BJT Amplifiers: Part 1

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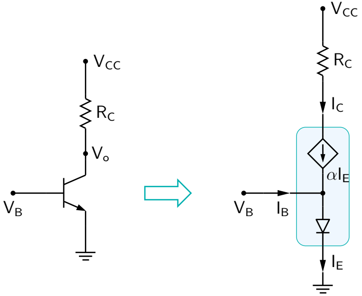
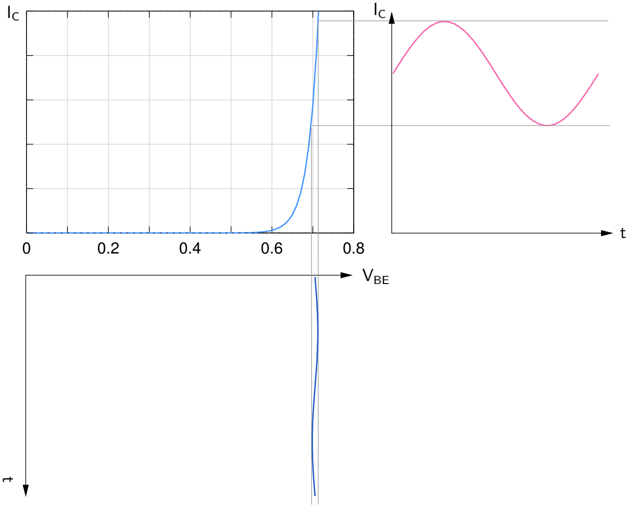
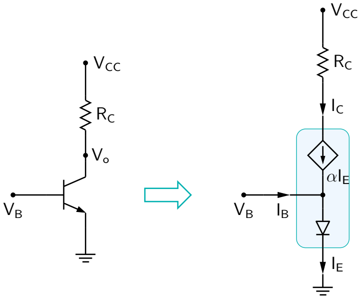
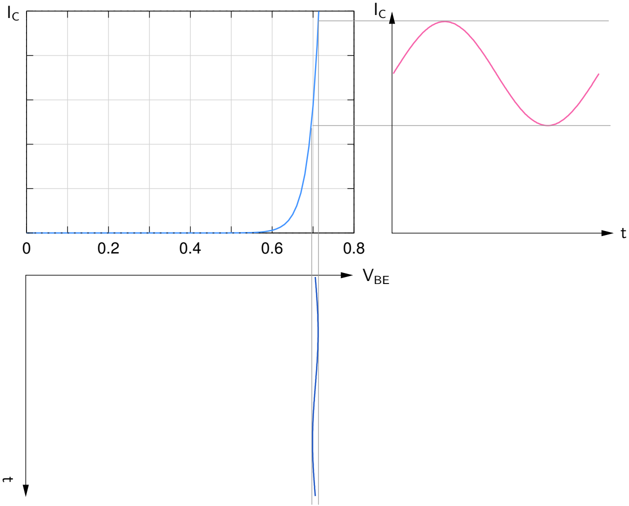
BJT amplifier: basic operation









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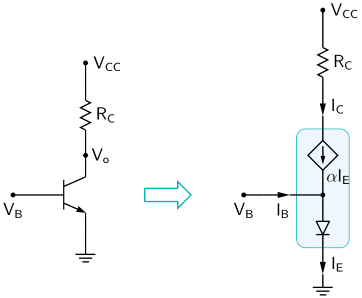

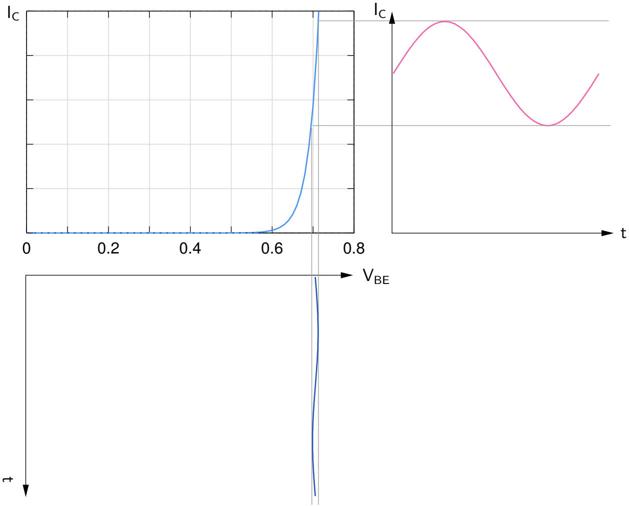

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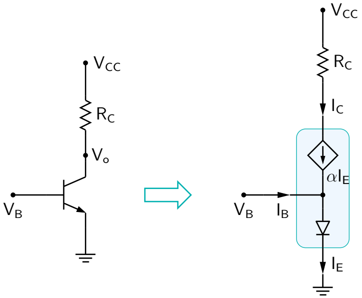
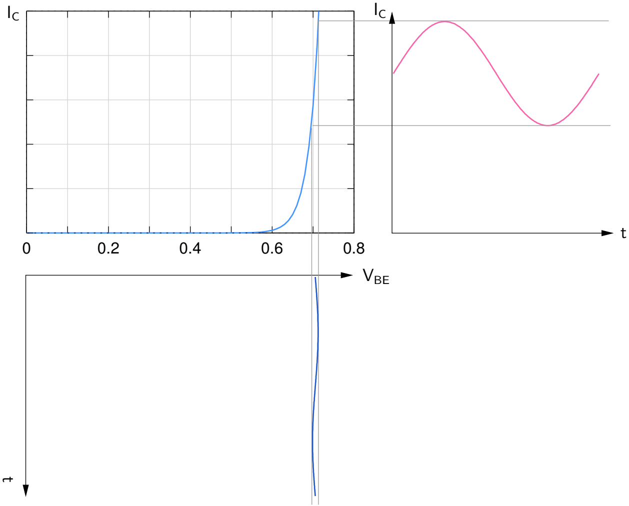
* $V_o(t) = V_{CC} - I_C(t)\, R_C$
  $\Rightarrow$ the amplitude of V_o, i.e., $\widehat{I_C}\, R_C$, can be made much larger than $\widehat{V_B}$.





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  $\Rightarrow$ the amplitude of V_o, i.e., $\widehat{I_C}\,R_C$, can be made much larger than $\widehat{V_B}$.
* Note that both the input (V_{BE}) and output (V_o) voltages have DC ("bias") components.

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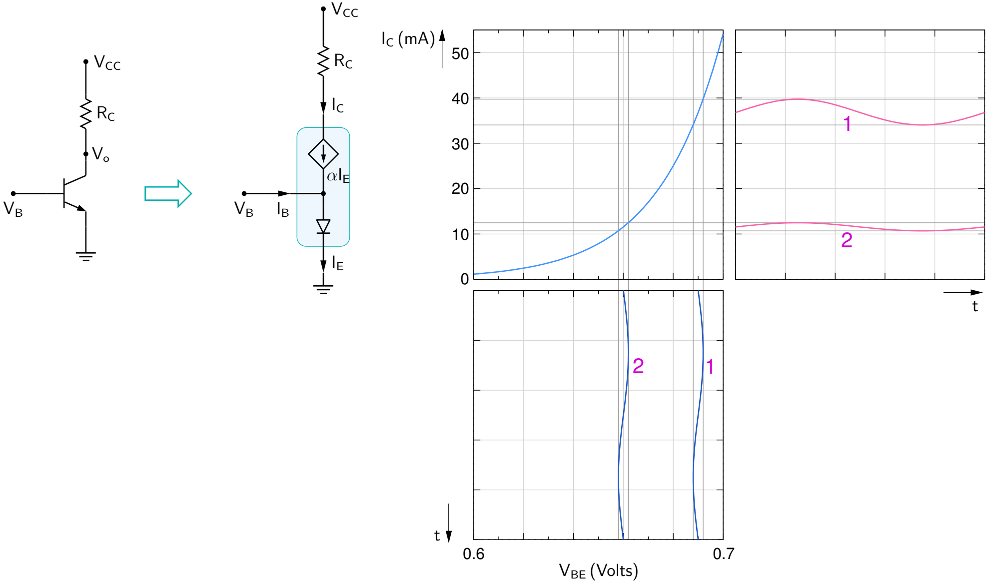
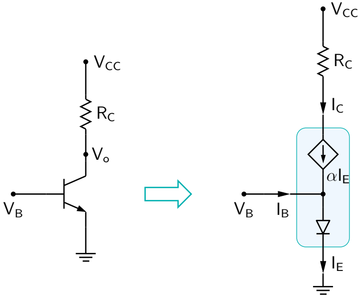
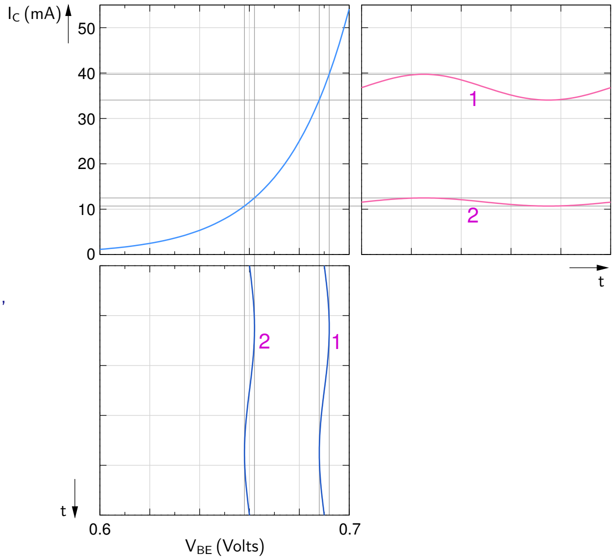
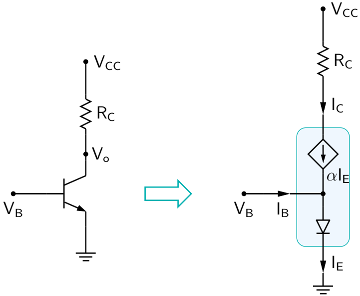
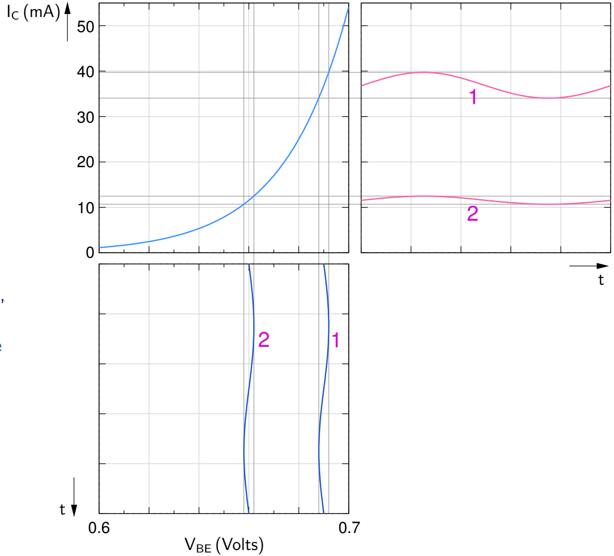






* The gain depends on the DC (bias) value of V_{BE}, the input voltage in this circuit.





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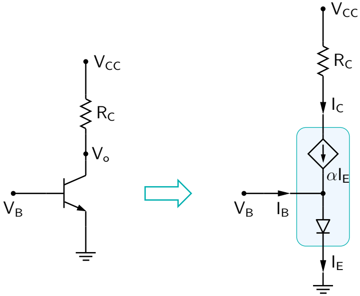

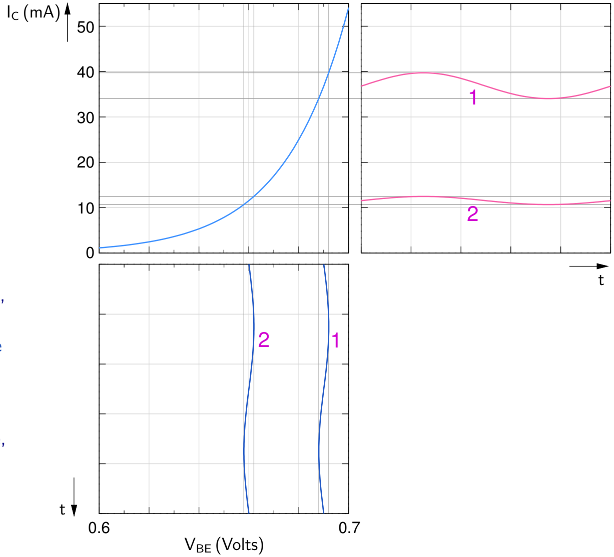

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* In practice, it is not possible to set the bias value of the input voltage to the desired value (e.g., 0.673 V).
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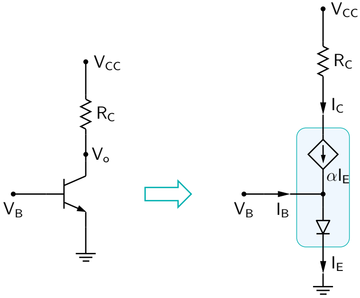
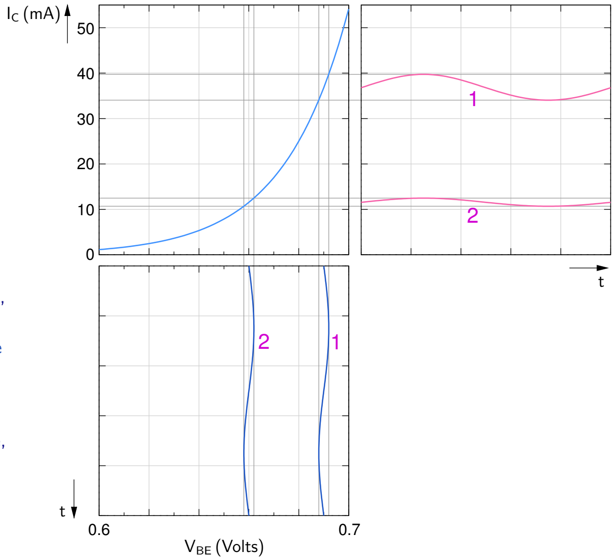
  → need a better biasing method.





