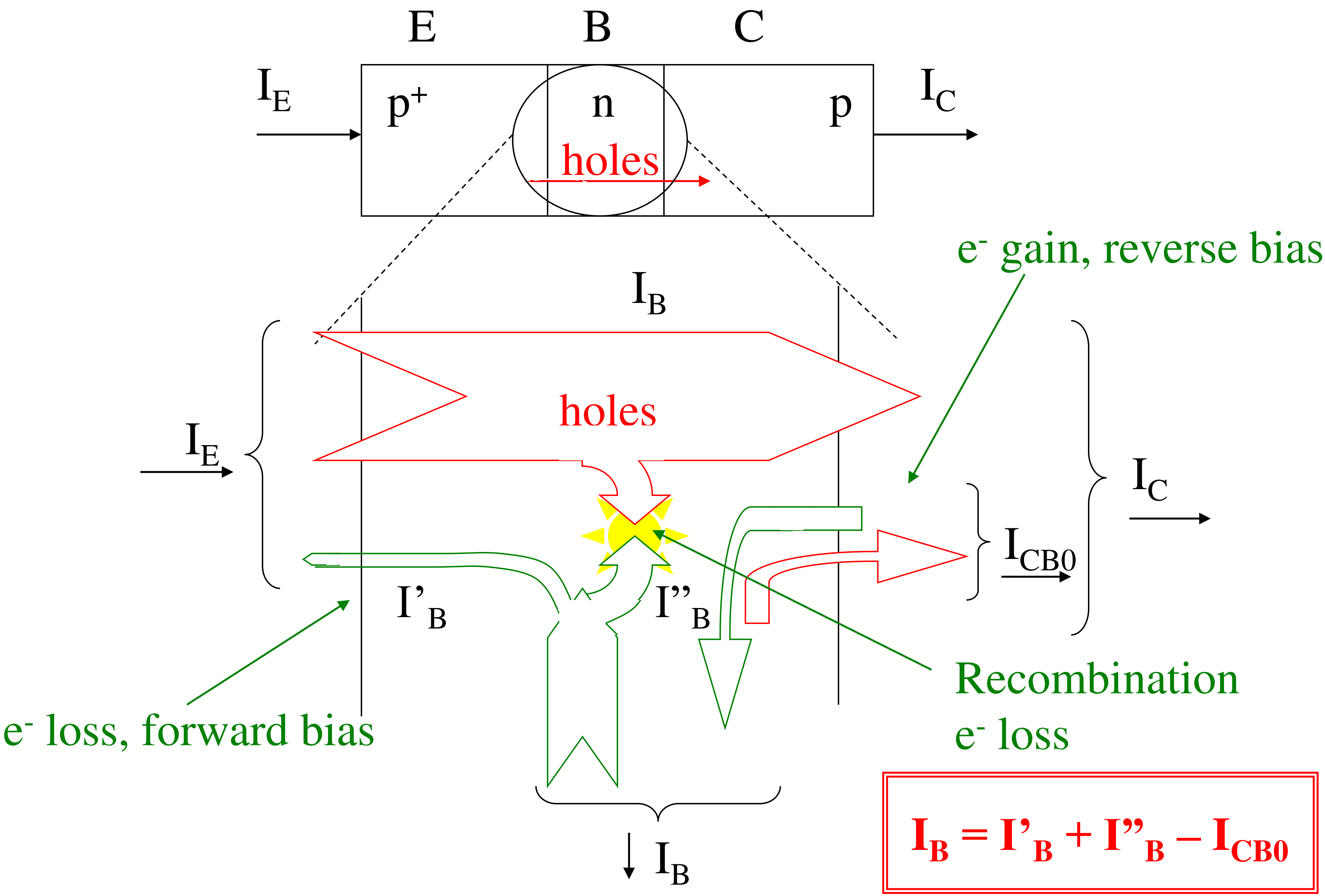
A reverse biased np diode is a good minority carrier collector



If W large → holes recombine

Excess hole concentration reduces exponentially in W to some small value.

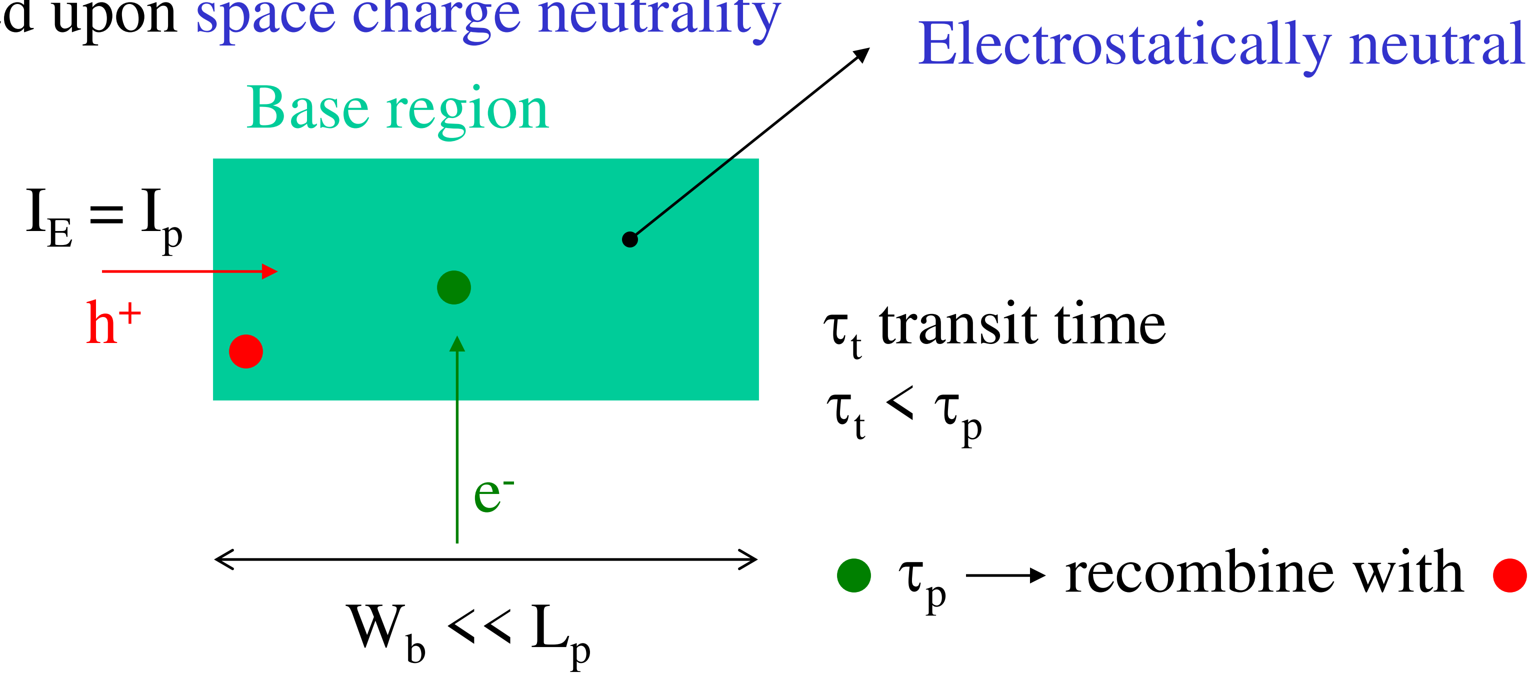
Carrier flow in BJTs



$$I_B = I'_B + I''_B - I_{CB0}$$

Control by base current : ideal case.

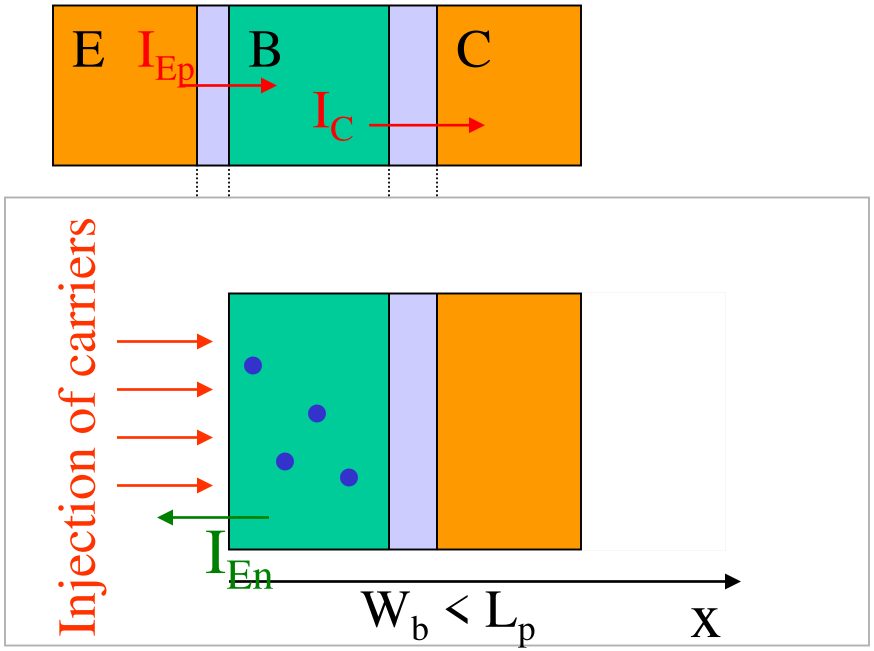
Based upon space charge neutrality



Based on the given timescales, holes can pass through the narrow base before a supplied electron recombines with one hole: $i_c/i_b = \tau_p/\tau_t$

The electron supply from the base contact controls the forward bias to ensure charge neutrality!

How good is the transistor?



- Wish list:
- $I_{Ep} >> I_{En}$
  or $\gamma = I_{Ep}/(I_{En} + I_{Ep}) \approx 1$
  γ: emitter injection efficiency
- $I_C \approx I_{Ep}$
  or $B = I_C/I_{Ep} \approx 1$
  B: base transport factor
  or $\alpha = I_C/I_E \approx 1$
  α: current transfer ratio
- $I_B \approx I_{En} + (1\text{-}B)\, I_{Ep}$
  thus $\beta = I_C/I_B = \alpha/(1-\alpha)$
  β: current amplification factor

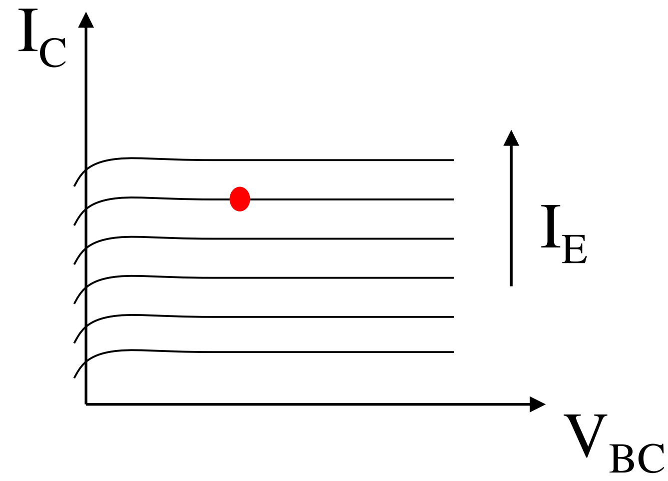
No amplification!

