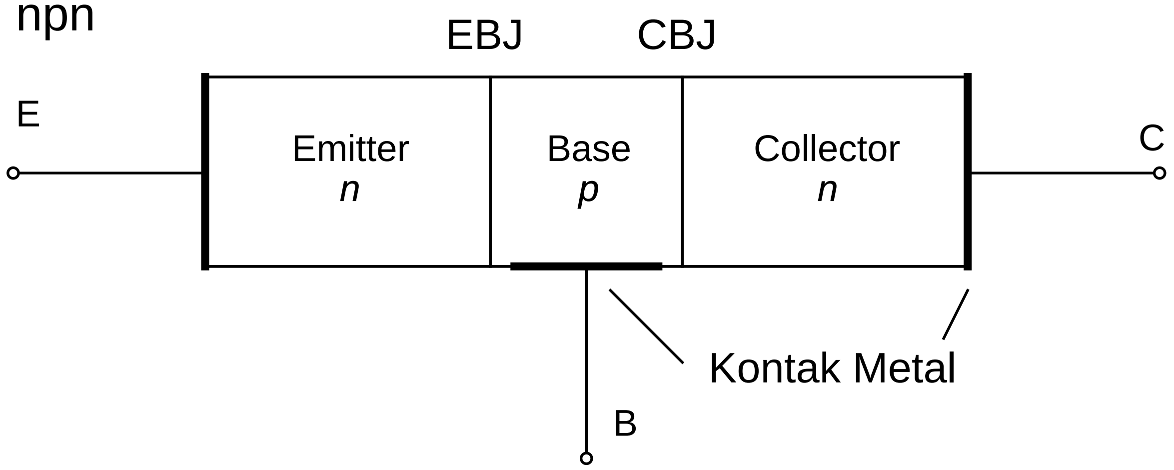
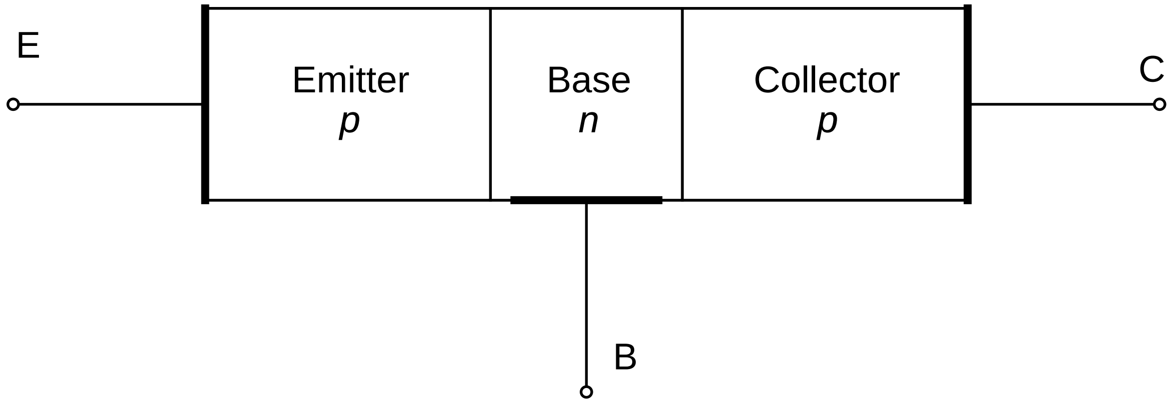
Struktur Fisik *Bipolar Junction Transistor* (BJT)