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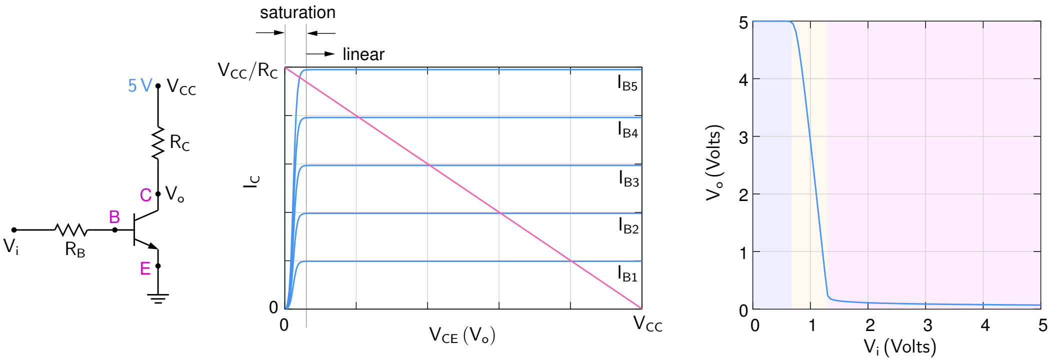
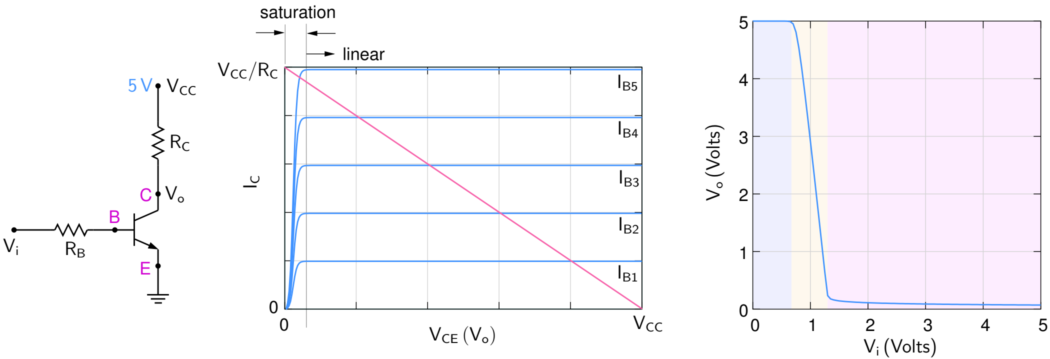
* Even if we could set the input bias as desired, device-to-device variation, change in temperature, etc. would cause the gain to change.
  $\rightarrow$ need a better biasing method.
* Biasing the transistor at a specific V_{BE} is equivalent to biasing it at a specific I_C.



Consider a more realistic BJT amplifier circuit, with R_B added to limit the base current (and thus protect the transistor).



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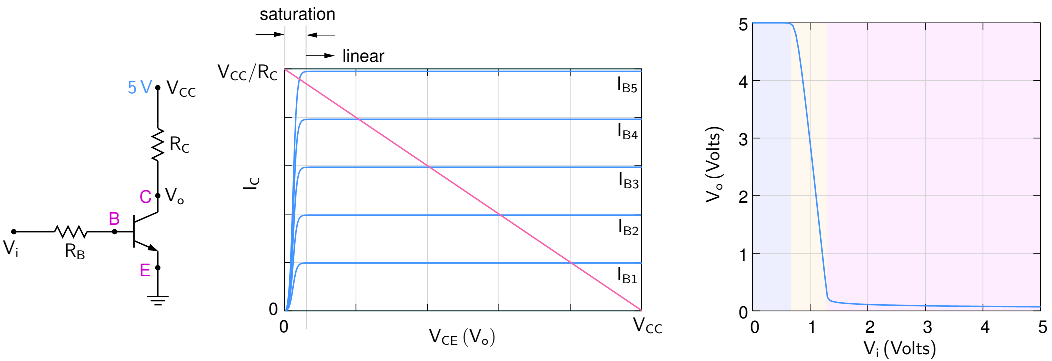

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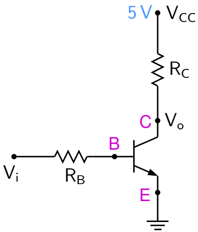
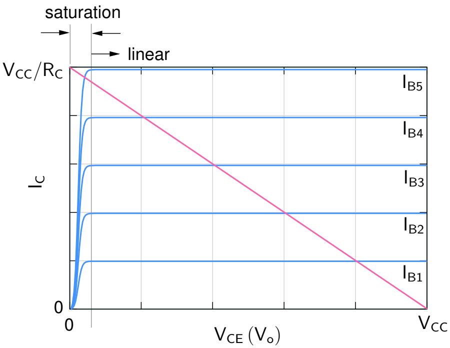
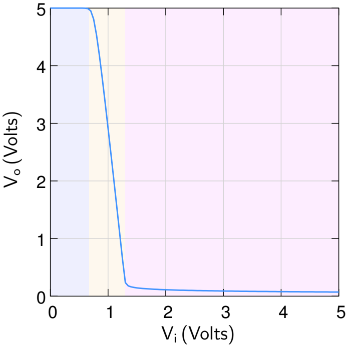
* When V_i exceeds 0.7 V, the BJT enters the linear region, and $I_B \approx \dfrac{V_i - 0.7}{R_B}$. As V_i increases, I_B and $I_C = \beta I_B$ also increase, and $V_o = V_{CC} - I_C R_C$ falls.







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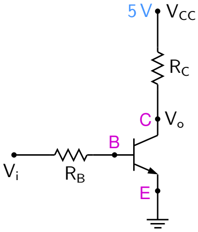
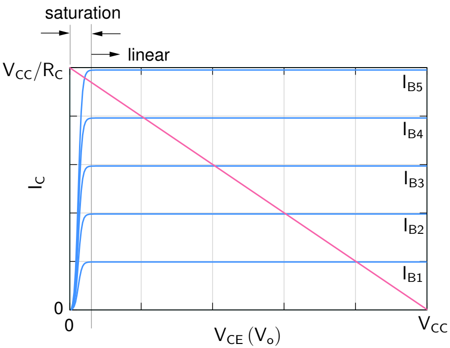
* As V_i is increased further, V_o reaches V_{CE}^{sat} (about 0.2 V), and the BJT enters the saturation region (both B-E and B-C junctions are forward biased).

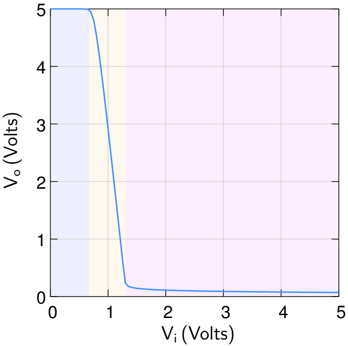
M. B. Patil, IIT Bombay



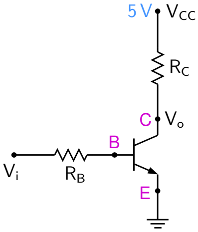
5 V
V_{CC}
R_C
C
V_o
B
V_i
R_B
E

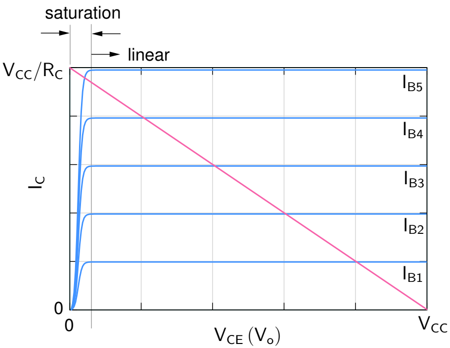


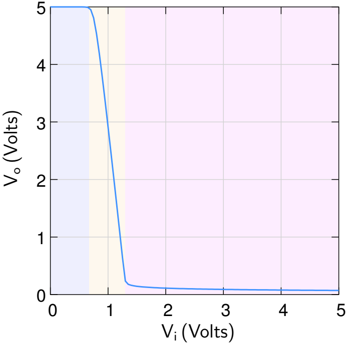
saturation
linear
V_{CC}/R_C
I_C
I_{B5}
I_{B4}
I_{B3}
I_{B2}
I_{B1}
0
0
V_{CE} (V_o)
V_{CC}



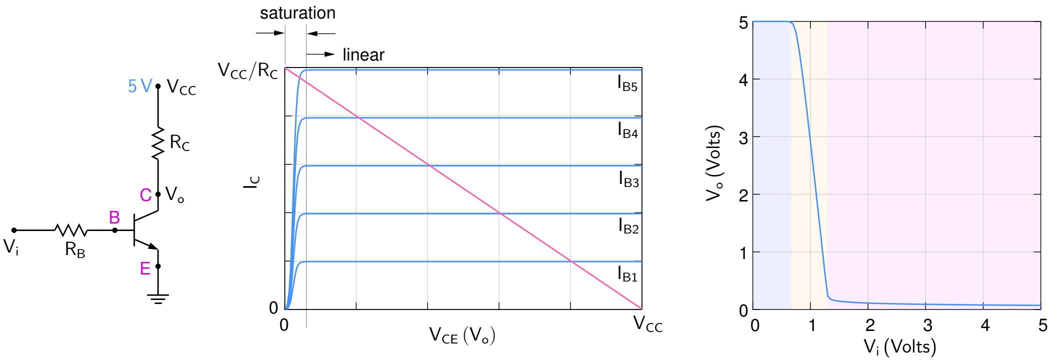
5
4
3
2
1
0
V_o (Volts)
0
1
2
3
4
5
V_i (Volts)







* The gain of the amplifier is given by $\dfrac{dV_o}{dV_i}$.



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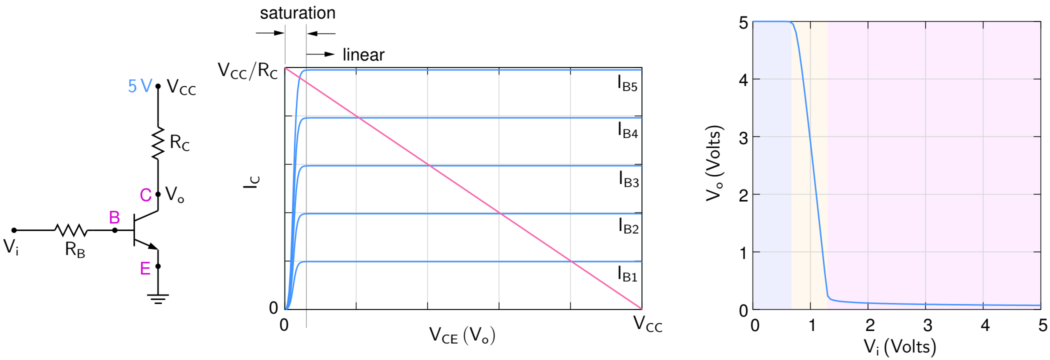
* Since V_o is nearly constant for $V_i < 0.7\ V$ (due to cut-off) and $V_i > 1.3\ V$ (due to saturation), the circuit will not work an an amplifier in this range.



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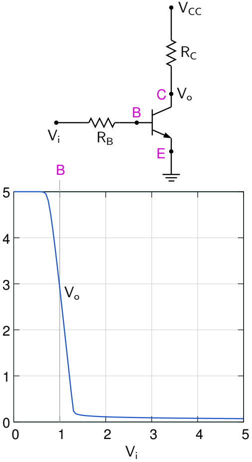
* Further, to get a large swing in V_o without distortion, the DC bias of V_i should be at the centre of the amplifying region, i.e., $V_i \approx 1\ V$.