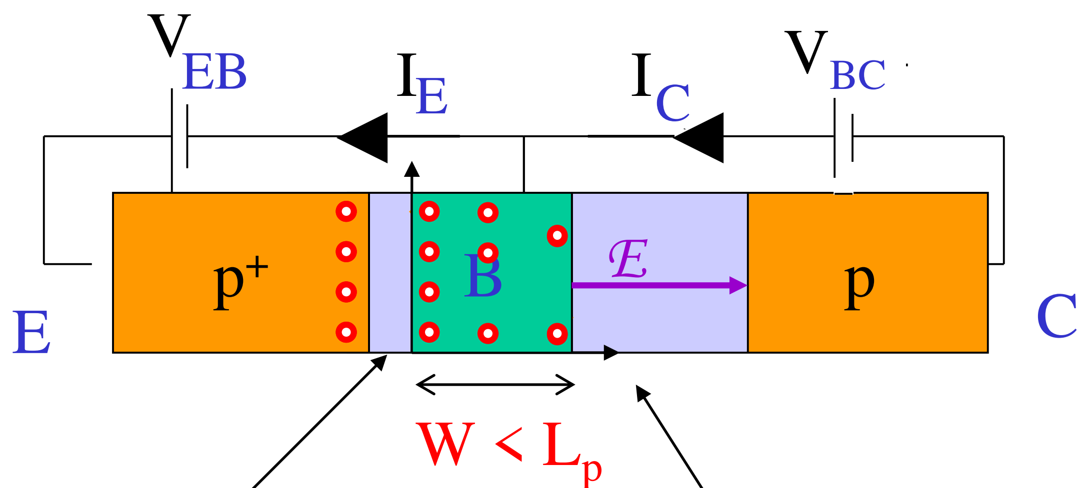
Amplification!

I_{CB0} ignored

Review 1 – BJT basics

Forward active mode (ON)



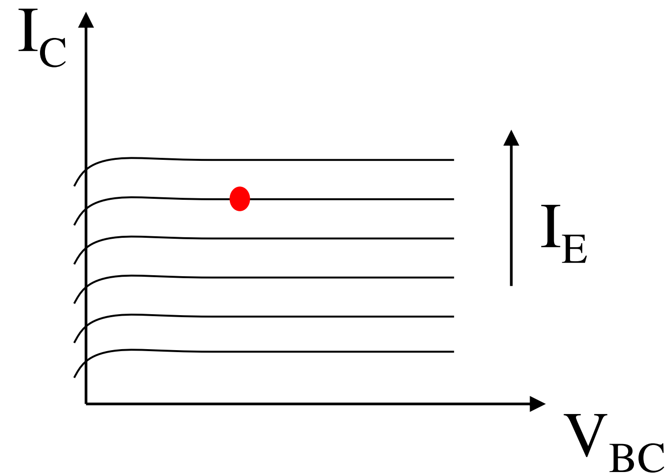


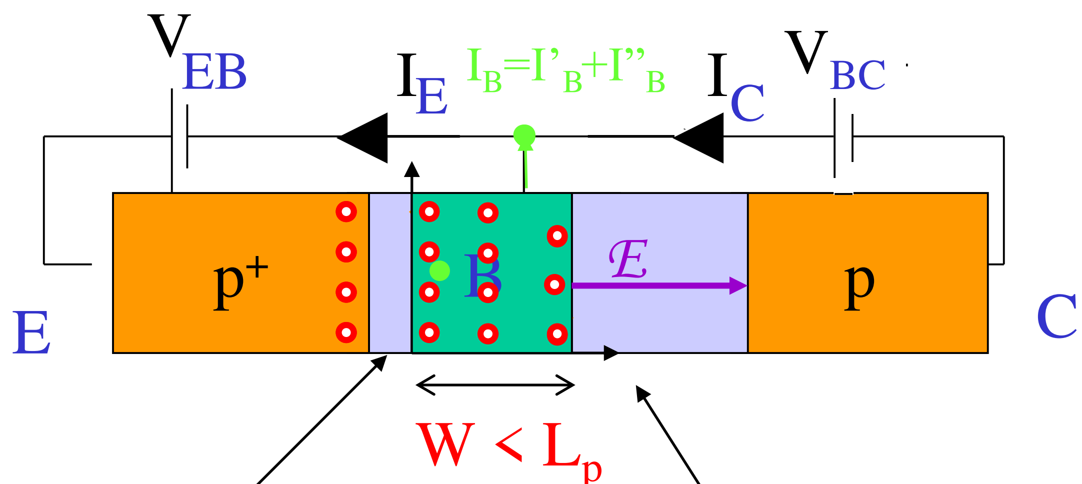
Forward biased p^+n junction is a hole injector

Reverse biased np junction is a hole collector

Review 1 – BJT basics

Forward active mode (ON)





Forward biased p^+n junction is a hole injector

Reverse biased np junction is a hole collector

Review 2

Amplification?

$$\mathbf{I_B = I'_B + I''_B - I_{CB0}}$$

Recombination only case: $\mathbf{I'_B}$, $\mathbf{I_{CB0}}$ negligible

$i_c/i_b = \tau_p/\tau_t$

$\beta = \tau_p/\tau_t$

Carriers supplied by the base current stay much longer in the base: τ_p than the carriers supplied by the emitter and travelling through the base: τ_t.

But in more realistic case: $\mathbf{I'_B}$ is not negligible

$\beta = I_C/I_B$

With I_B electrons supplied by base = $I'_B = I_n$
I_C holes collected by the collector = I_p

Currents?

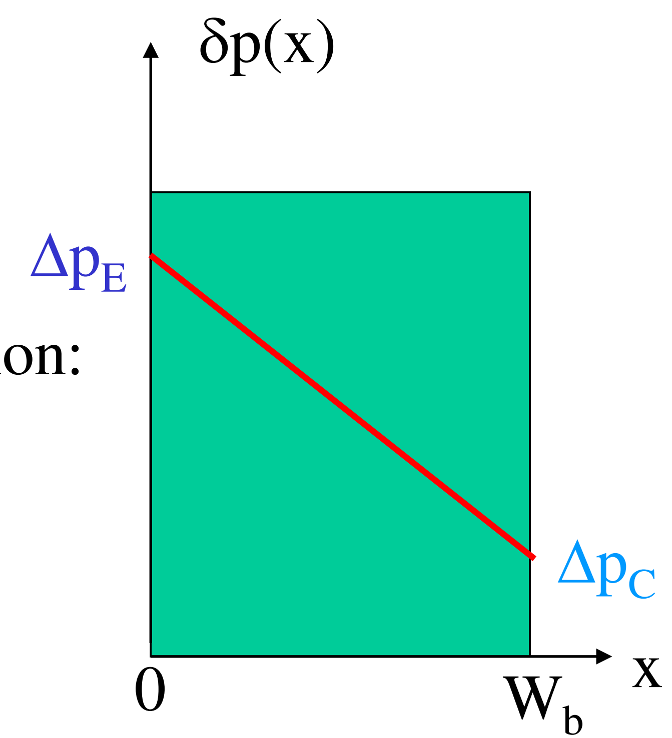
- In order to calculate currents in pn junctions, knowledge of the variation of the minority carrier concentration is required in each layer.
- The current flowing through the base will be determined by the excess carrier distribution in the base region.
- Simple to calculate when the short diode approximation is used: this means *linear variations* of the minority carrier distributions in all regions of the transistor. (recombination neglected)
- Complex when recombination in the base is also taken into account: then *exponential* based minority carrier concentration in base.

Narrow base: no recombination: I_p

→ minority carrier density gradient in the base

$\Delta p_E = p_{n0}(e^{eV_{EB}/kT} - 1) \approx p_{n0}\, e^{eV_{EB}/kT}$

$\Delta p_C = p_{n0}(e^{-e|V_{BC}|/kT} - 1) \approx -p_{n0}$



Linear variation of excess carrier concentration:

$$\delta p(x) = Ax + B$$

$$A = \frac{\Delta p_E - \Delta p_C}{-W_b} \approx -\frac{\Delta p_E}{W_b}$$

$$B = \Delta p_E + \Delta p_C \approx \Delta p_E$$

$$\delta p(x) = \Delta p_E \left(1 - \frac{x}{W_b}\right)$$

Note: no recombination

Collector current: I_p

Diffusion current: $I_p = -eAD_p \dfrac{d\delta p(x)}{dx}$

$$\frac{d\delta p(x)}{dx} = -\frac{\Delta p_E}{W_b}$$

Hole current: $I_p = eAD_p \dfrac{\Delta p_E}{W_b} = \dfrac{eAD_p p_{n_0} e^{\left(\frac{eV_{EB}}{kT}\right)}}{W_b}$

Collector current $I_C = I_p$ No recombination, thus all injected holes across the BE junction are collected.

Base current??