npn



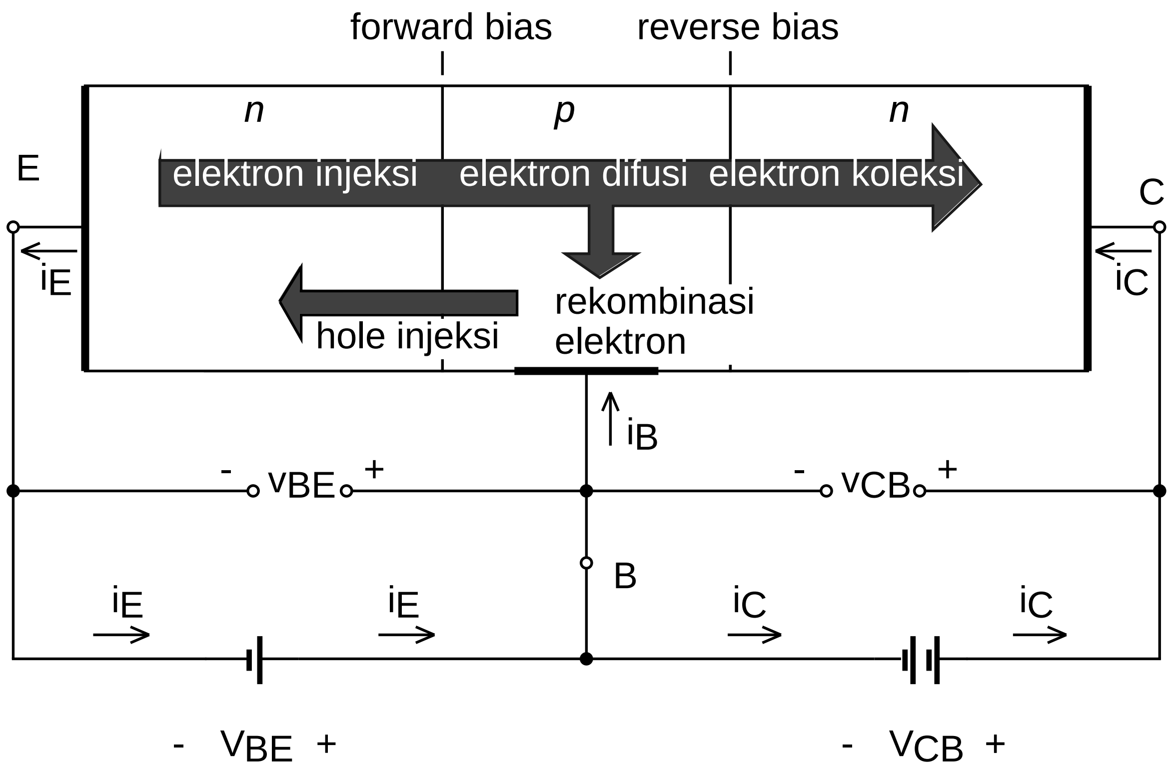
pnp



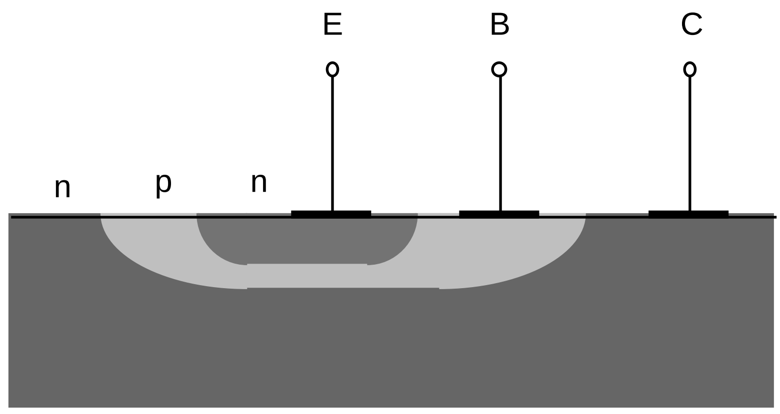
Mode Operasi BJT

Mode	Junction E-B	Junction C-B
cut-off	reverse	reverse
active	forward	reverse
saturation	forward	forward