BJT amplifier biasing



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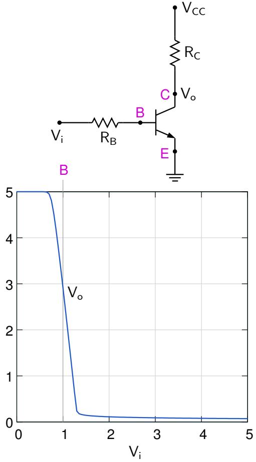

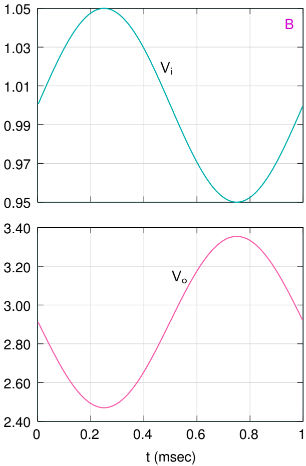

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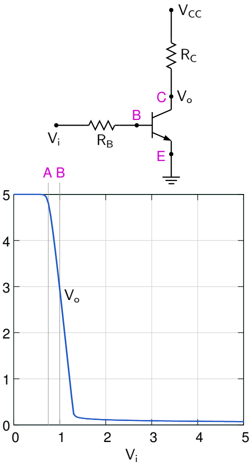

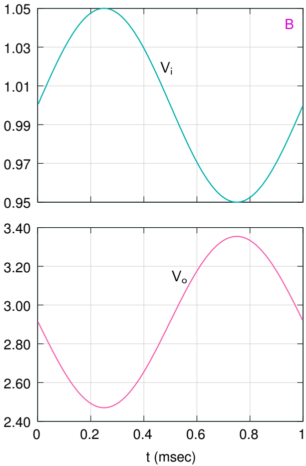

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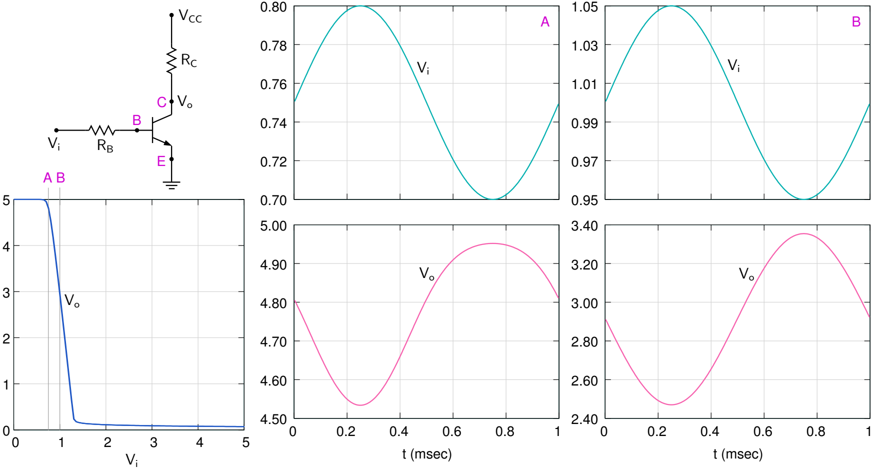

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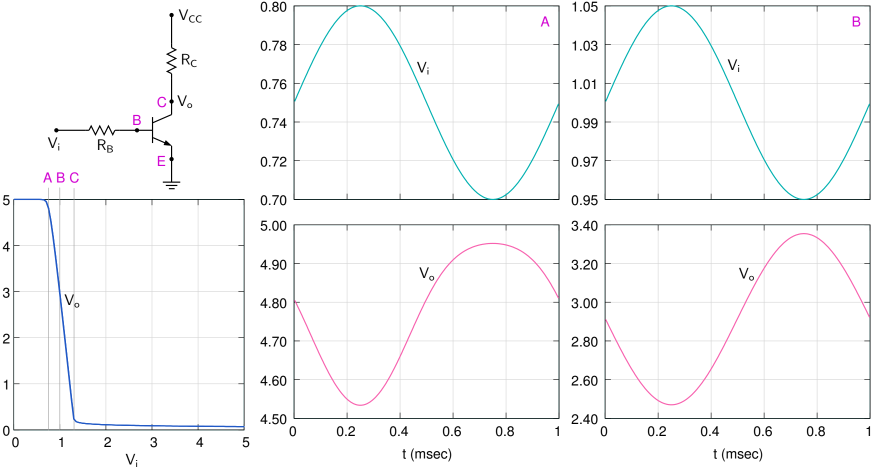

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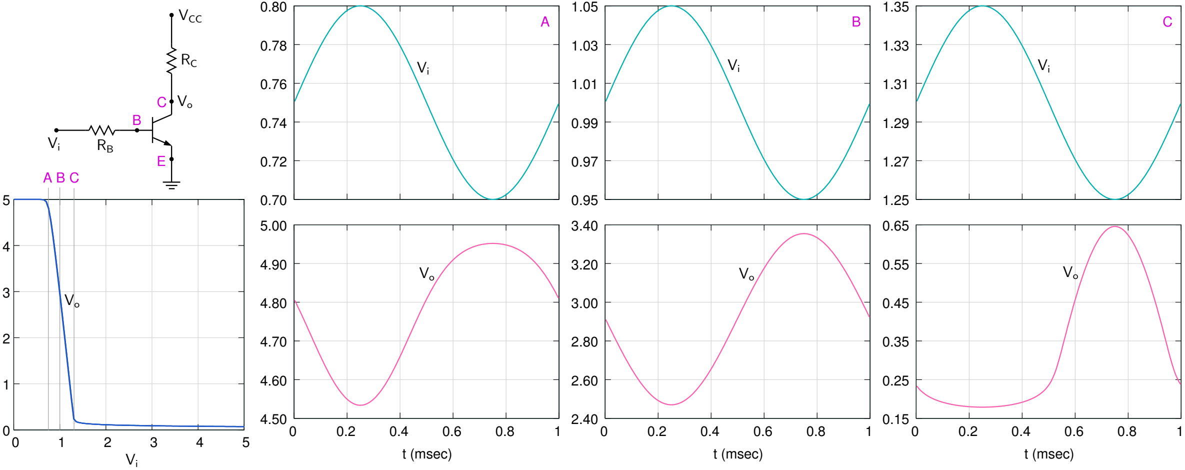

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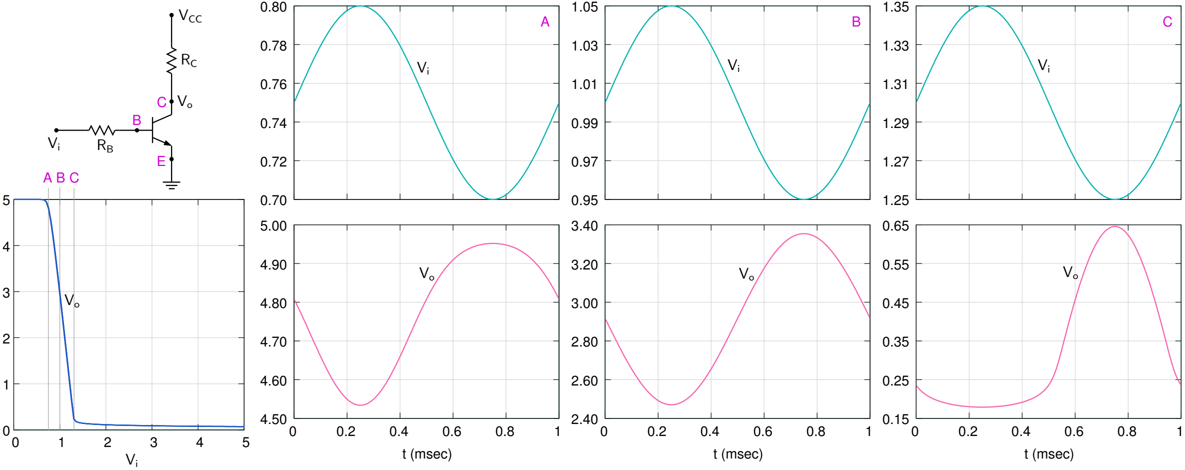

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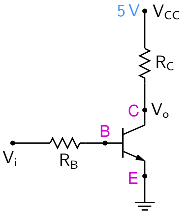

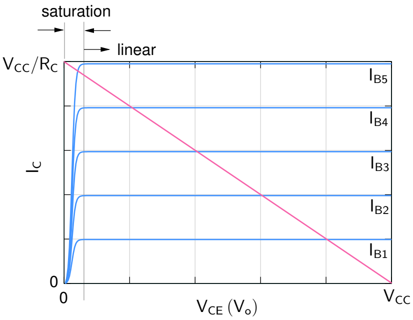

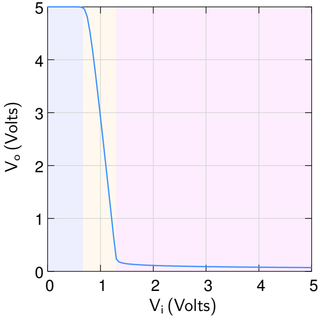

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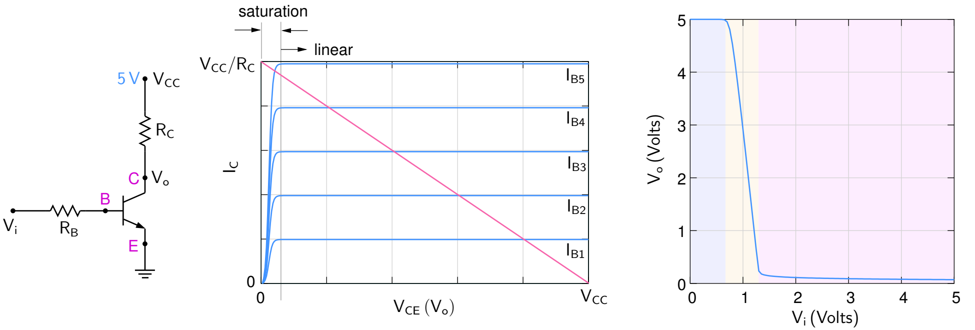

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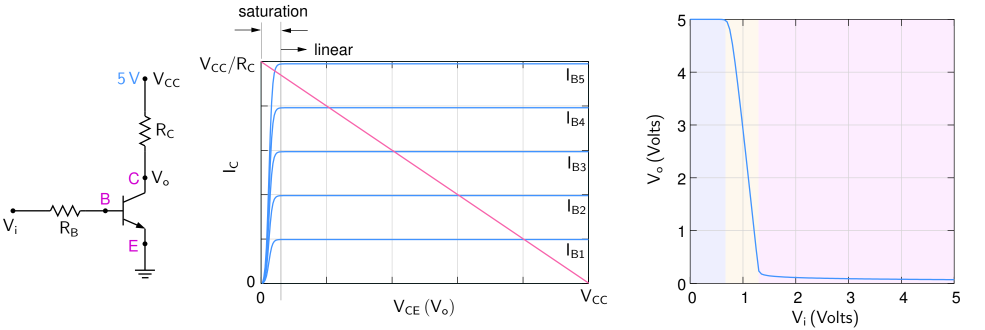

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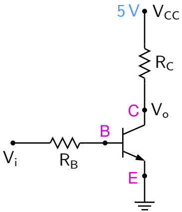

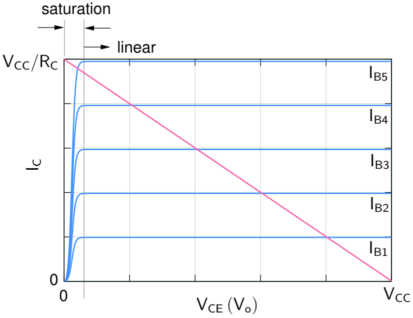

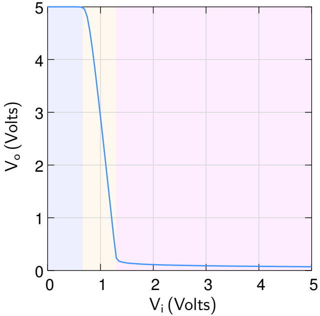

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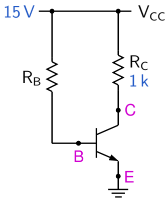
* The first issue is addressed by using a suitable biasing scheme, and the second by using "coupling" capacitors.

BJT amplifier: a simple biasing scheme



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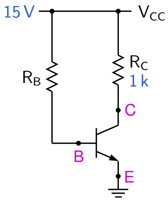

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Equivalently, we may bias an amplifier for a certain DC value of V_{CE}, since I_C and V_{CE} are related: $V_{CE} + I_C R_C = V_{CC}$.