Emitter current

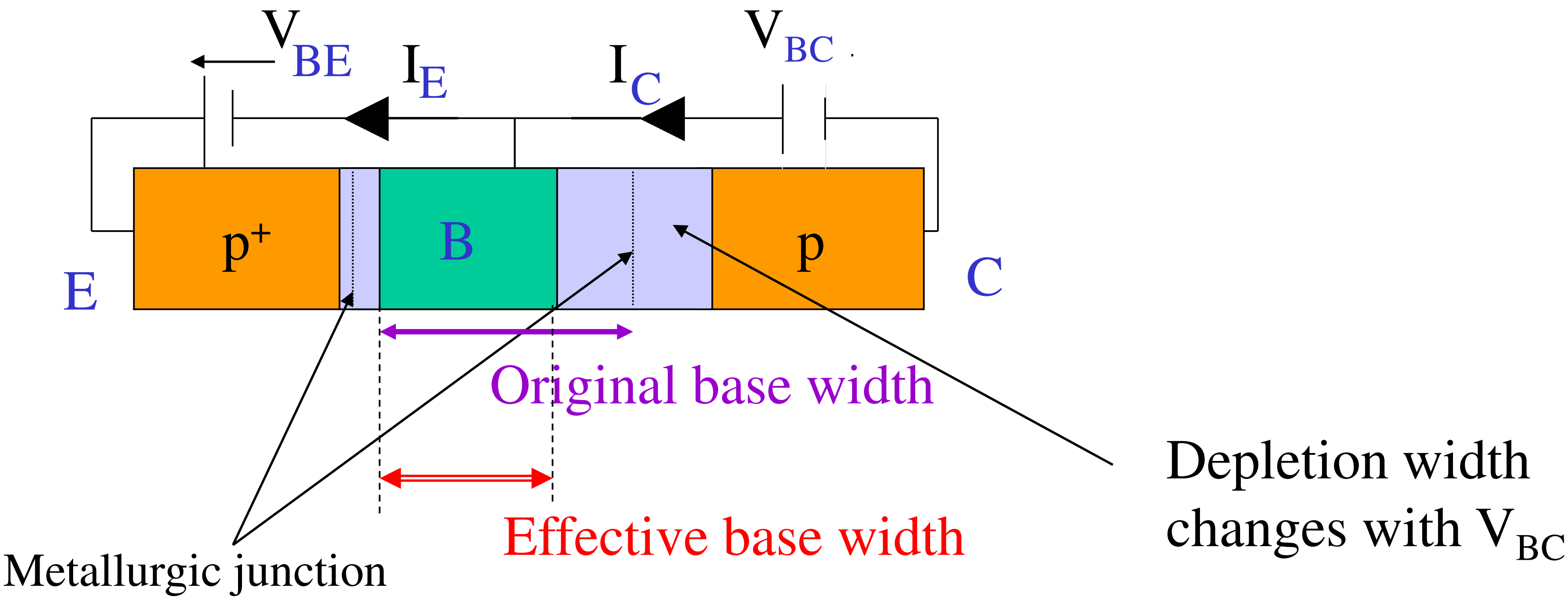
The emitter current is the total current flowing through the base emitter contact since $I_E=I_C+I_B$ (current continuity)

Emitter current: $$I_E = I_n + I_p = eA\left(\frac{D_n n_{p_0}}{x_e} + \frac{D_p p_{n_0}}{W_B}\right)e^{\left(\frac{eV_{EB}}{kT}\right)}$$

Current gain: $$\beta = \frac{I_C}{I_B} = \frac{I_p}{I_n} = \frac{D_p p_{n_0} x_e}{D_n n_{p_0} W_b}$$

Non-ideal effects in BJTs

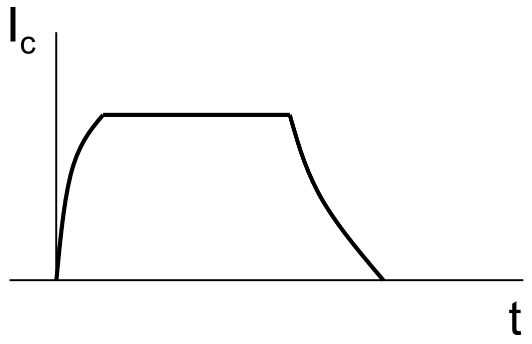
- Base width modulation

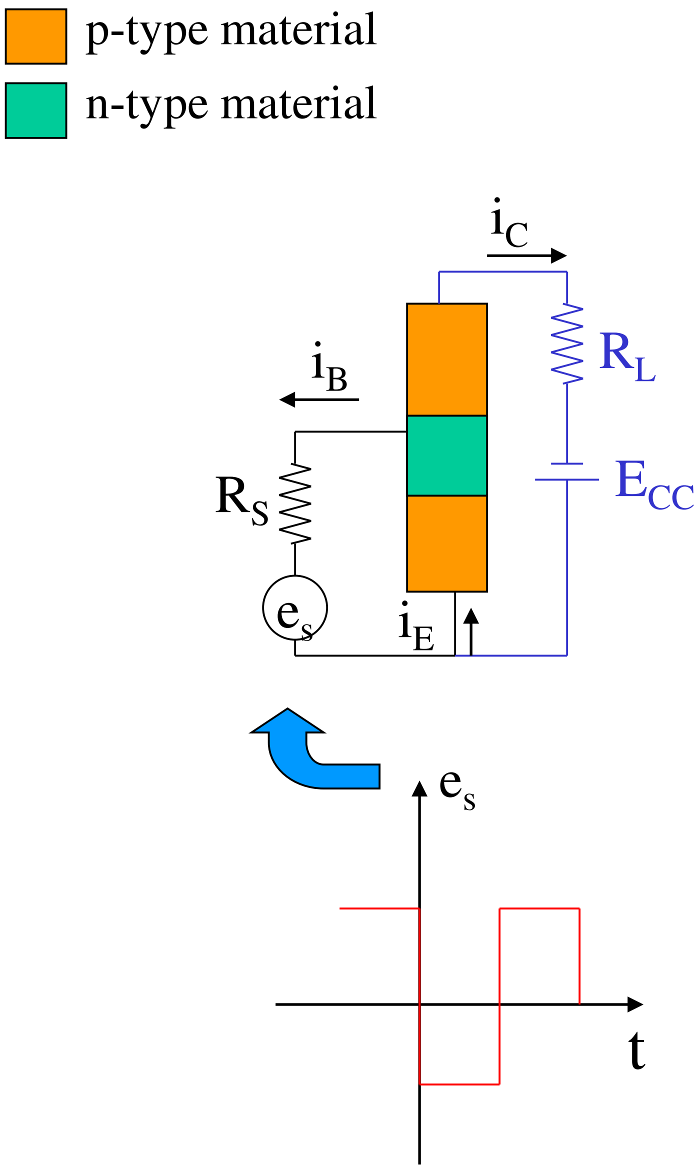


Conclusions

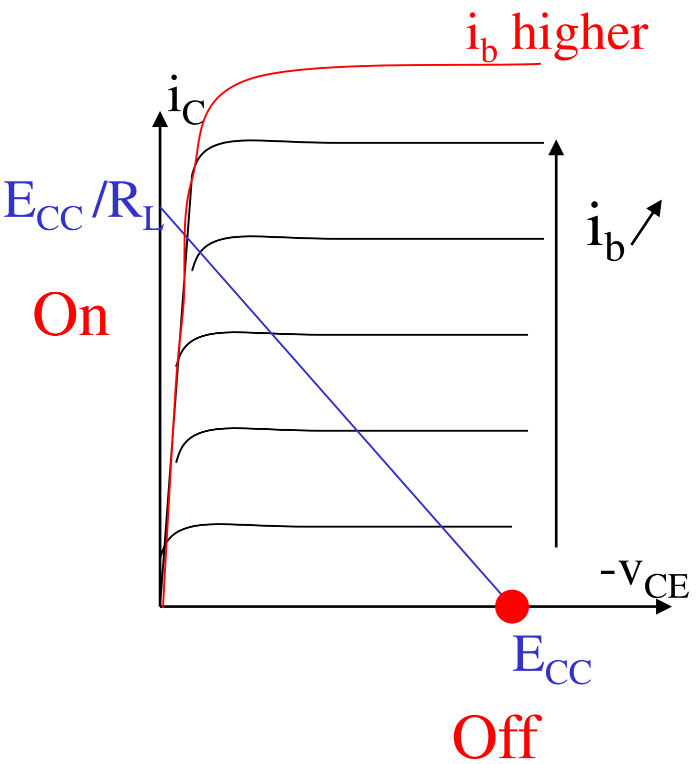
- Characteristics of bipolar transistors are based on diffusion of minority carriers in the base.
- Diffusion is based on excess carrier concentrations:
  - $\delta p(x)$
- The base of the BJT is very small:
  - $\delta p(x) = C_1\, e^{x/L_p} + C_2\, e^{-x/L_p}$
- Base width modulation changes output impedance of BJT.