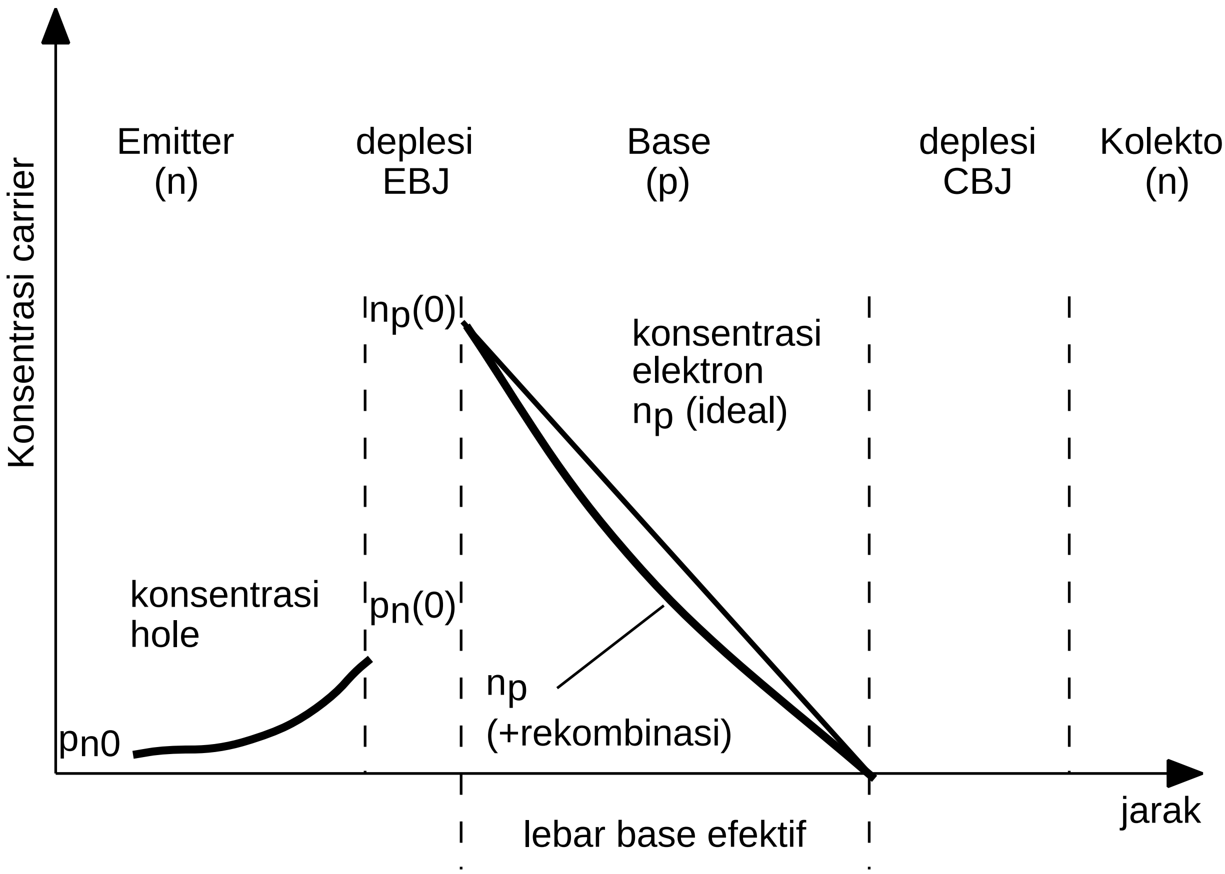
Aliran Arus pada BJT npn



Struktur Planar BJT npn



Persamaan Arus pada BJT npn



arus kolektor $\qquad i_C = I_S \exp(v_{BE}/V_T)$

arus basis $\qquad i_B = i_C / \beta$

$i_B = I_S / \beta \exp(v_{BE}/V_T)$

arus emitor

$i_E = i_C + i_B$ (KCL) $\qquad i_C = \alpha \; i_E$

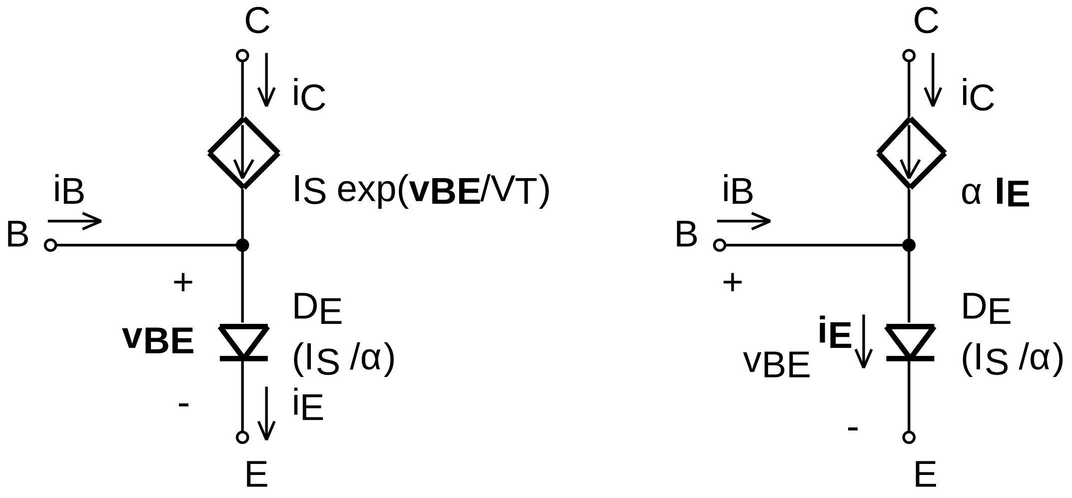
$i_E = i_C (\beta + 1)/\beta \qquad \alpha = \beta/(\beta + 1)$