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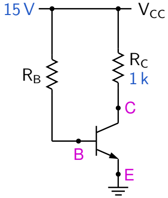

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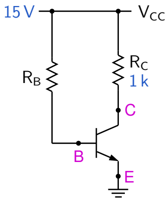

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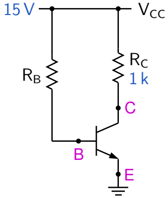
$$I_B = \frac{I_C}{\beta} = \frac{3.3\,\text{m}A}{100} = 33\,\mu A = \frac{V_{CC} - V_{BE}}{R_B} = \frac{15 - 0.7}{R_B}$$



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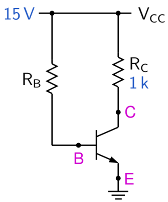
Equivalently, we may bias an amplifier for a certain DC value of V_{CE}, since I_C and V_{CE} are related: $V_{CE} + I_C R_C = V_{CC}$.

As an example, for $R_C = 1\,\text{k}$, $\beta = 100$, let us calculate R_B for $I_C = 3.3\,\text{m}A$, assuming the BJT to be operating in the active mode.

$$I_B = \frac{I_C}{\beta} = \frac{3.3\,\text{m}A}{100} = 33\,\mu A = \frac{V_{CC} - V_{BE}}{R_B} = \frac{15 - 0.7}{R_B}$$

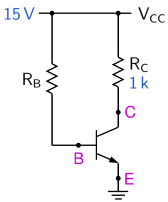
$$\rightarrow R_B = \frac{14.3\,V}{33\,\mu A} = 430\,\text{k}\Omega\,.$$

BJT amplifier: a simple biasing scheme (continued)



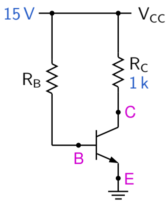
With $R_B = 430\,\text{k}$, we expect $I_C = 3.3\,\text{m}A$, assuming $\beta = 100$.

BJT amplifier: a simple biasing scheme (continued)



With $R_B = 430\,\text{k}$, we expect $I_C = 3.3\,\text{m}A$, assuming $\beta = 100$.

However, in practice, there is a substantial variation in the β value (even for the same transistor type). The manufacturer may specify the nominal value of β as 100, but the actual value may be 150, for example.



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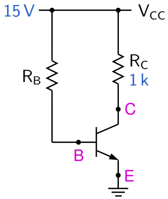
With $\beta = 150$, the actual I_C is,

$$I_C = \beta \times \frac{V_{CC} - V_{BE}}{R_B} = 150 \times \frac{(15 - 0.7)\,V}{430\,k} = 5\,mA\,,$$

which is significantly different than the intended value, viz., 3.3 mA.



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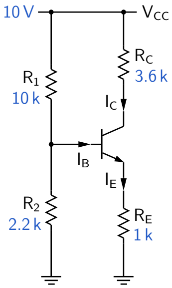
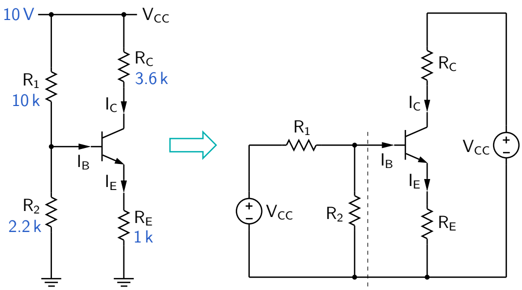
which is significantly different than the intended value, viz., 3.3 mA.

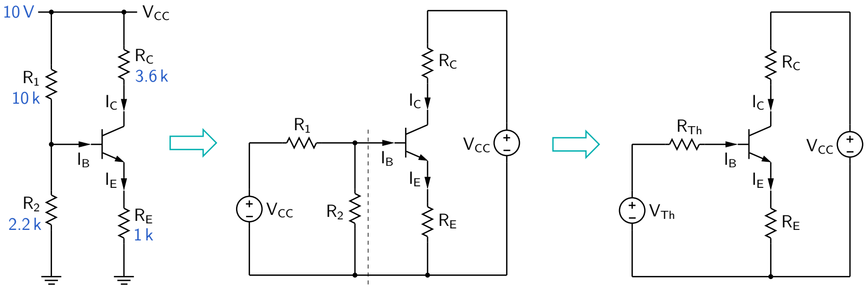
$\rightarrow$ need a biasing scheme which is not so sensitive to β.

BJT amplifier: improved biasing scheme

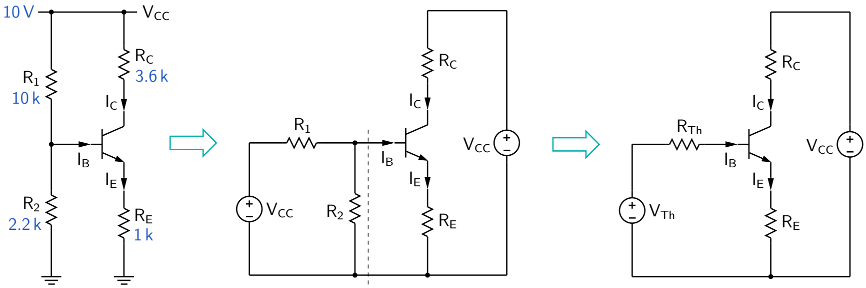


BJT amplifier: improved biasing scheme



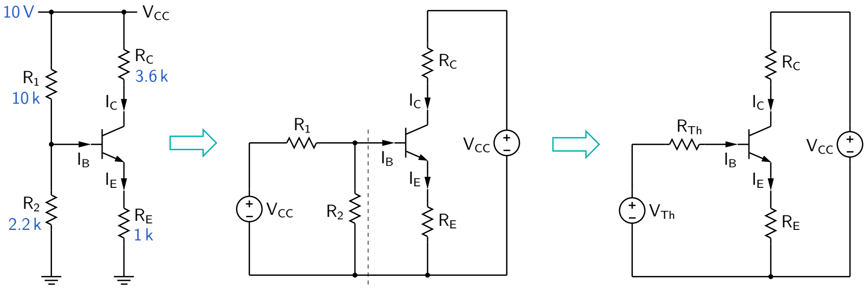

10 V
VCC
RC
3.6 k
R1
10 k
IC
IB
IE
R2
2.2 k
RE
1 k
R1
RC
IC
VCC
IB
IE
VCC
R2
RE
RC
RTh
IC
VCC
IB
IE
VTh
RE

BJT amplifier: improved biasing scheme



$$V_{Th} = \frac{R_2}{R_1 + R_2} V_{CC} = \frac{2.2\,\text{k}}{10\,\text{k} + 2.2\,\text{k}} \times 10\ V = 1.8\ V, \quad R_{Th} = R_1 \parallel R_2 = 1.8\,\text{k}$$

BJT amplifier: improved biasing scheme



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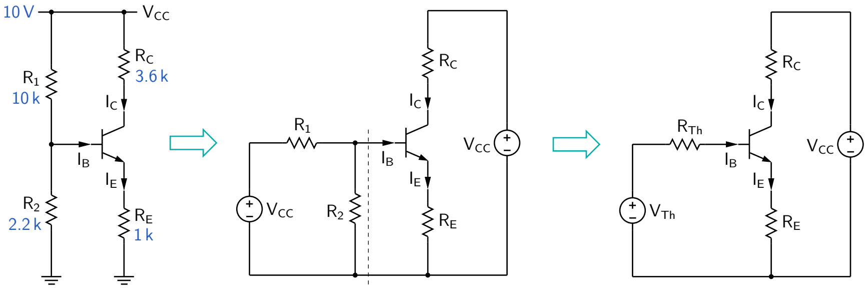
Assuming the BJT to be in the active mode,

KVL: $V_{Th} = R_{Th}\, I_B + V_{BE} + R_E\, I_E = R_{Th}\, I_B + V_{BE} + (\beta + 1)\, I_B\, R_E$

BJT amplifier: improved biasing scheme



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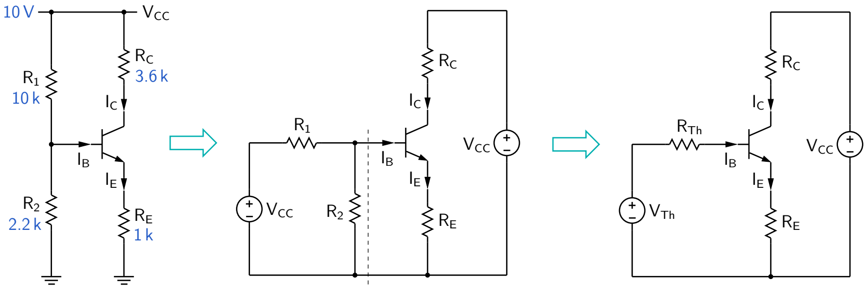

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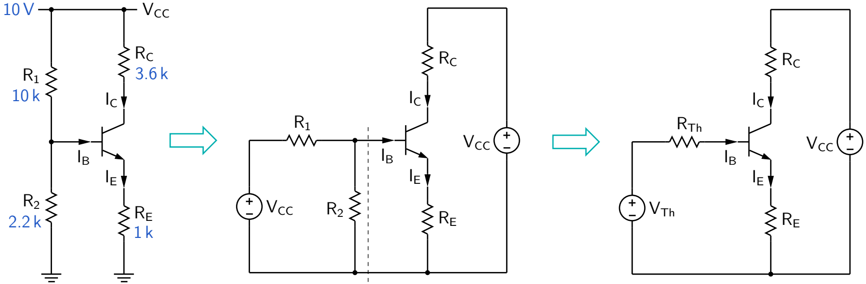
For $\beta = 100$, I_C=1.07 mA.



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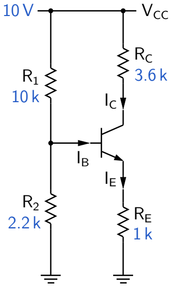
For $\beta = 200$, I_C=1.085 mA.

BJT amplifier: improved biasing scheme (continued)



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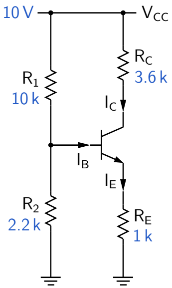
BJT amplifier: improved biasing scheme (continued)



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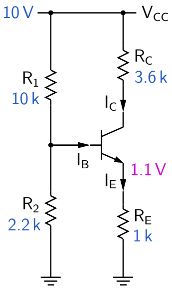

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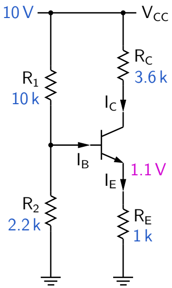

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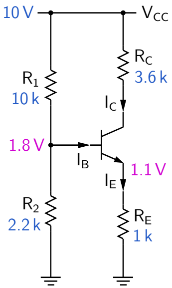

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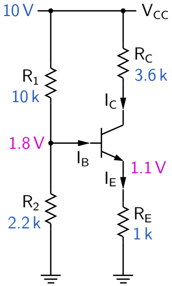

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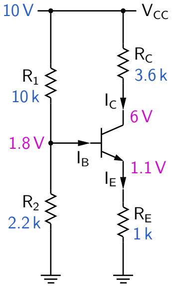

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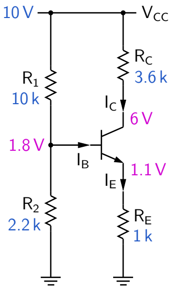

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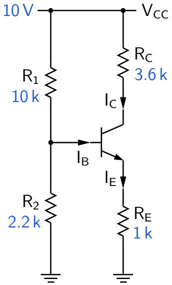
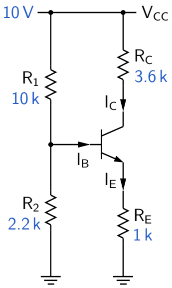
$$V_{CE} = V_C - V_E = 6 - 1.1 = 4.9\,V.$$



A quick estimate of the bias values can be obtained by ignoring I_B (which is fair if β is large). In that case,

BJT amplifier: improved biasing scheme (continued)



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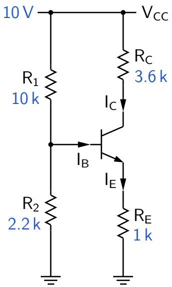
BJT amplifier: improved biasing scheme (continued)



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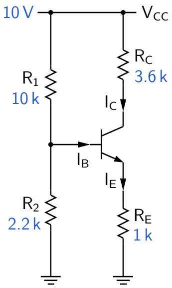
BJT amplifier: improved biasing scheme (continued)



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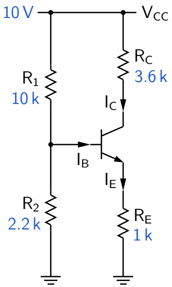

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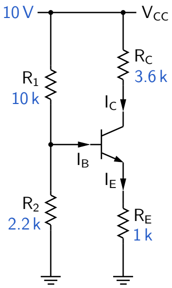
BJT amplifier: improved biasing scheme (continued)



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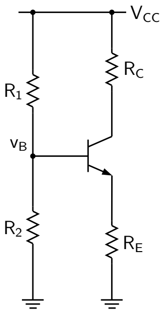
$$V_{CE} = V_{CC} - I_C\, R_C - I_E\, R_E = 10\ V - (3.6\,\text{k} \times 1.1\,\text{m}A) - (1\,\text{k} \times 1.1\,\text{m}A) \approx 5\ V.$$

Adding signal to bias



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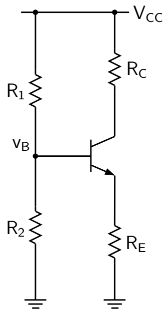

* As we have seen earlier, the input signal $v_s(t) = \widehat{V}$ sin ωt (for example) needs to be mixed with the desired bias value V_B so that the net voltage at the base is $v_B(t) = V_B + \widehat{V}$ sin ωt.