Transistor switching

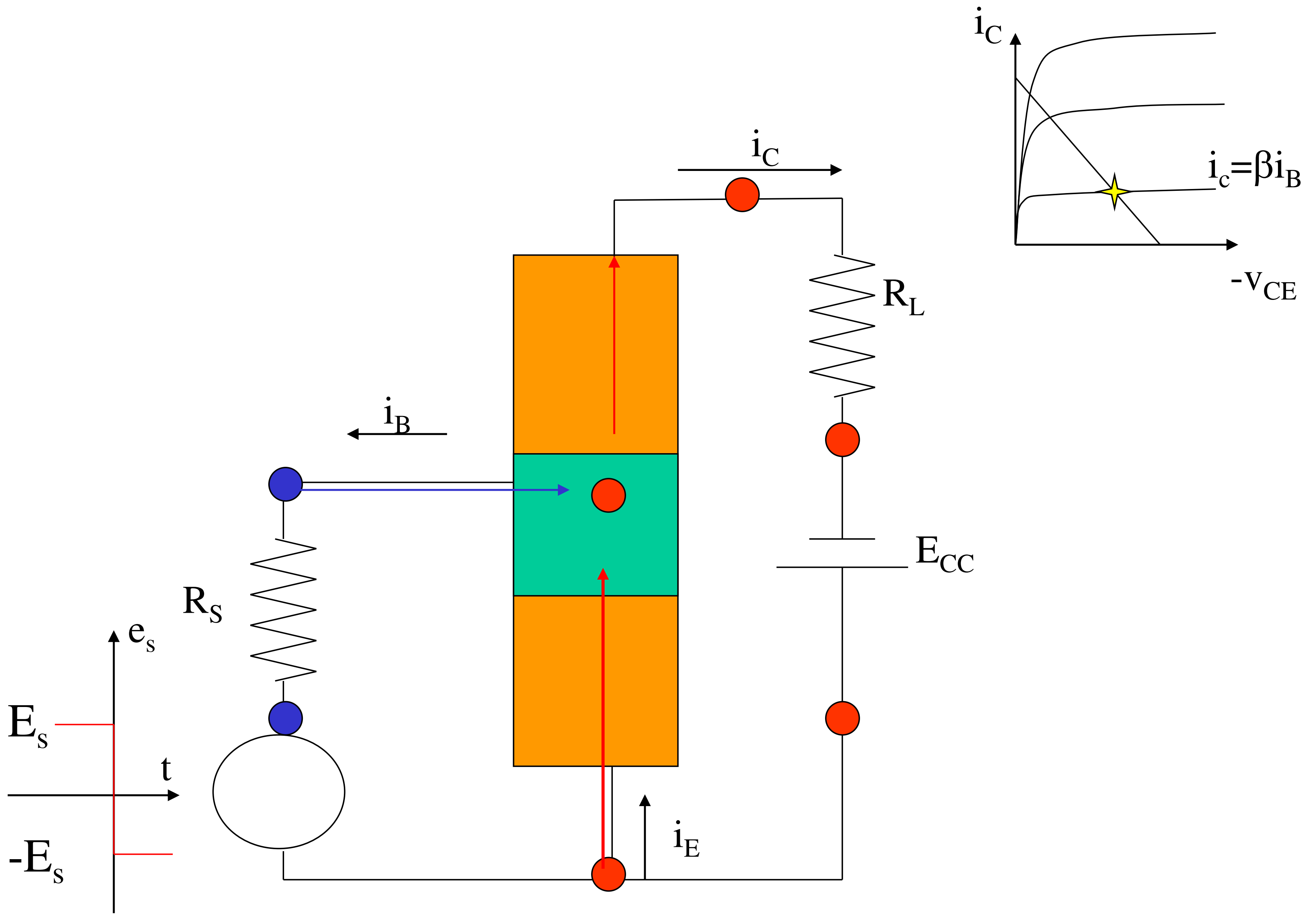




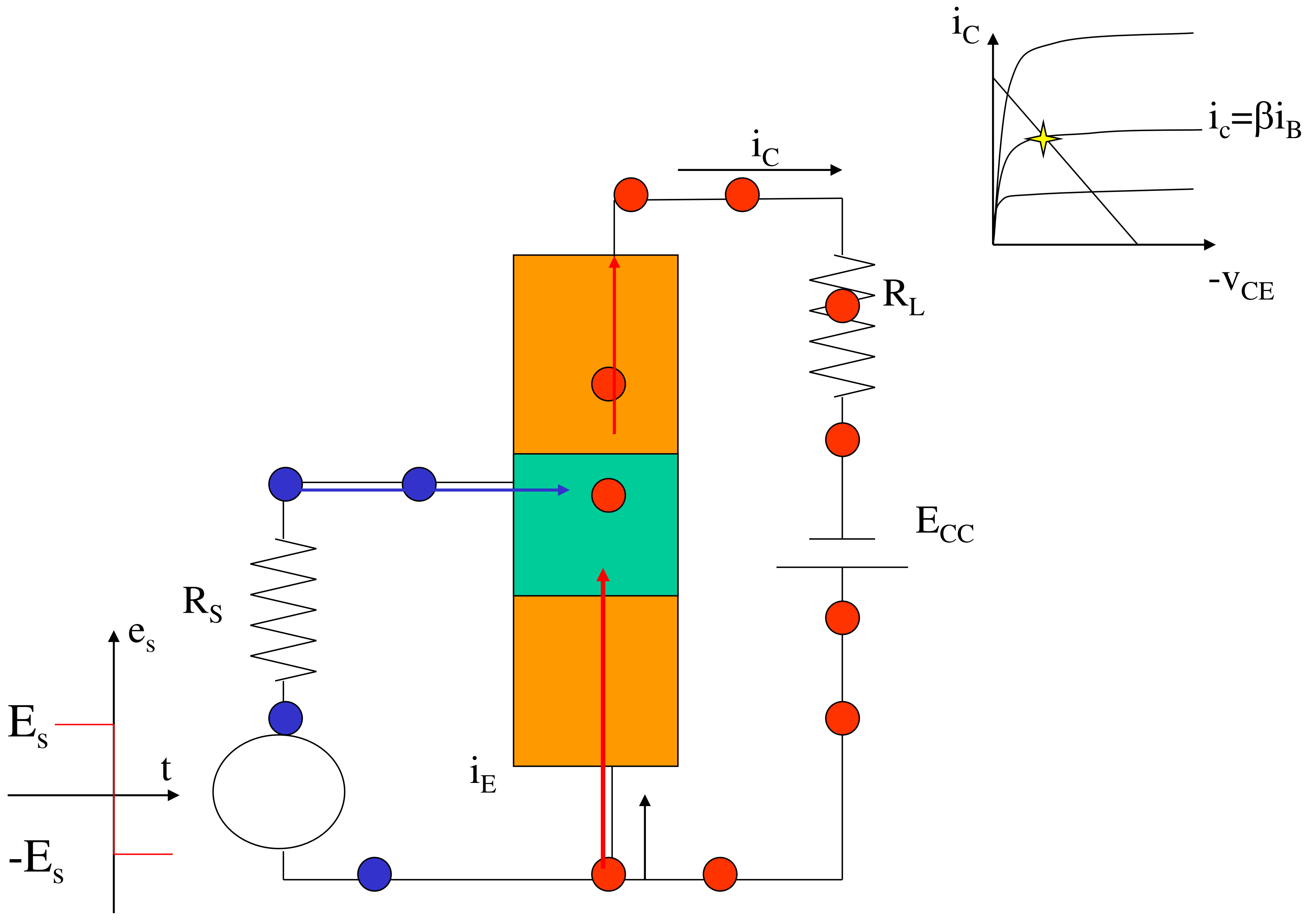
p-type material
n-type material
i_C
i_B
R_L
E_{CC}
R_S
e_s
i_E
e_s
t



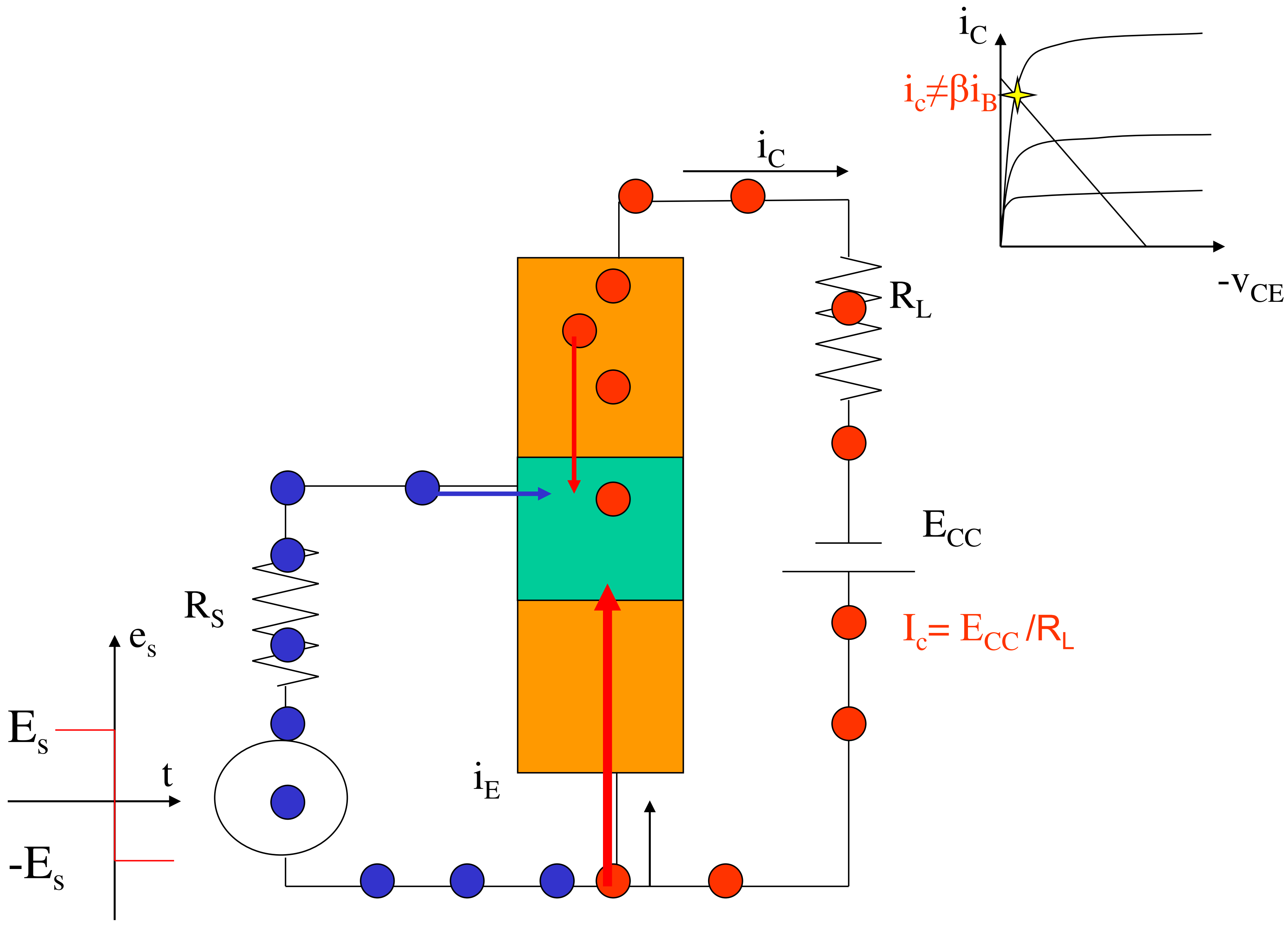
i_b higher
i_C
E_{CC} /R_L
i_b
On
$-v_{CE}$
E_{CC}
Off