$i_E = I_S(\beta + 1)/\beta \; \exp(v_{BE}/V_T) \qquad i_E = I_S/\alpha \; \exp(v_{BE}/V_T)$

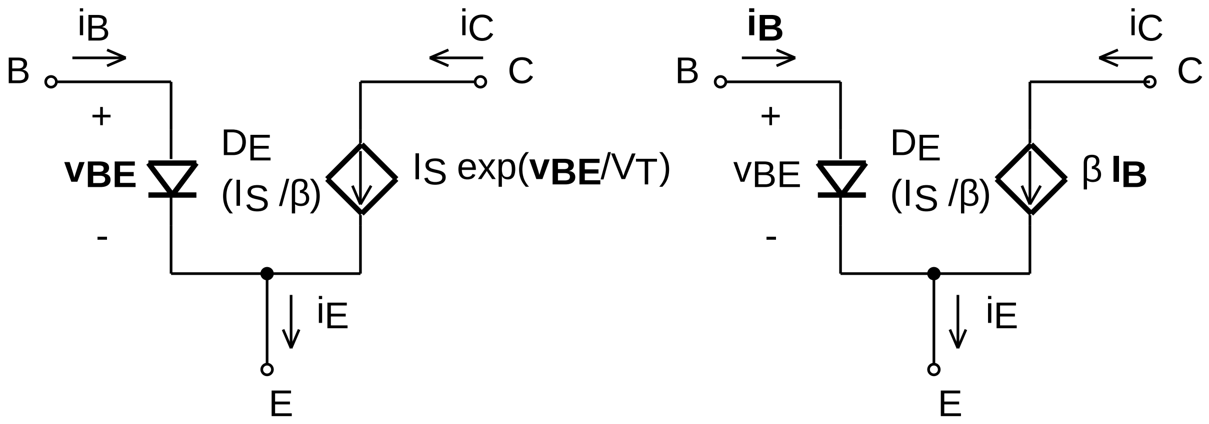
$$\beta = \alpha/(1-\alpha)$$

Model Rangkaian Pengganti (Sinyal Besar)

model T (letak simpul bersama di basis)



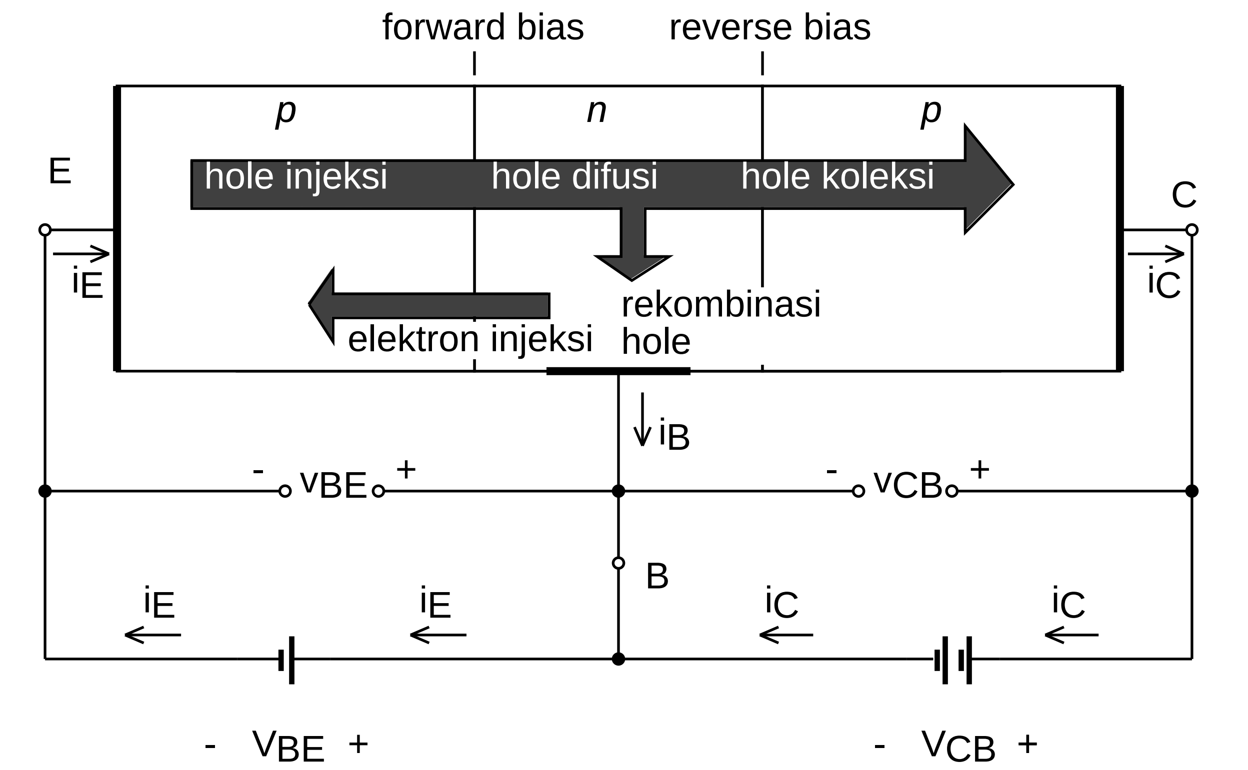
model π (letak simpul bersama di emitor)