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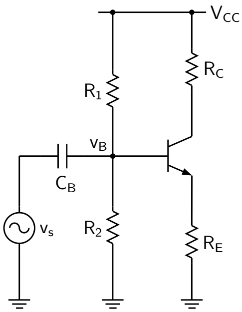

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* This can be achieved by using a coupling capacitor C_B.

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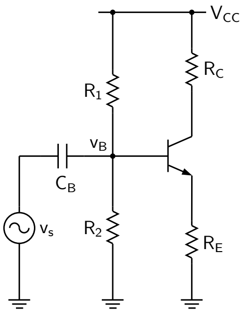
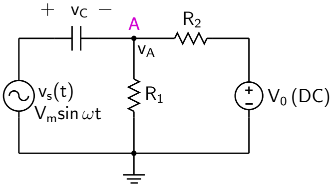
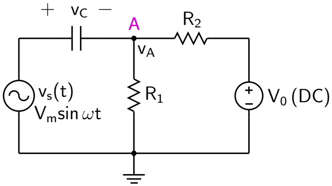


* As we have seen earlier, the input signal $v_s(t) = \widehat{V}\ \sin\ \omega t$ (for example) needs to be mixed with the desired bias value V_B so that the net voltage at the base is $v_B(t) = V_B + \widehat{V}\ \sin\ \omega t$.
* This can be achieved by using a coupling capacitor C_B.
* Let us consider a simple circuit to illustrate how a coupling capacitor works.



We are interested in the solution (currents and voltages) in the "sinusoidal steady state" when the exponential transients have vanished and each quantity $x(t)$ is of the form X_0 (constant) $+ X_m \sin(\omega t + \alpha)$.



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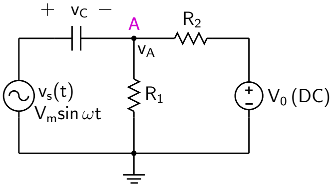
There are two ways to obtain the solution:

RC circuit with DC + AC sources



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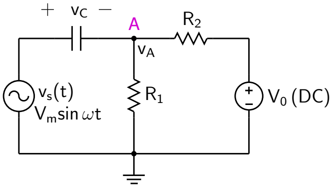
There are two ways to obtain the solution:

(1) Solve the circuit equations directly:

$$\frac{v_A(t)}{R_1} + \frac{v_A(t) - V_0}{R_2} = C\,\frac{d}{dt}\,\left(v_s(t) - v_A(t)\right).$$



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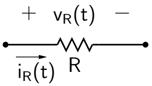
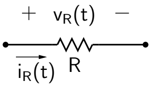
(1) Solve the circuit equations directly:

$$\frac{v_A(t)}{R_1} + \frac{v_A(t) - V_0}{R_2} = C\,\frac{d}{dt}\,(v_s(t) - v_A(t))\,.$$

(2) Use the DC circuit + AC circuit approach.



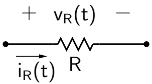
+ $v_R(t)$ −
$i_R(t)$
R



Let $v_R(t) = V_R + v_r(t)$ where V_R = constant, $v_r(t) = \widehat{V}_R \sin(\omega t + \alpha)$,

$i_R(t) = I_R + i_r(t)$ where I_R = constant, $i_r(t) = \widehat{I}_R \sin(\omega t + \alpha)$.

Resistor in sinusoidal steady state

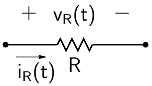


Let $v_R(t) = V_R + v_r(t)$ where V_R = constant, $v_r(t) = \widehat{V}_R \sin(\omega t + \alpha)$,

$i_R(t) = I_R + i_r(t)$ where I_R = constant, $i_r(t) = \widehat{I}_R \sin(\omega t + \alpha)$.

Since $v_R(t) = R \times i_R(t)$, we get $[V_R + v_r(t)] = R \times [I_R + i_r(t)]$.

Resistor in sinusoidal steady state



Let $v_R(t) = V_R + v_r(t)$ where V_R = constant, $v_r(t) = \widehat{V}_R \sin(\omega t + \alpha)$,

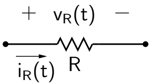
$i_R(t) = I_R + i_r(t)$ where I_R = constant, $i_r(t) = \widehat{I}_R \sin(\omega t + \alpha)$.

Since $v_R(t) = R \times i_R(t)$, we get $[V_R + v_r(t)] = R \times [I_R + i_r(t)]$.

This relationship can be split into two:

$V_R = R \times I_R$, and $v_r(t) = R \times i_r(t)$.

Resistor in sinusoidal steady state



Let $v_R(t) = V_R + v_r(t)$ where V_R = constant, $v_r(t) = \widehat{V}_R \sin(\omega t + \alpha)$,

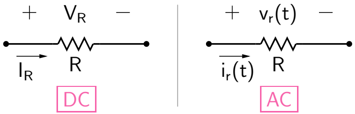
$i_R(t) = I_R + i_r(t)$ where I_R = constant, $i_r(t) = \widehat{I}_R \sin(\omega t + \alpha)$.

Since $v_R(t) = R \times i_R(t)$, we get $[V_R + v_r(t)] = R \times [I_R + i_r(t)]$.

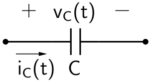
This relationship can be split into two:

$V_R = R \times I_R$, and $v_r(t) = R \times i_r(t)$.

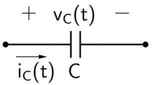
In other words, a resistor can be described by



Capacitor in sinusoidal steady state

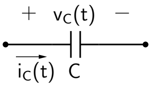


Capacitor in sinusoidal steady state



Let $v_C(t) = V_C + v_c(t)$ where V_C = constant, $v_c(t) = \widehat{V}_C \sin(\omega t + \alpha)$,

$i_C(t) = I_C + i_c(t)$ where I_C = constant, $i_c(t) = \widehat{I}_C \sin(\omega t + \beta)$.



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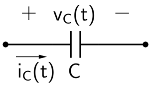
Since $i_C(t) = C \dfrac{dv_C}{dt}$, we get $[I_C + i_c(t)] = C \dfrac{d}{dt} (V_C + v_c(t))$.

Capacitor in sinusoidal steady state



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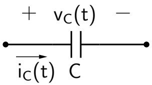
Since $i_C(t) = C\,\dfrac{dv_C}{dt}$, we get $[I_C + i_c(t)] = C\,\dfrac{d}{dt}\,(V_C + v_c(t))$.

This relationship can be split into two:

$I_C = C\,\dfrac{dV_C}{dt} = 0$, and $i_c(t) = C\,\dfrac{dv_c}{dt}$.

Capacitor in sinusoidal steady state



Let $v_C(t) = V_C + v_c(t)$ where V_C = constant, $v_c(t) = \widehat{V}_C \sin(\omega t + \alpha)$,

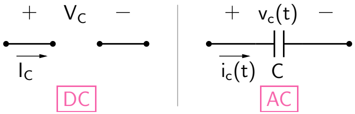
$i_C(t) = I_C + i_c(t)$ where I_C = constant, $i_c(t) = \widehat{I}_C \sin(\omega t + \beta)$.

Since $i_C(t) = C\,\dfrac{dv_C}{dt}$, we get $[I_C + i_c(t)] = C\,\dfrac{d}{dt}\,(V_C + v_c(t))$.

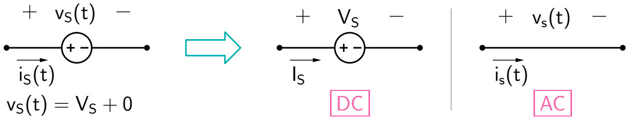
This relationship can be split into two:

$I_C = C\,\dfrac{dV_C}{dt} = 0$, and $i_c(t) = C\,\dfrac{dv_c}{dt}$.

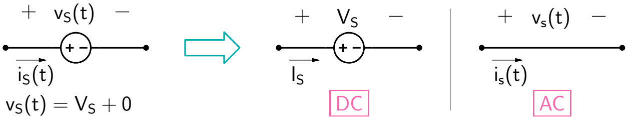
In other words, a capacitor can be described by



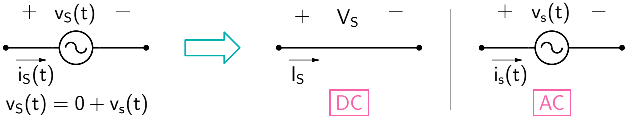
DC voltage source:



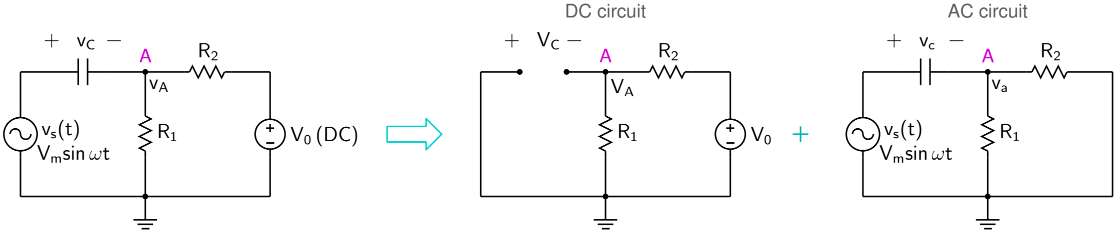
DC voltage source:



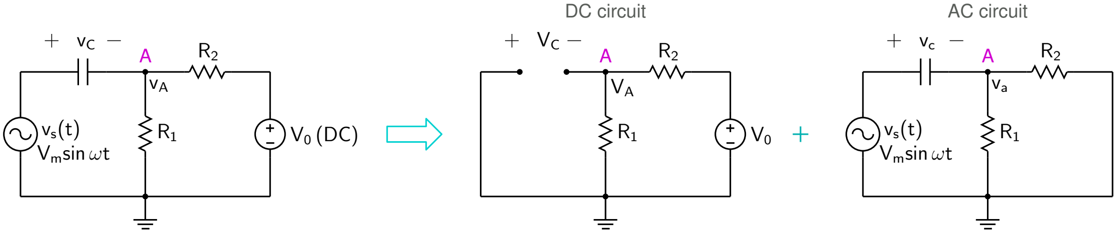
AC voltage source:



RC circuit with DC + AC sources

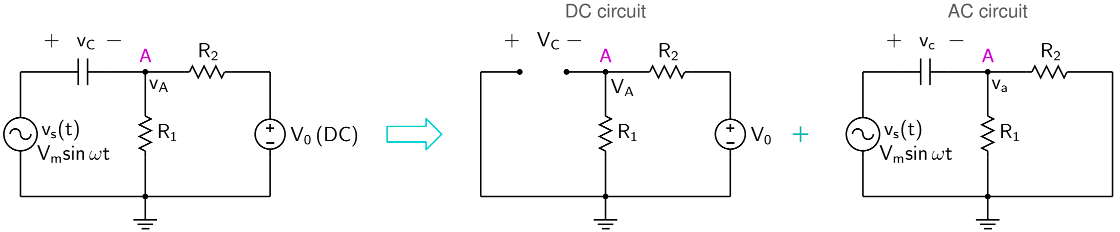


RC circuit with DC + AC sources



DC circuit: $$\frac{V_A}{R_1} + \frac{V_A - V_0}{R_2} = 0. \quad (1)$$

RC circuit with DC + AC sources



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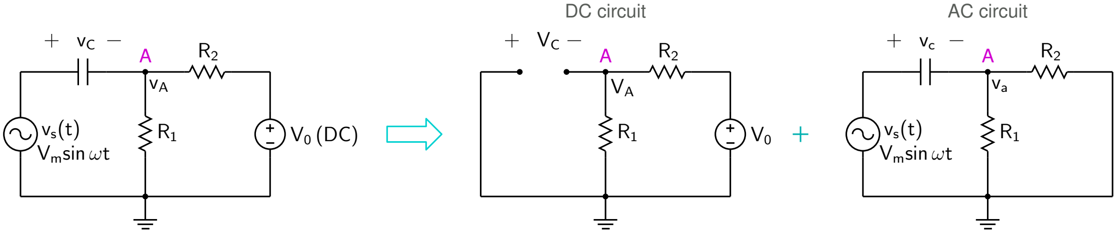
AC circuit: $$\frac{v_a}{R_1} + \frac{v_a}{R_2} = C\,\frac{d}{dt}\,(v_s - v_a). \quad (2)$$