i_C
$-v_{CE}$
$i_c=\beta i_B$
i_C
R_L
i_B
E_{CC}
R_S
e_s
E_s
t
$-E_s$
i_E

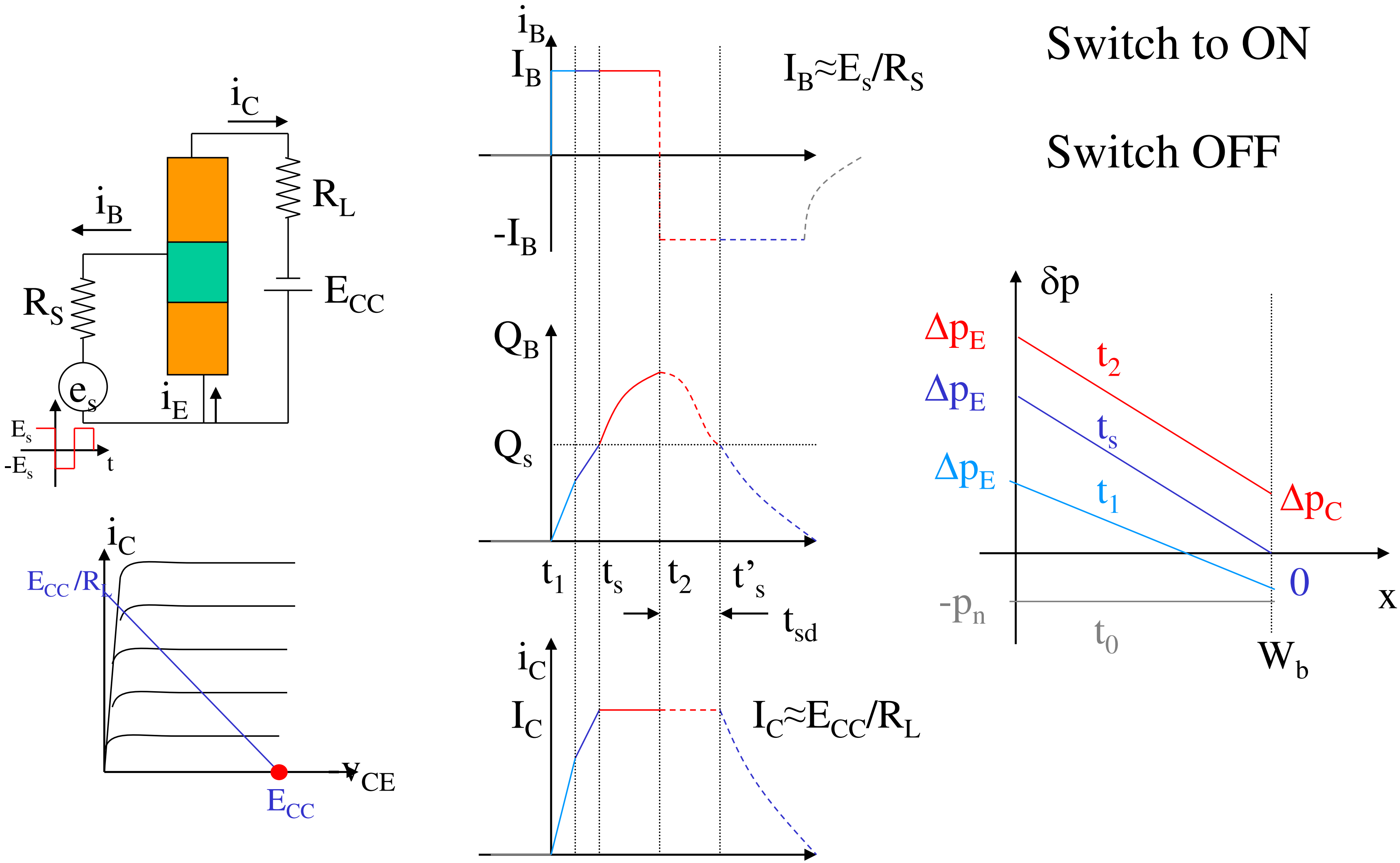


iC
ic=βiB
-vCE
iC
RL
ECC
RS
es
Es
t
-Es
iE



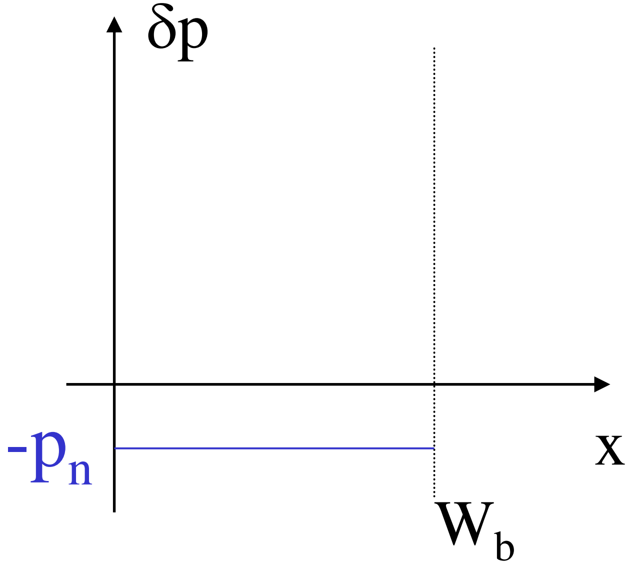
i_C
$i_c \neq \beta i_B$
$-v_{CE}$
i_C
R_L
E_{CC}
$I_c = E_{CC}/R_L$
R_S
e_s
E_s
t
$-E_s$
i_E

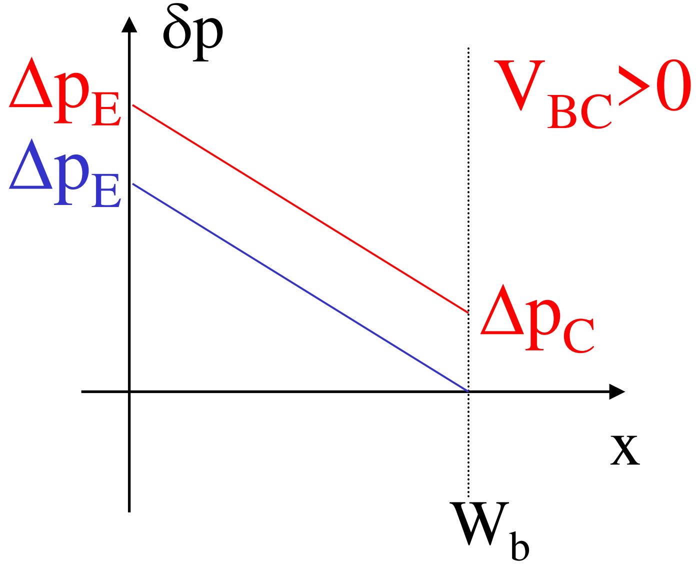
Switching cycle



Charge in base (linear)

- Cut-off
  - $V_{EB}<0$ & $V_{BC}<0$
  - $\Delta p_E = -p_n$ & $\Delta p_C = -p_n$
- Saturation
  - $V_{EB}>0$ & $V_{BC}\geq 0$
  - $\Delta p_E = p_n\,(e^{eV_{EB}/kT} - 1)$
  - $\Delta p_C = 0$ ($V_{BC}=0$)





Currents - review.

forward active mode

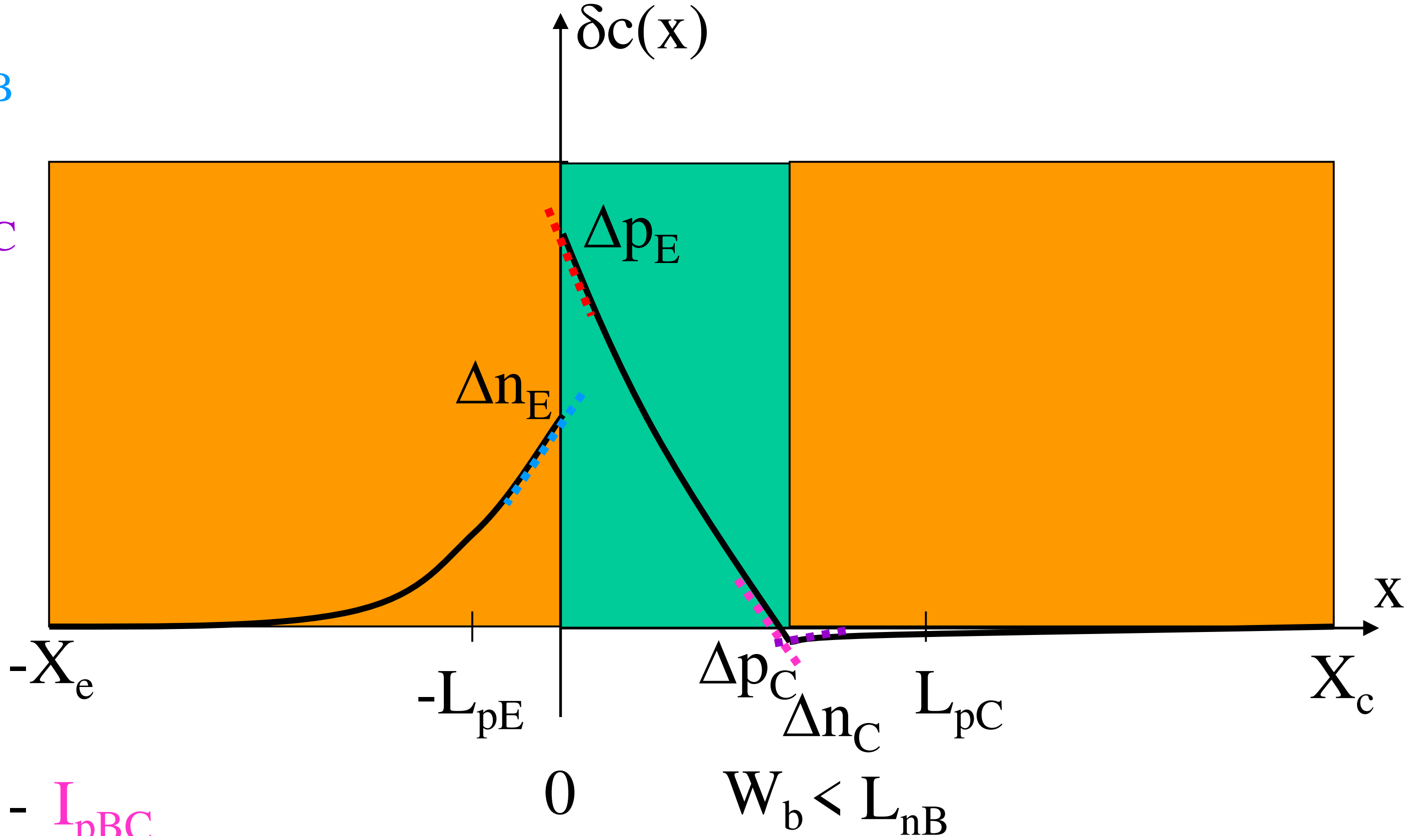
$$I_E = I_{pEB} + I_{nEB}$$

$$I_C = I_{pBC} + I_{nBC}$$

$$I_C \approx I_{pBC}$$

$$I_E = I_B + I_C$$

$$I_B = I_E - I_C$$

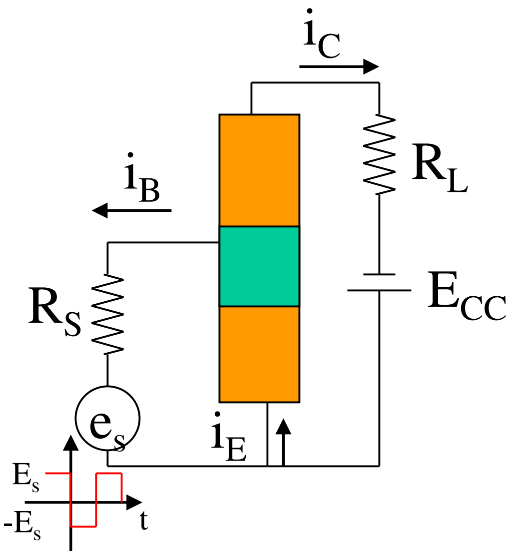


$$I_B = I_{nEB} + \underbrace{I_{pEB} - I_{pBC}}_{\text{Term due to recombination}}$$