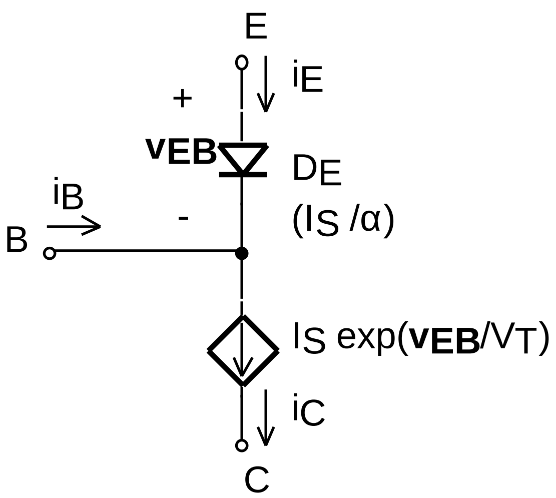


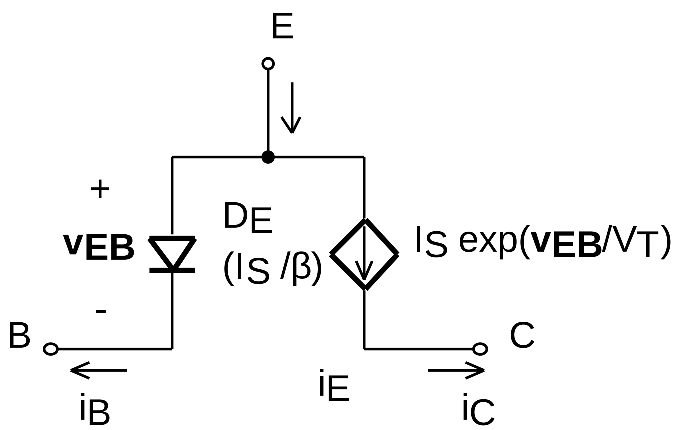
besaran kontrol berupa tegangan (v_{BE}) atau arus (i_B)

faktor idealitas (N) pada persamaan arus junction di atas adalah 1 (satu)

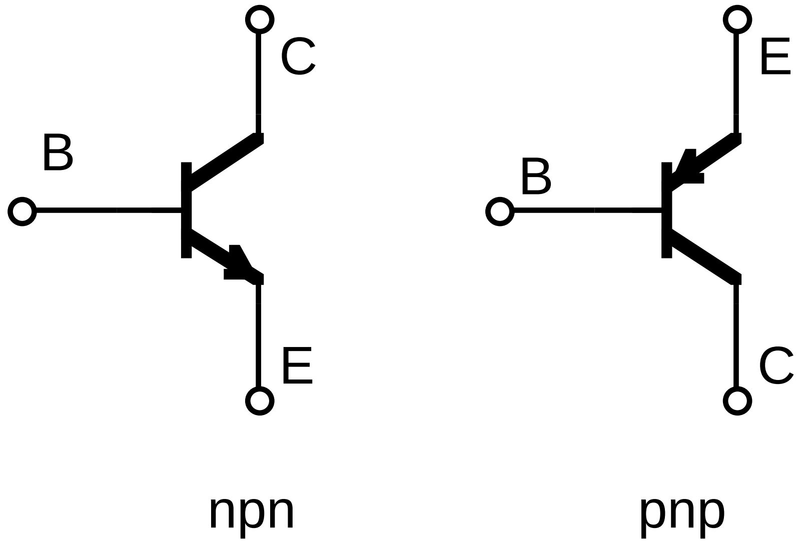
arus mundur kolektor-basis (i_{CBO}) dianggap nol