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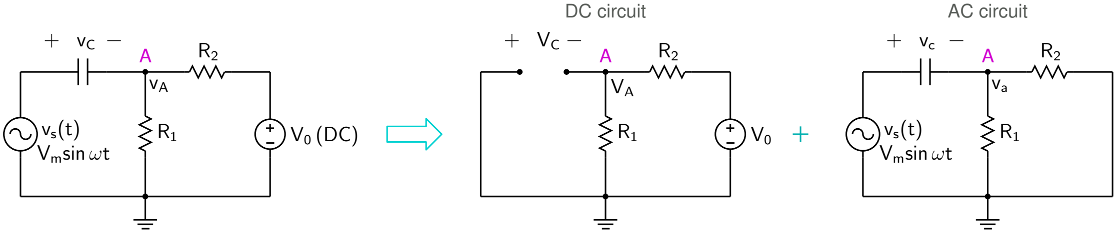
Adding (1) and (2), we get $$\frac{V_A + v_a}{R_1} + \frac{V_A + v_a - V_0}{R_2} = C\,\frac{d}{dt}\,(v_s - v_a). \quad (3)$$

RC circuit with DC + AC sources



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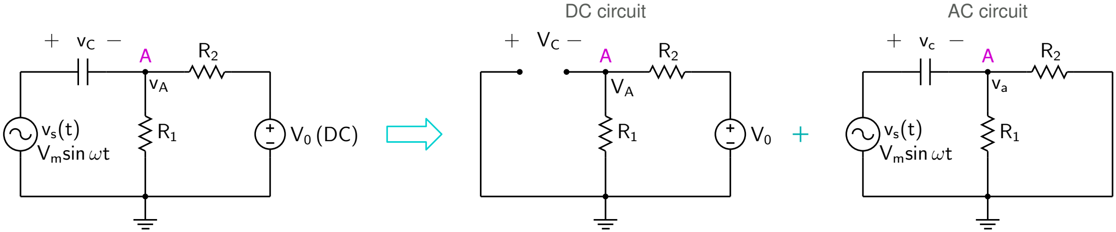
Compare with the equation obtained directly from the original circuit:

$$\frac{v_A}{R_1} + \frac{v_A - V_0}{R_2} = C\,\frac{d}{dt}\,(v_s - v_A). \qquad (4)$$



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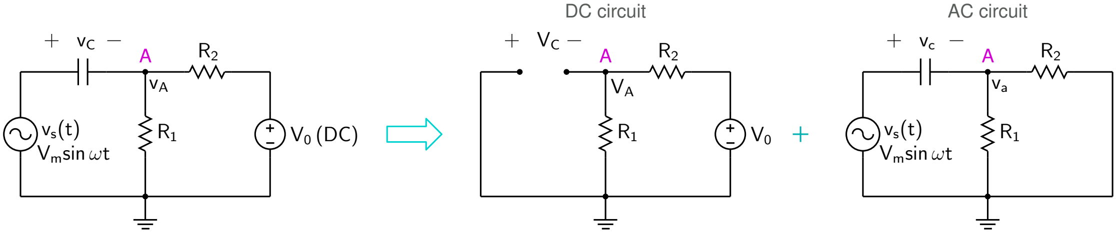
Eqs. (3) and (4) are identical since $v_A = V_A + v_a$.



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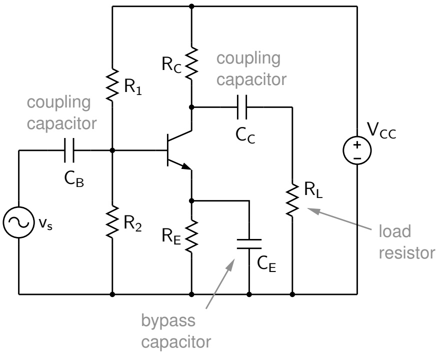
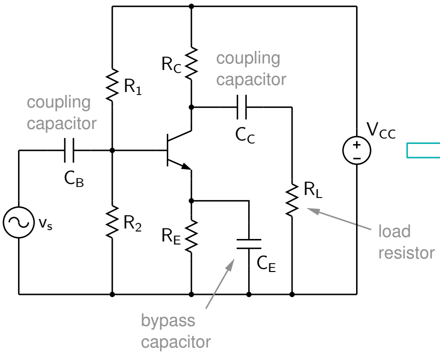
Eqs. (3) and (4) are identical since $v_A = V_A + v_a$.

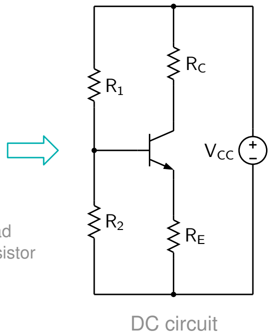
→ Instead of computing $v_A(t)$ directly, we can compute V_A and $v_a(t)$ separately, and then use $v_A(t) = V_A + v_a(t)$.

Common-emitter amplifier

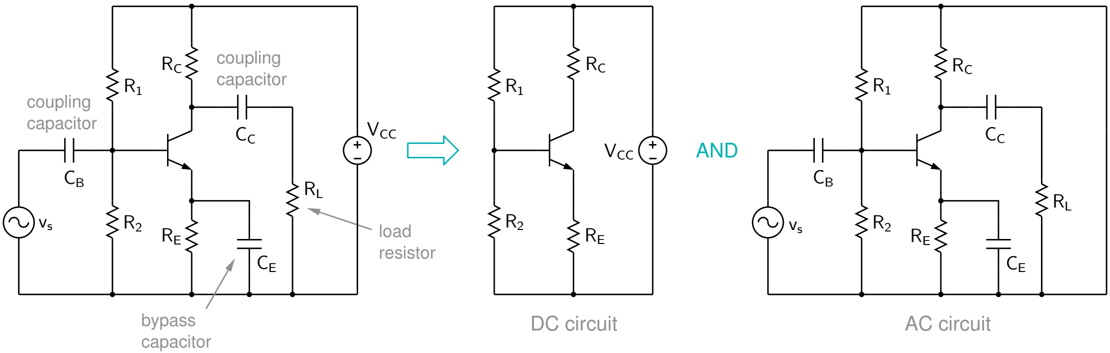


Common-emitter amplifier

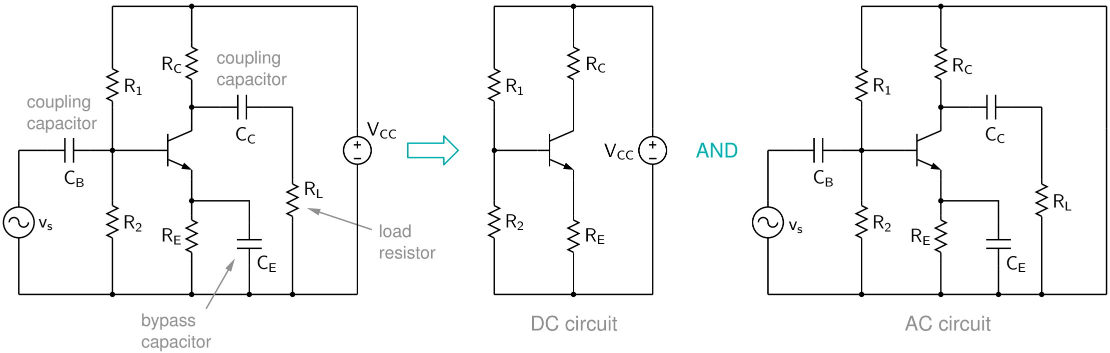




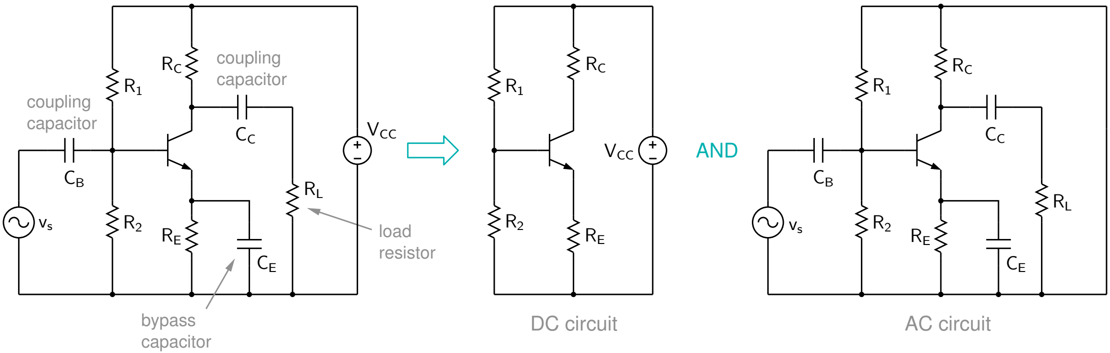
Common-emitter amplifier



Common-emitter amplifier

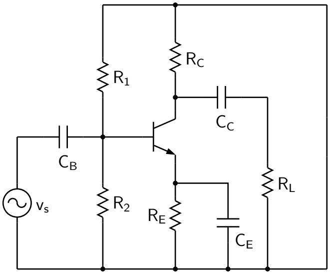


* The coupling capacitors ensure that the signal source and the load resistor do not affect the DC bias of the amplifier. (We will see the purpose of C_E a little later.)

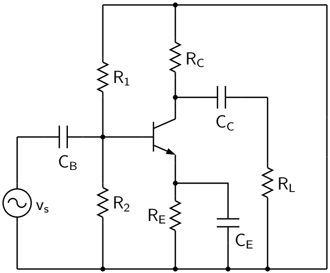


* The coupling capacitors ensure that the signal source and the load resistor do not affect the DC bias of the amplifier. (We will see the purpose of C_E a little later.)
* This enables us to bias the amplifier without worrying about what load it is going to drive.

Common-emitter amplifier: AC circuit



Common-emitter amplifier: AC circuit



* The coupling and bypass capacitors are "large" (typically, a few μF), and at frequencies of interest, their impedance is small.

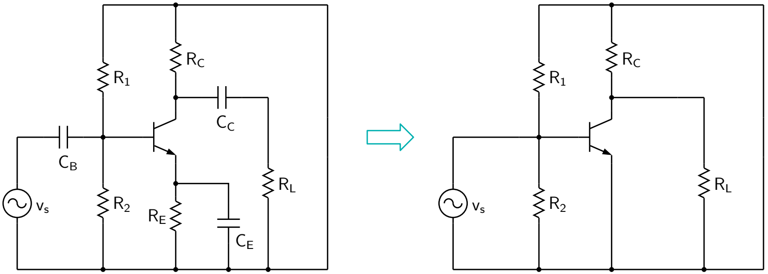
  For example, for $C = 10\,\mu F$, $f = 1\,\text{kHz}$,

  $$Z_C = \frac{1}{2\pi \times 10^3 \times 10 \times 10^{-6}} = 16\,\Omega,$$

  which is much smaller than typical values of R_1, R_2, R_C, R_E (a few kΩ).

  $\Rightarrow$ C_B, C_C, C_E can be replaced by short circuits at the frequencies of interest.

Common-emitter amplifier: AC circuit



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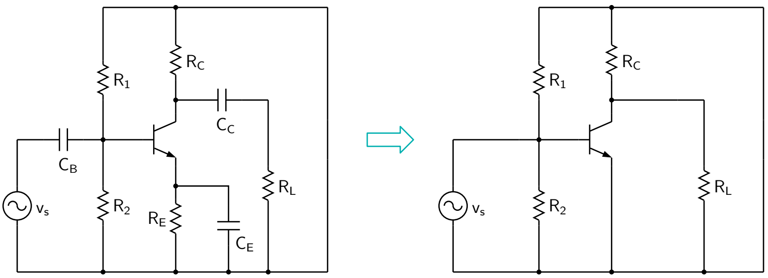

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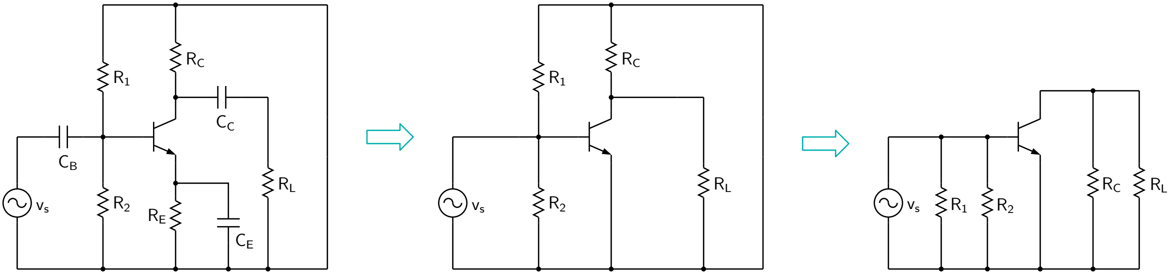
  $\Rightarrow$ C_B, C_C, C_E can be replaced by short circuits at the frequencies of interest.