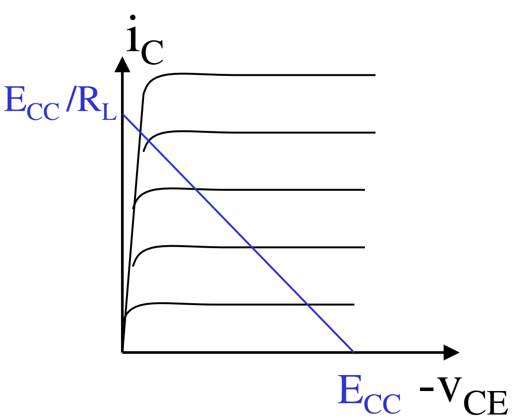
Term due to recombination

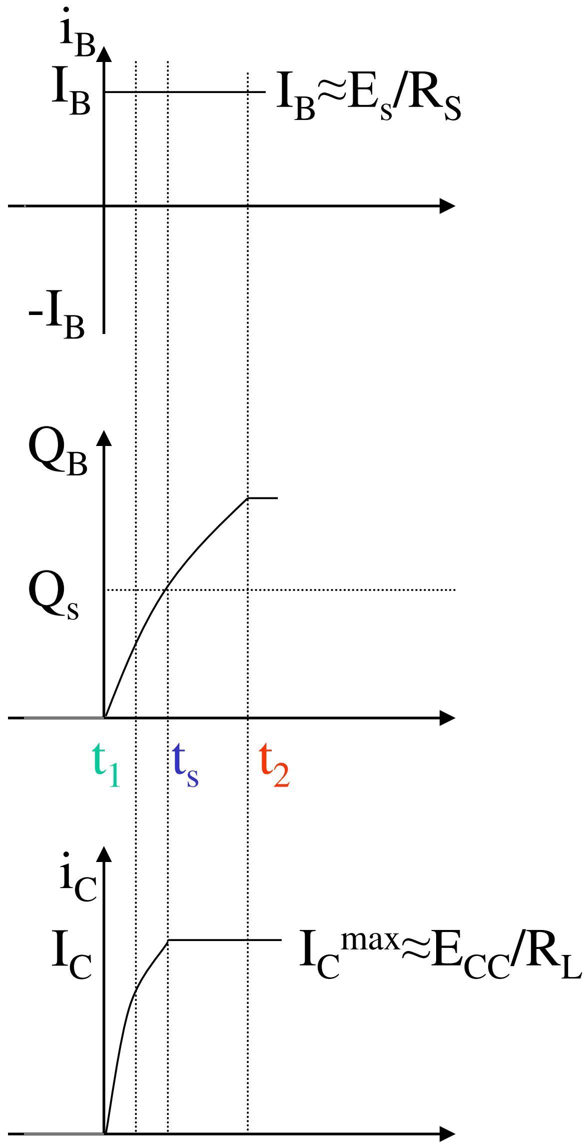
Switching cycle - review

Common emitter cicuit



Load line technique

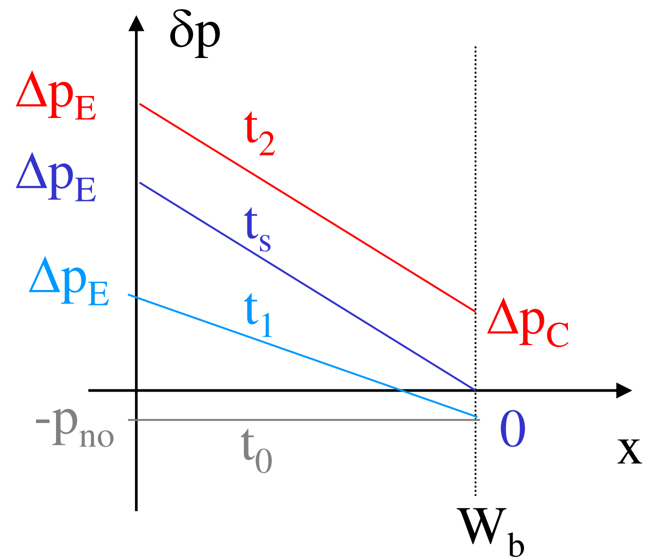




Switch to ON

With $I_B > I_C^{max}/\beta$

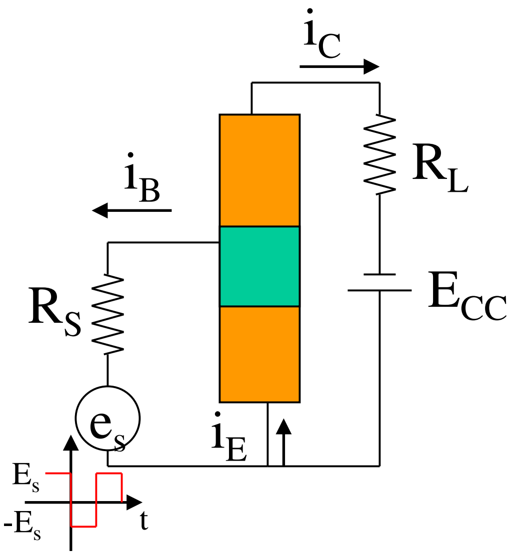
Over-saturation



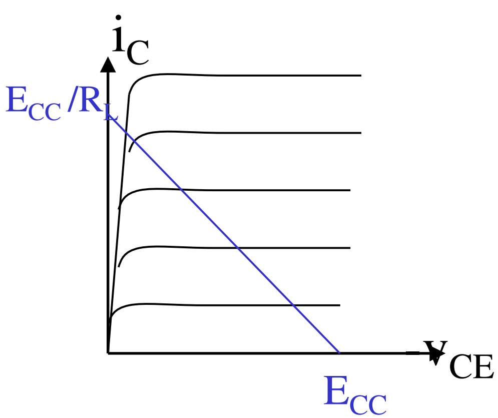
$p_{no} << \Delta p_E$

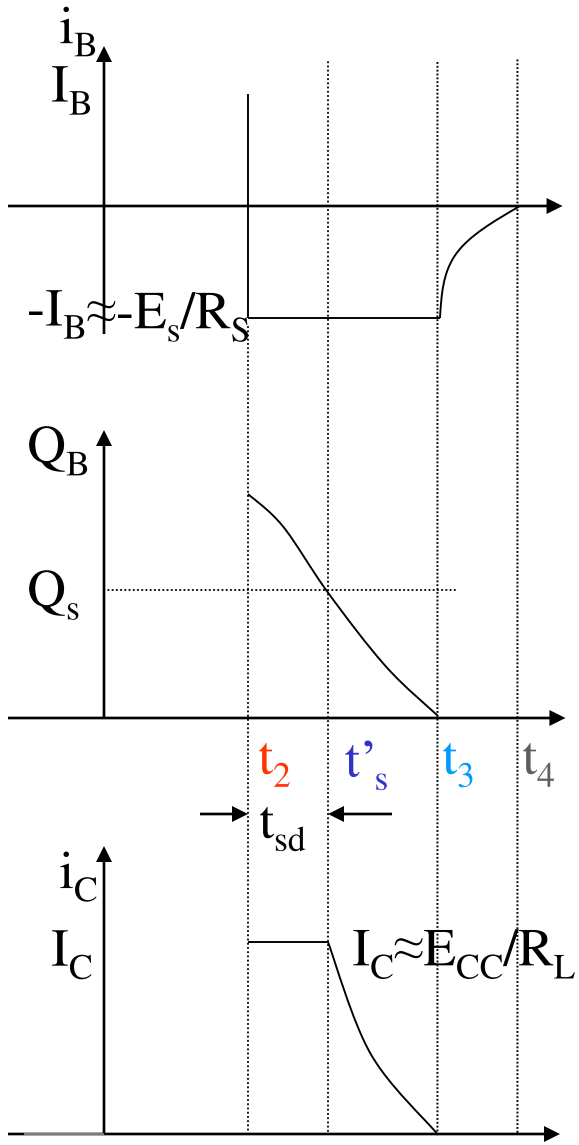
Switching cycle - review

Common emitter cicuit

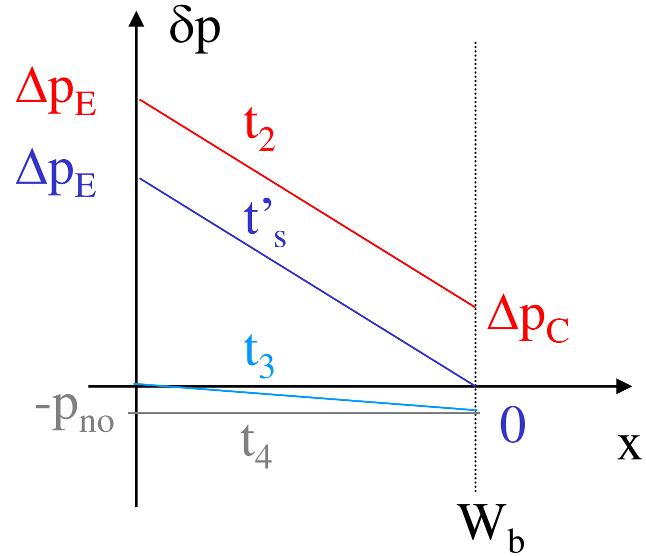


Load line technique



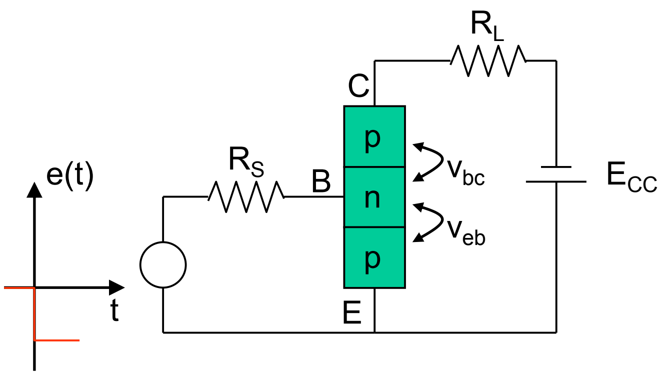


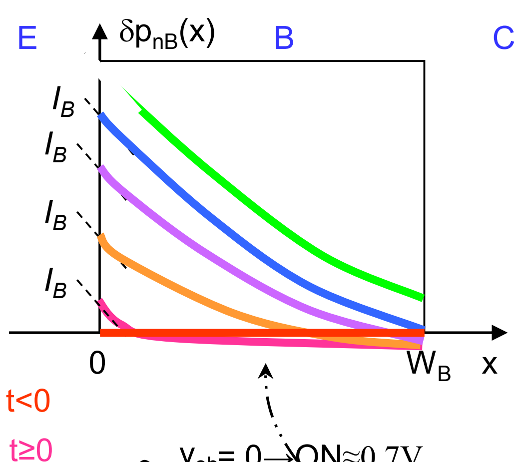
Switch OFF

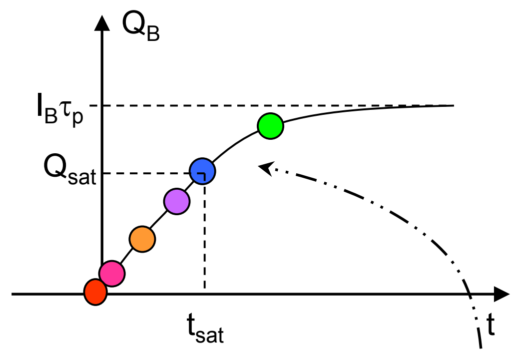


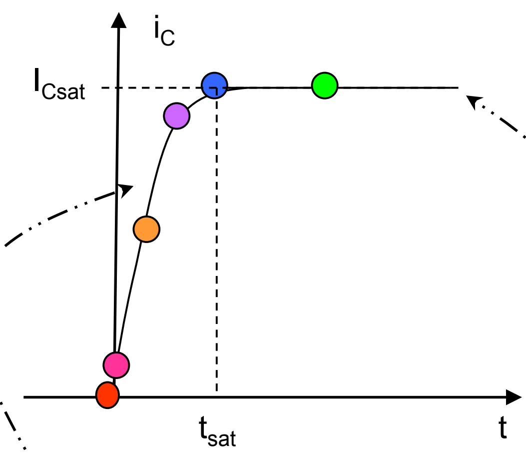
ON switching

OFF=0→ON









$$i(t) = \frac{dQ_B(t)}{dt} + \frac{Q_B(t)}{\tau_p}$$

$$\Rightarrow$$

$$Q_B = I_B \tau_p \left[1 - \exp\left(\frac{-t}{\tau_p} \right) \right]$$

&

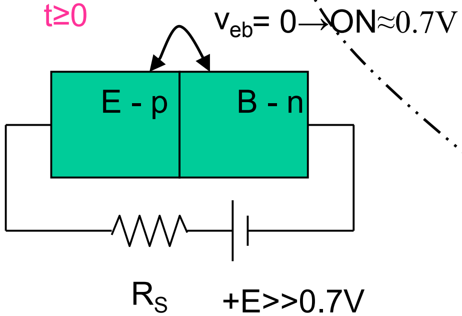
$$Q_B = \int_{x=0}^{x=W_B} e\, A\, \delta n_{pB}(x) dx$$