forward bias
reverse bias
p
n
p
E
hole injeksi
hole difusi
hole koleksi
C
iE
iC
rekombinasi
hole
elektron injeksi
iB
- vBE +
- vCB +
B
iE
iE
iC
iC
- VBE +
- VCB +

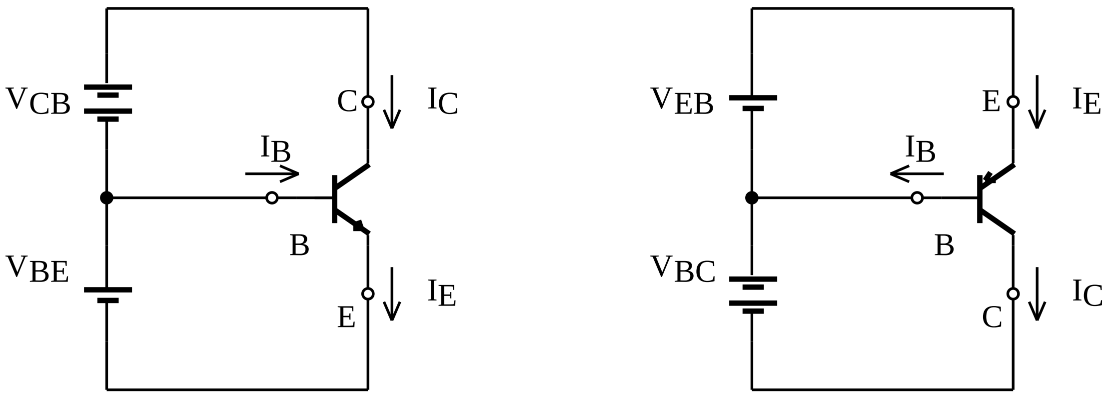

E
iE
+
vEB
DE
(IS /α)
iB
-
B
IS exp(vEB/VT)
iC
C


E
+
DE
vEB
(IS /β)
IS exp(vEB/VT)
-
B
C
iB
iE
iC

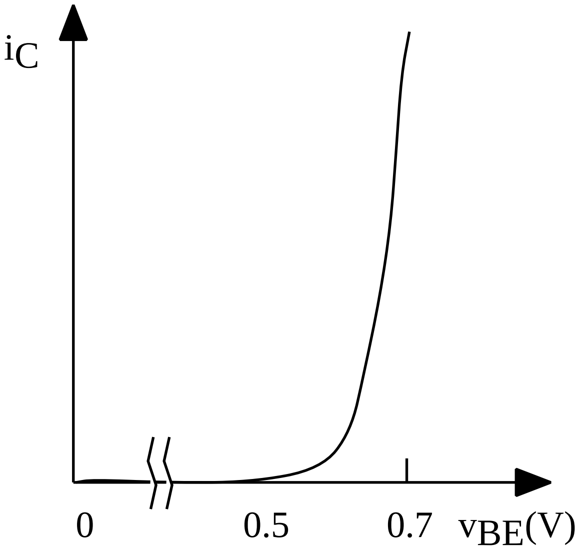
Simbol BJT

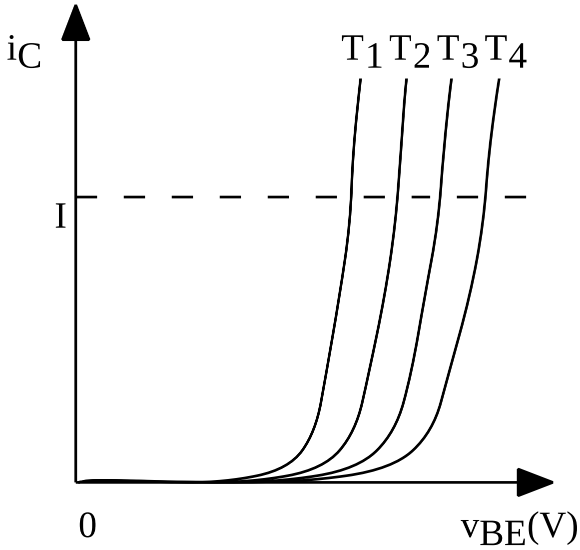


Polaritas tegangan dan arah arus