* The circuit can be re-drawn in a more friendly format.

Common-emitter amplifier: AC circuit



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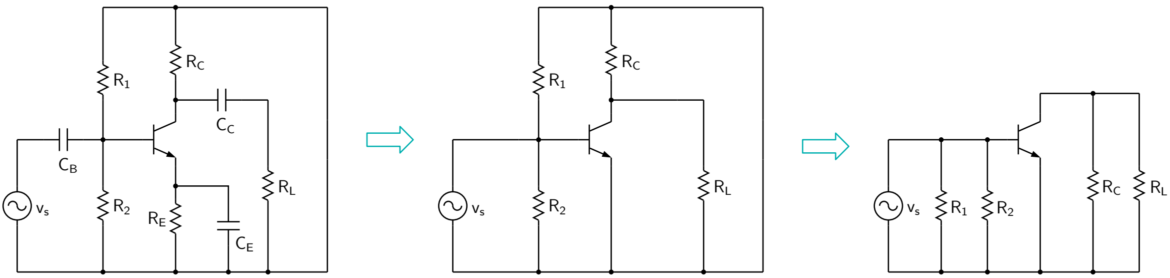
Common-emitter amplifier: AC circuit



- The coupling and bypass capacitors are "large" (typically, a few μF), and at frequencies of interest, their impedance is small.
  For example, for $C = 10\,\mu F$, $f = 1\,\text{kHz}$,

  $$Z_C = \frac{1}{2\pi \times 10^3 \times 10 \times 10^{-6}} = 16\,\Omega,$$

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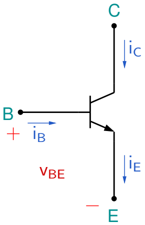
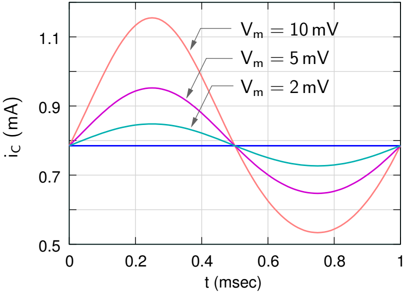
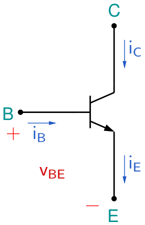
  $\Rightarrow$ C_B, C_C, C_E can be replaced by short circuits at the frequencies of interest.
- The circuit can be re-drawn in a more friendly format.
- We now need to figure out the AC description of a BJT.



$v_{BE}(t) = V_0 + V_m \sin \omega t$

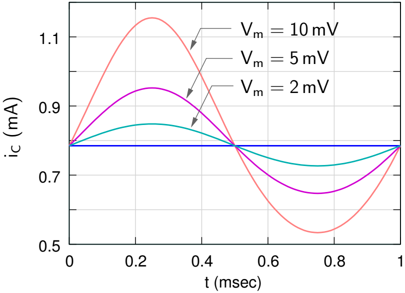
$V_0 = 0.65\,\text{V}, \quad f = 1\,\text{kHz}$



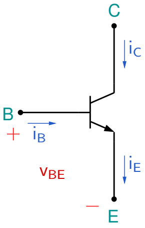


$v_{BE}(t) = V_0 + V_m \sin \omega t$

$V_0 = 0.65\,V, \quad f = 1\,kHz$



* As the v_{BE} amplitude increases, the shape of $i_C(t)$ deviates from a sinusoid $\rightarrow$ distortion.



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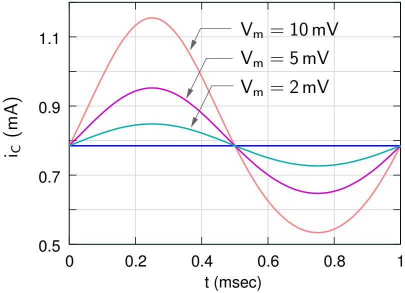
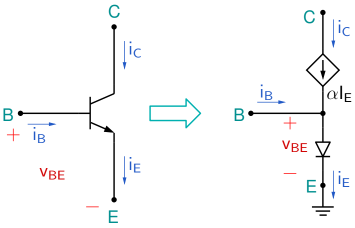
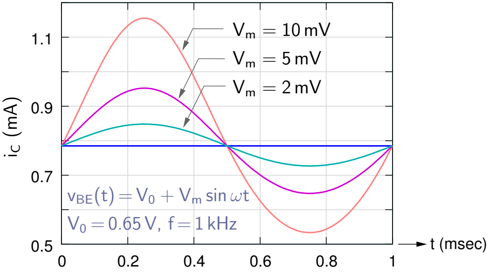
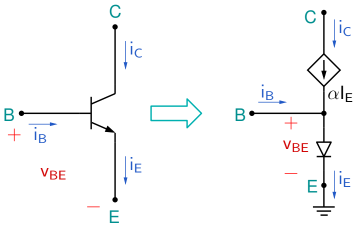


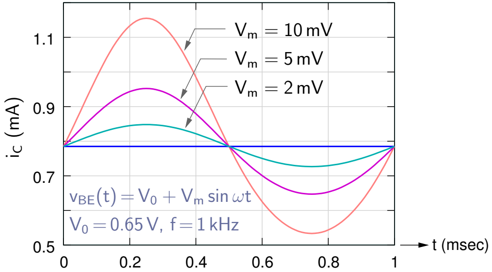
* As the v_{BE} amplitude increases, the shape of $i_C(t)$ deviates from a sinusoid $\rightarrow$ distortion.
* If $v_{be}(t)$, i.e., the time-varying part of v_{BE}, is kept small, i_C varies linearly with v_{BE}. How small? Let us look at this in more detail.





Let $v_{BE}(t) = V_{BE} + v_{be}(t)$ (bias+signal), and $i_C(t) = I_C + i_c(t)$.





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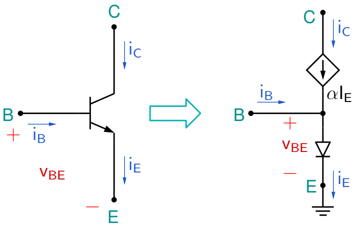
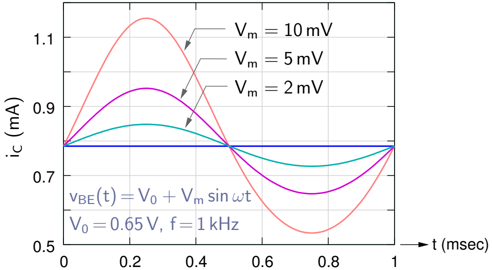
Assuming active mode, $i_C(t) = \alpha\, i_E(t) = \alpha\, I_{ES} \left[\exp\left(\frac{v_{BE}(t)}{V_T}\right) - 1 \right]$.

BJT: small-signal model





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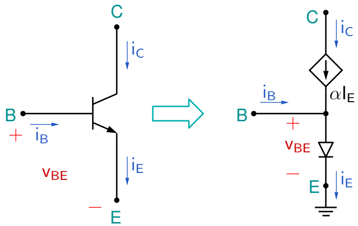
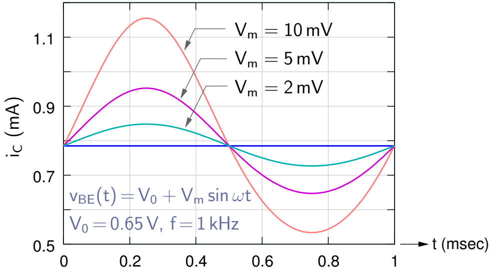
Since the B-E junction is forward-biased, $\exp\left(\frac{v_{BE}(t)}{V_T}\right) \gg 1$, and we get

$$i_C(t) = \alpha\, I_{ES}\, \exp\left(\frac{v_{BE}(t)}{V_T}\right) = \alpha\, I_{ES}\, \exp\left(\frac{V_{BE} + v_{be}(t)}{V_T}\right) = \alpha\, I_{ES}\, \exp\left(\frac{V_{BE}}{V_T}\right) \times \exp\left(\frac{v_{be}(t)}{V_T}\right).$$

BJT: small-signal model





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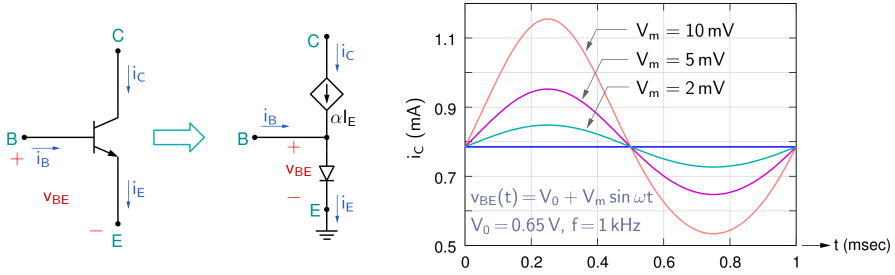
If $v_{be}(t) = 0$, $i_C(t) = I_C$ (the bias value of i_C), i.e., $I_C = \alpha\, I_{ES}\, \exp\left(\dfrac{V_{BE}}{V_T} \right)$

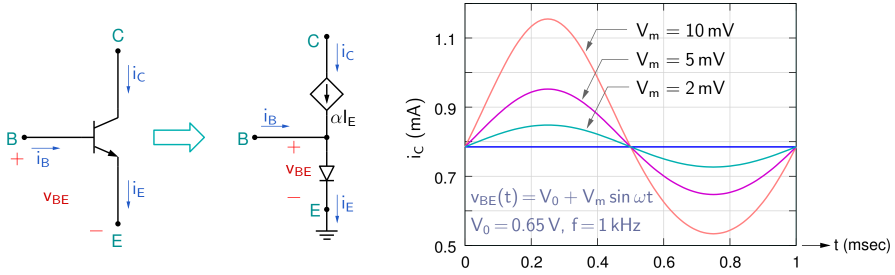
$$\Rightarrow i_C(t) = I_C\, \exp\left(\frac{v_{be}(t)}{V_T} \right).$$

BJT: small-signal model



$$i_C(t) = I_C \exp\left(\frac{v_{be}(t)}{V_T}\right) = I_C \left[1 + x + \frac{x^2}{2} + \cdots\right], \quad x = v_{be}(t)/V_T\,.$$

BJT: small-signal model



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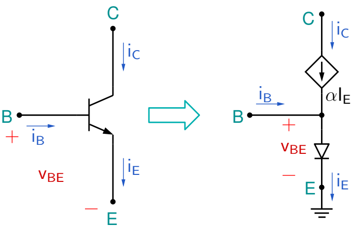
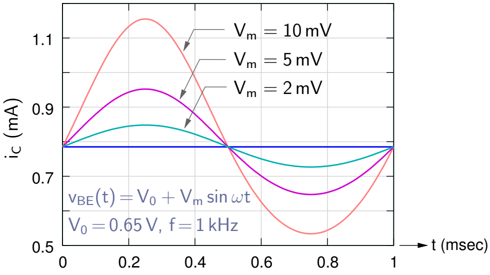
If x is small, i.e., if the amplitude of $v_{be}(t)$ is small compared to the thermal voltage V_T, we get

$$i_C(t) = I_C\left[1 + \frac{v_{be}(t)}{V_T}\right].$$

BJT: small-signal model





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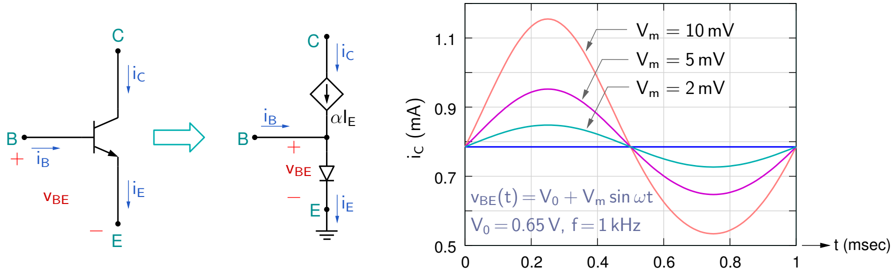
BJT: small-signal model



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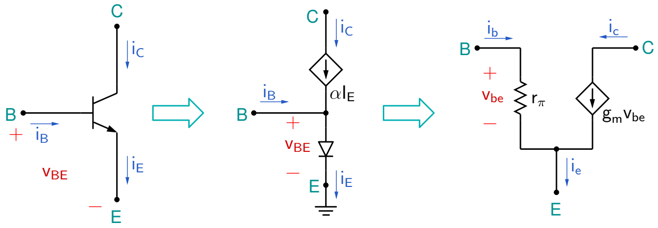
We can now see that, for $|v_{be}(t)| \ll V_T$, the relationship between $i_C(t)$ and $v_{be}(t)$ is linear, as we have observed previously.