$t<t_{sat}$

$$i_C(t) = \frac{Q_B(t)}{\tau_t} = \frac{I_B \tau_p}{\tau_t} \left[1 - \exp\left(\frac{-t}{\tau_p} \right) \right]$$

$t \geq t_{sat}$

$$i_C(t) = \frac{E_{CC}}{R_L} = I_{Csat}$$

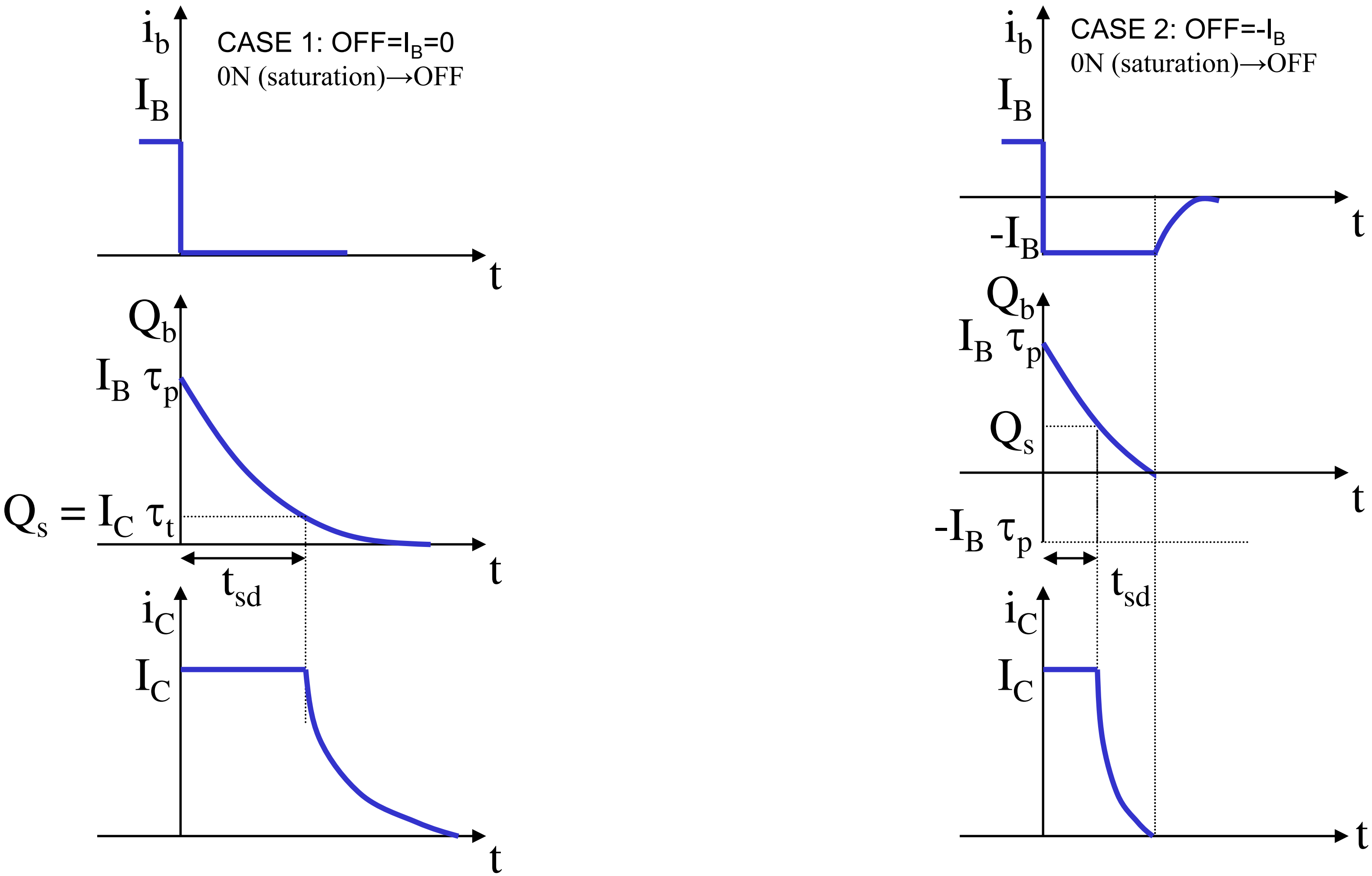


$$I_B = \frac{E}{R_S}$$

Driving off

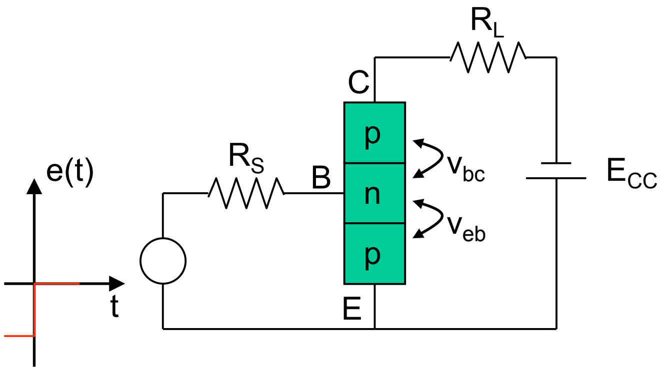
Time to turn the BJT OFF is determined by:

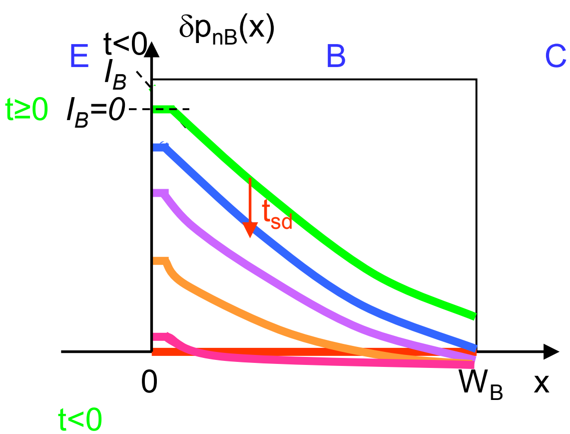
1) The degree of over-saturation (BC junction)
2) The off-switching of the emitter-base diode

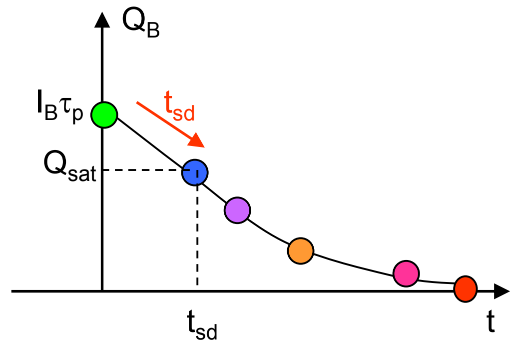


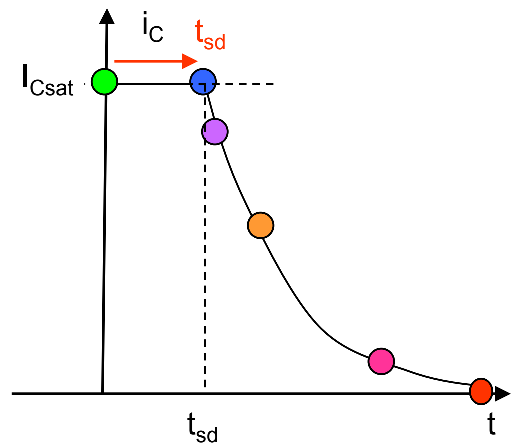
OFF switching

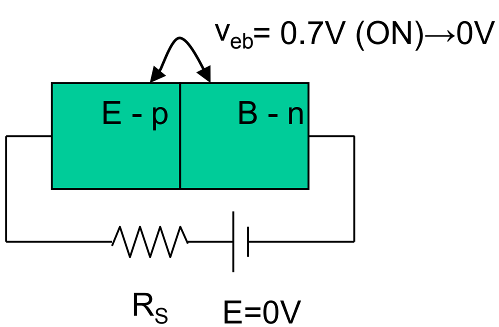
0N (saturation)→OFF - CASE 1: OFF=I_B=0











$$I_B = \frac{E}{R_S} = 0$$

$$i(t) = \frac{dQ_B(t)}{dt} + \frac{Q_B(t)}{\tau_p}$$

$\Rightarrow$

$$Q_B(t) = I_B \tau_p \exp\left(\frac{-t}{\tau_p}\right)$$

&

$$Q_B = \int_{x=0}^{x=W_B} e\, A\, \delta n_{pB}(x)dx$$

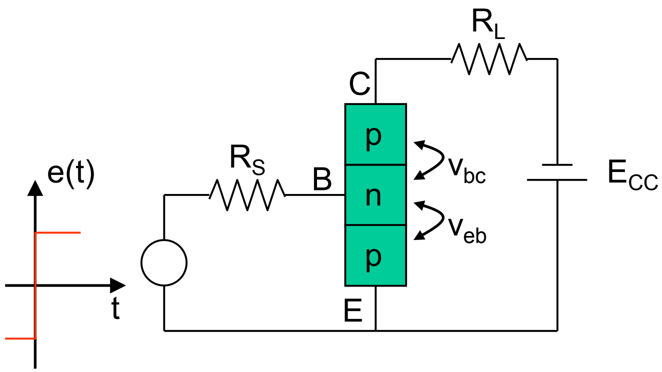
$t<t_{sd}$

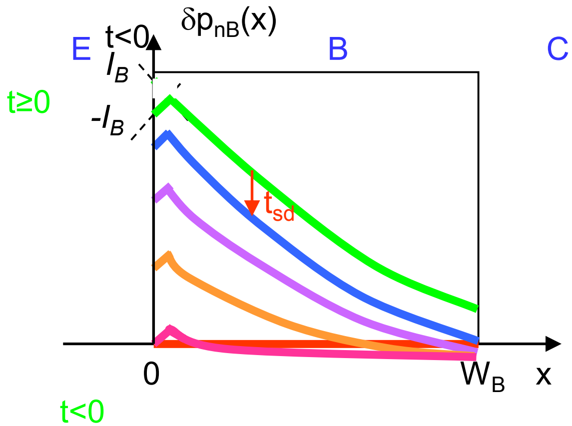
$$i_C(t) = \frac{E_{CC}}{R_L} = I_{Csat}$$