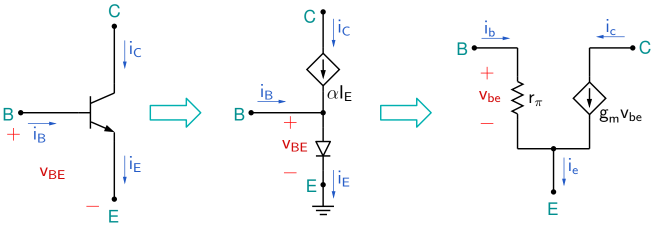
$$i_C(t) = I_C + i_c(t) = I_C\left[1 + \frac{v_{be}(t)}{V_T}\right] \Rightarrow \boxed{i_c(t) = \frac{I_C}{V_T}\, v_{be}(t)}$$



The relationship, $i_c(t) = \dfrac{I_C}{V_T}\, v_{be}(t)$ can be represented by a VCCS, $i_c(t) = g_m\, v_{be}(t)$,

where $g_m = I_C/V_T$ is the "transconductance."

BJT: small-signal model



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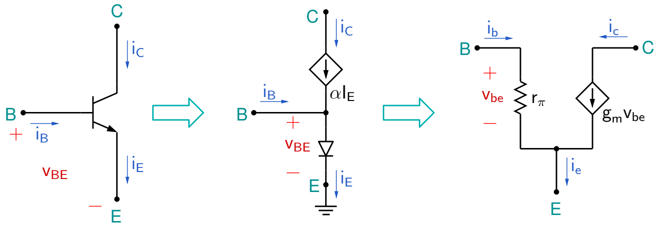
For the base current, we have,

$$i_B(t) = I_B + i_b(t) = \frac{1}{\beta}\,[I_C + i_c(t)]$$

$$\rightarrow i_b(t) = \frac{1}{\beta}\, i_c(t) = \frac{1}{\beta}\, g_m\, v_{be}(t) \rightarrow v_{be}(t) = (\beta/g_m)\, i_b(t).$$



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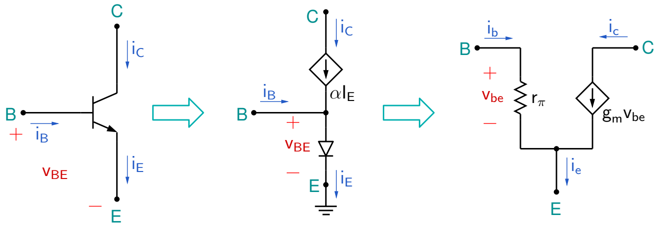
The above relationship is represented by a resistance, $r_\pi = \beta/g_m$, connected between B and E.

BJT: small-signal model



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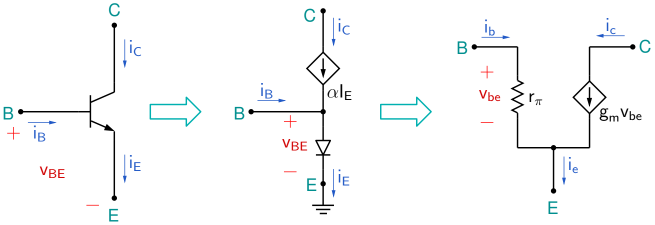
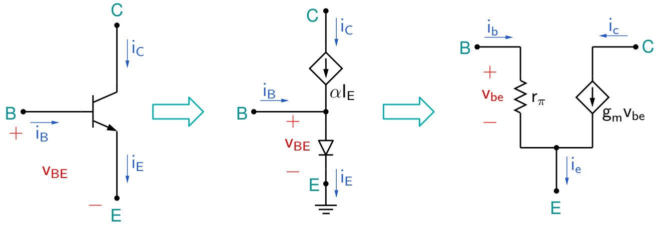
The resulting model is called the π-model for small-signal description of a BJT.

BJT: small-signal model



∗ The transconductance g_m depends on the biasing of the BJT, since $g_m = I_C/V_T$. For $I_C = 1\,mA$, $V_T \approx 25\,mV$ (room temperature), $g_m = 1\,mA/25\,mV = 40\,m℧$ (milli-mho or milli-siemens).



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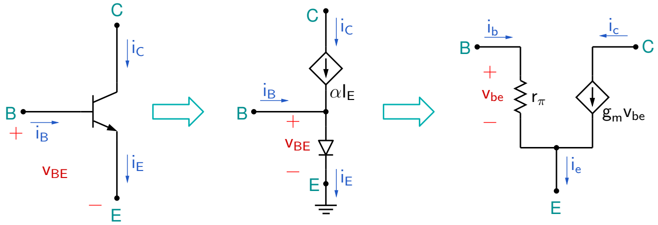
* r_π also depends on I_C, since $r_\pi = \beta/g_m = \beta\,V_T/I_C$. For $I_C = 1\,\text{m}A$, $V_T \approx 25\,\text{m}V$, $\beta = 100$, $r_\pi = 2.5\,\text{k}\Omega$.

BJT: small-signal model



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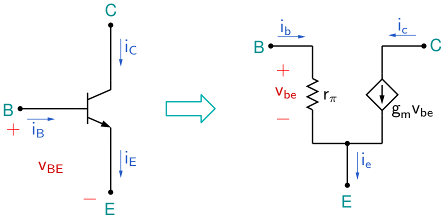
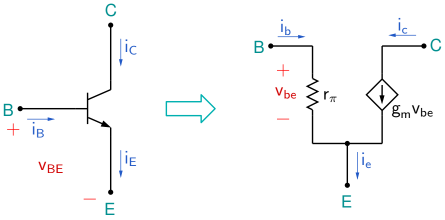
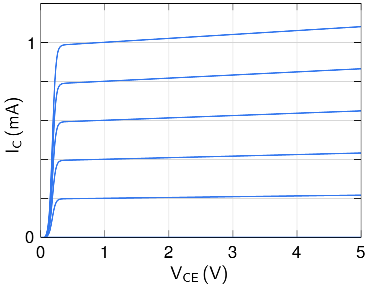
* Note that the small-signal model is valid only for small v_{be} (small compared to V_T).



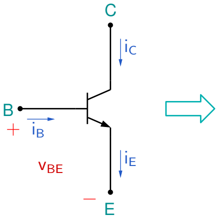
* In the above model, note that i_c is independent of v_{ce}.

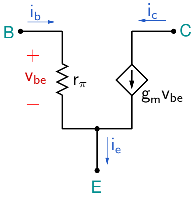


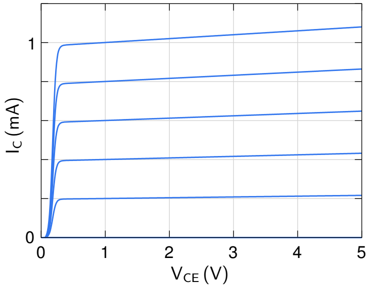


- ∗ In the above model, note that i_c is independent of v_{ce}.
- ∗ In practice, i_c does depend on v_{ce} because of the Early effect, and $\dfrac{dI_C}{dV_{CE}} \approx \text{constant} = 1/r_o$, where r_o is called the output resistance.

BJT: small-signal model







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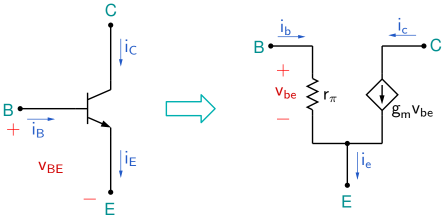
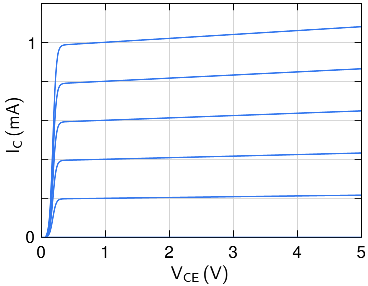
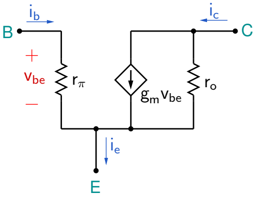
* A more accurate model includes r_o as well.







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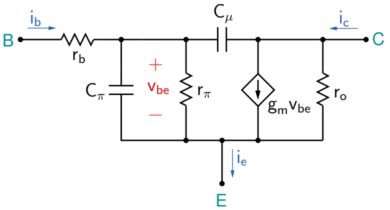
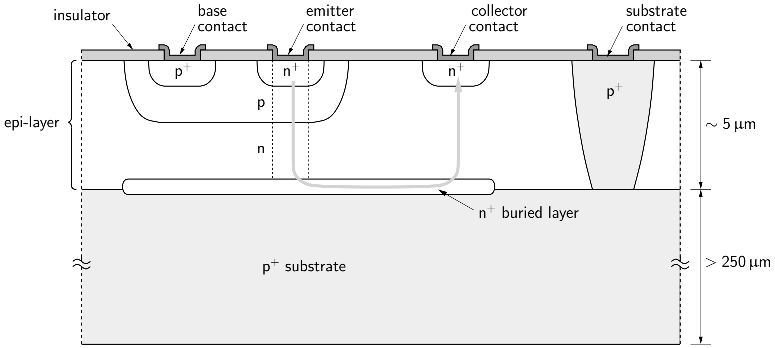
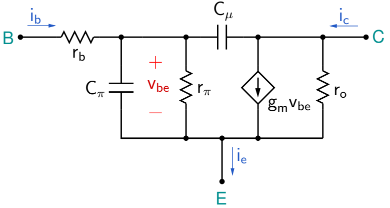
BJT: small-signal model

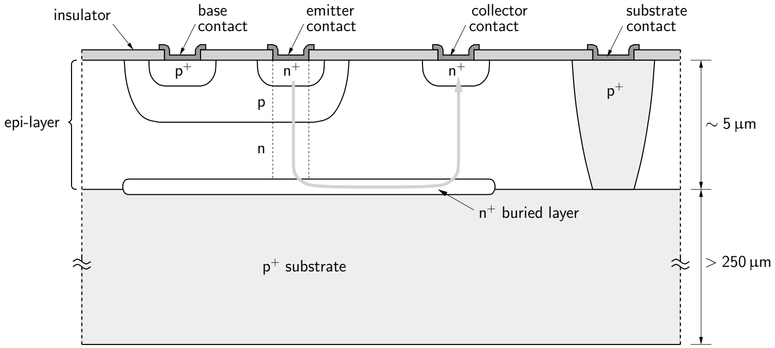




* A few other components are required to make the small-signal model complete:
  r_b: base spreading resistance
  C_π: base charging capacitance + B-E junction capacitance
  C_μ: B-C junction capacitance

BJT: small-signal model





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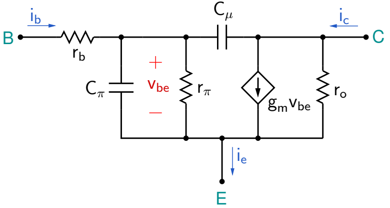
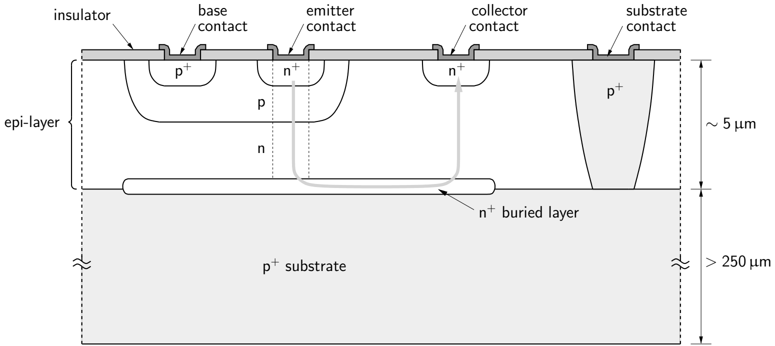
* The capacitances are typically in the pF range. At low frequencies, $1/\omega C$ is large, and the capacitances can be replaced by open circuits.

BJT: small-signal model





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- The capacitances are typically in the pF range. At low frequencies, $1/\omega C$ is large, and the capacitances can be replaced by open circuits.
- Note that the small-signal models we have described are valid in the active region only.