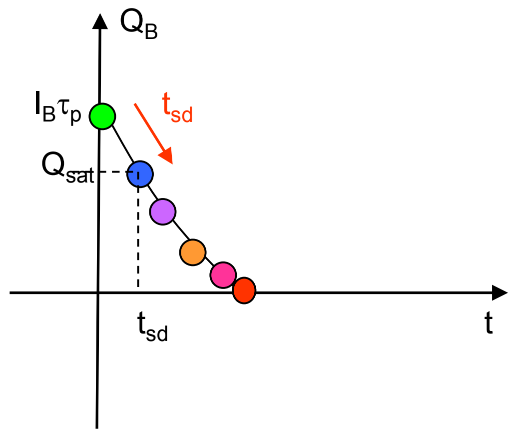
$t \geq t_{sd}$

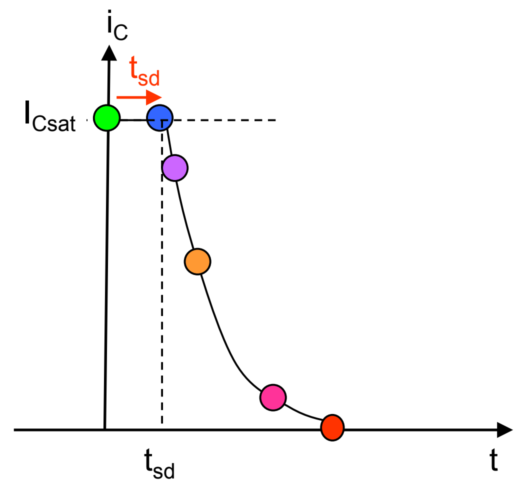
$$i_C(t) = \frac{Q_B(t)}{\tau_t} = \frac{I_B \tau_p}{\tau_t} \exp\left(\frac{-t}{\tau_p}\right)$$

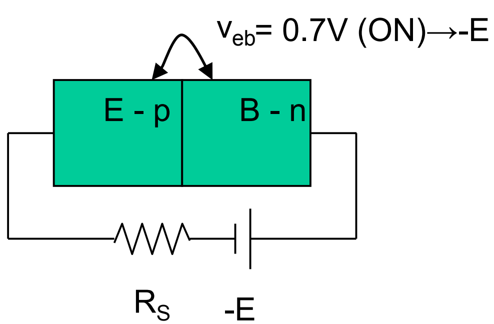
0N (saturation)→OFF - CASE 2: OFF=$-I_B$











$$I_B = \frac{-E}{R_S}$$

$$i(t) = \frac{dQ_B(t)}{dt} + \frac{Q_B(t)}{\tau_p}$$

$$\Rightarrow$$

$$Q_B(t) = I_B \tau_p \left[2\exp\left(\frac{-t}{\tau_p}\right) - 1 \right]$$

&

$$Q_B = \int_{x=0}^{x=W_B} e\, A\, \delta n_{pB}(x)\, dx$$

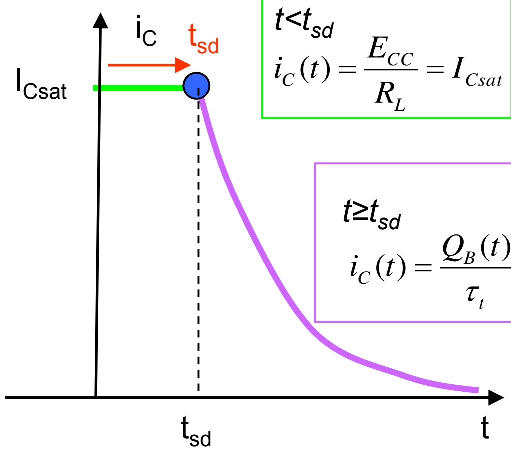
$t<t_{sd}$

$$i_C(t) = \frac{E_{CC}}{R_L} = I_{Csat}$$

$t \geq t_{sd}$

$$i_C(t) = \frac{Q_B(t)}{\tau_t} = \frac{I_B \tau_p}{\tau_t} \left[2\exp\left(\frac{-t}{\tau_p}\right) - 1 \right]$$

0N (saturation)→OFF - CASE 1: OFF=I_B=0



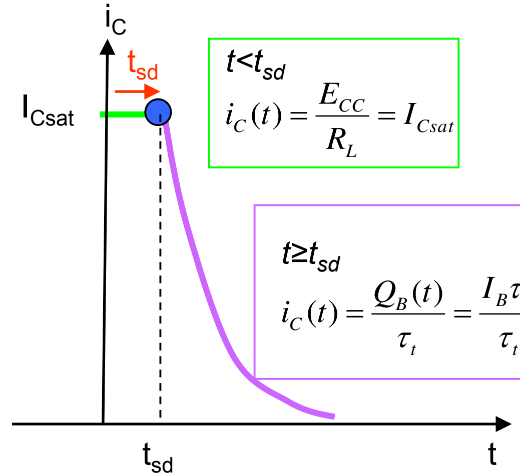
$t<t_{sd}$

$$i_C(t)=\frac{E_{CC}}{R_L}=I_{Csat}$$

$t\geq t_{sd}$

$$i_C(t)=\frac{Q_B(t)}{\tau_t}=\frac{I_B\tau_p}{\tau_t}\exp\left(\frac{-t}{\tau_p}\right)$$

0N (saturation)→OFF - CASE 1: OFF=-I_B



$t<t_{sd}$

$$i_C(t)=\frac{E_{CC}}{R_L}=I_{Csat}$$

$t\geq t_{sd}$

$$i_C(t)=\frac{Q_B(t)}{\tau_t}=\frac{I_B\tau_p}{\tau_t}\left[2\exp\left(\frac{-t}{\tau_p}\right)-1\right]$$

STORAGE DELAY TIME: t_{sd}

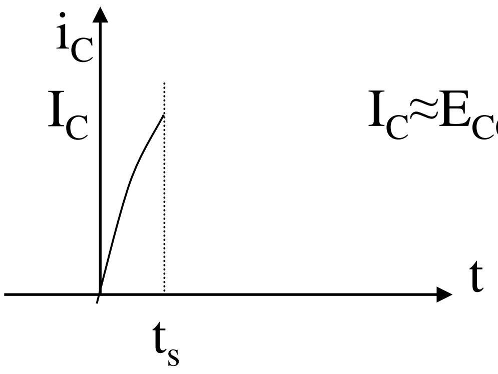
$$i_C(t_{sd})=I_{Csat}=\frac{E_{CC}}{R_L}=\frac{I_B\tau_p}{\tau_t}\exp\left(\frac{-t_{sd}}{\tau_p}\right)$$

$$i_C(t_{sd})=I_{Csat}=\frac{E_{CC}}{R_L}=\frac{I_B\tau_p}{\tau_t}\left[2\exp\left(\frac{-t_{sd}}{\tau_p}\right)-1\right]$$

shorter delay

Transients

Turn-on: off to saturation

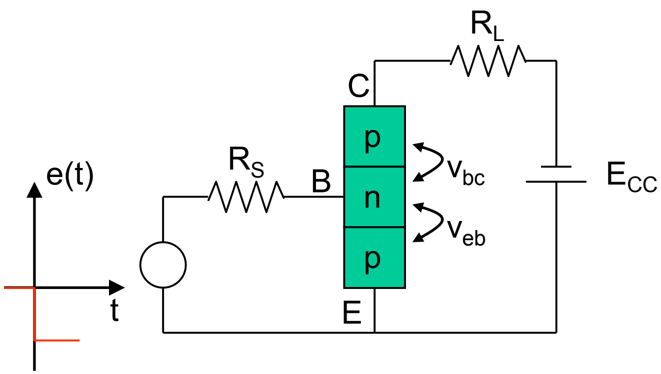


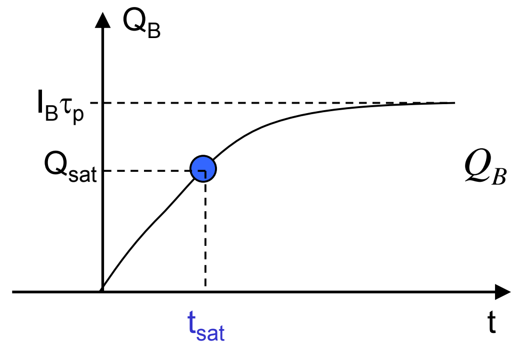
$I_C \approx E_{CC}/R_L$

Time to saturation

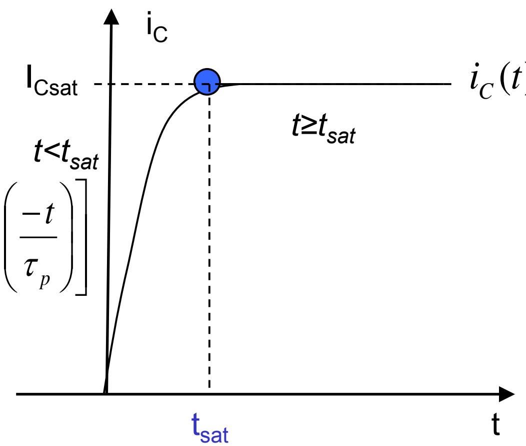
ON switching

OFF=0→ON





$$Q_B = I_B \tau_p \left[1 - \exp\left(\frac{-t}{\tau_p} \right) \right]$$



$$i_C(t) = \frac{E_{CC}}{R_L} = I_{Csat}$$

$$i_C(t) = \frac{Q_B(t)}{\tau_t} = \frac{I_B \tau_p}{\tau_t} \left[1 - \exp\left(\frac{-t}{\tau_p} \right) \right]$$

$t=t_{sat}$ $$i_C(t_{sat}) = \frac{I_B \tau_p}{\tau_t} \left[1 - \exp\left(\frac{-t_{sat}}{\tau_p} \right) \right] = I_{Csat}$$