Representasi Grafis Karakteristik BJT





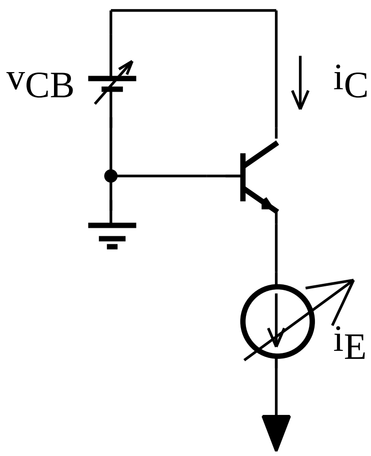
$T_1 > T_2 > T_3 > T_4$

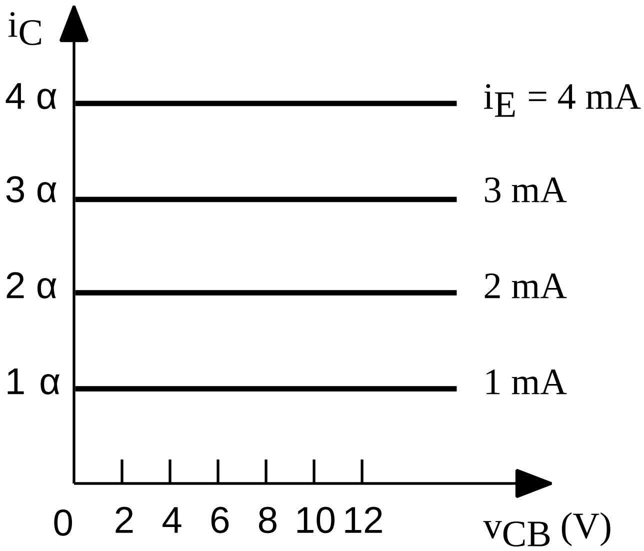
kurva i_C - v_{BE}

$i_C = I_S \exp (v_{BE}/V_T)$

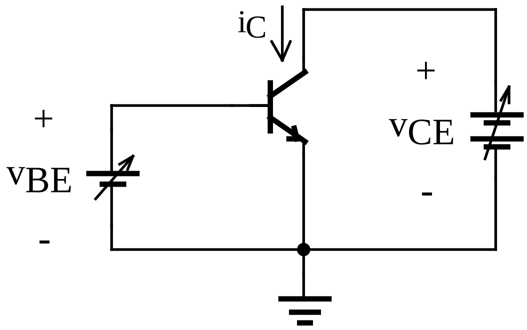
Efek temeperatur kurva i_C - v_{BE}

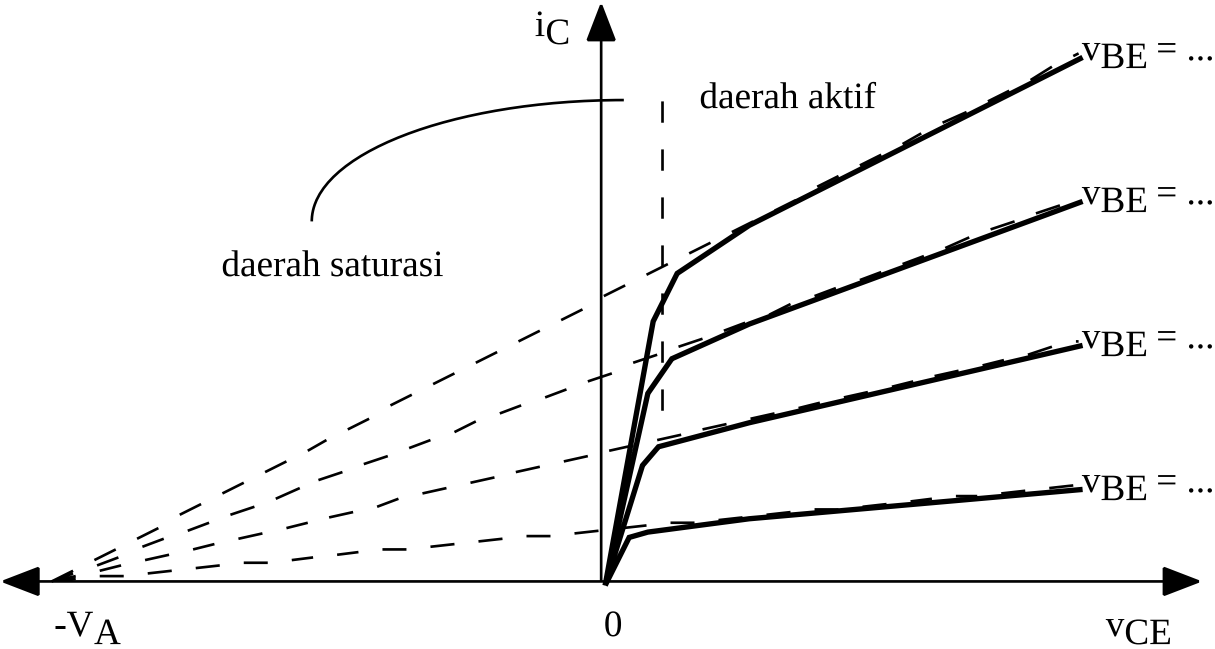
v_{BE} naik dengan suhu sebesar -2 mV / ^oC





Tegangan Early





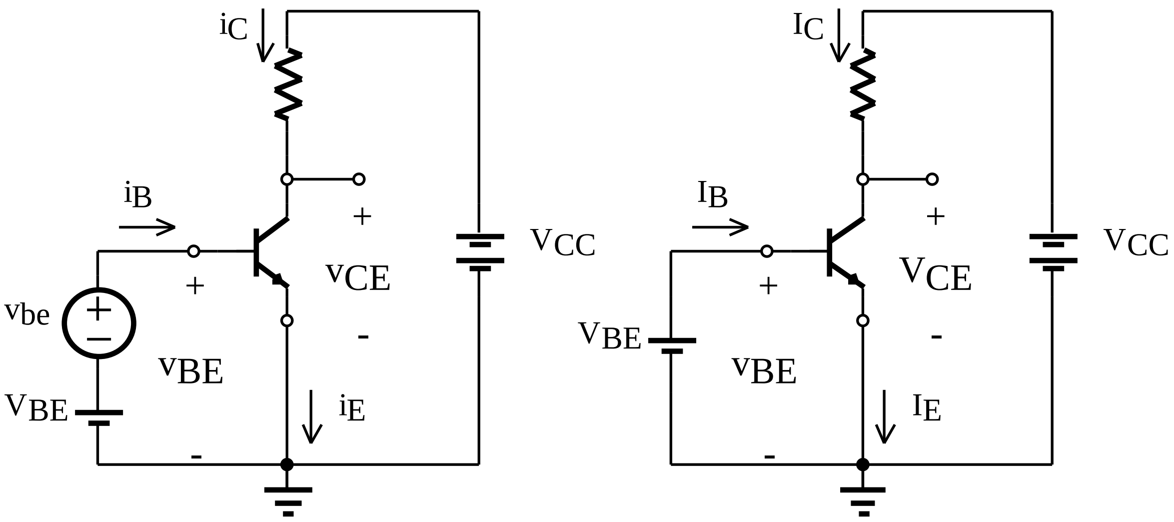
penyebab:
perubahan lebar efektif basis akibat penambahan daerah deplesi kolektor-basis dengan peningkatan tegangan v_{CE}

Perubahan dianggap linier

$$i_C = I_S \exp(v_{BE}/V_T)\,(1 + v_{CE}/V_A)$$

$$r_o \equiv \left(\frac{\partial i_C}{\partial v_{CE}}\right)^{-1} \approx V_A/I_C$$

Transistor sebagai Penguat



$v_{BE} = V_{BE} + v_{be}$

(a) rangkaian dengan sinyal lengkap (b) rangkaian DC dari (a)

Titik Kerja (Keadaan DC)

$I_C = I_S \exp(V_{BE}/V_T)$

$I_E = I_C / \alpha$

$I_B = I_C / \beta$

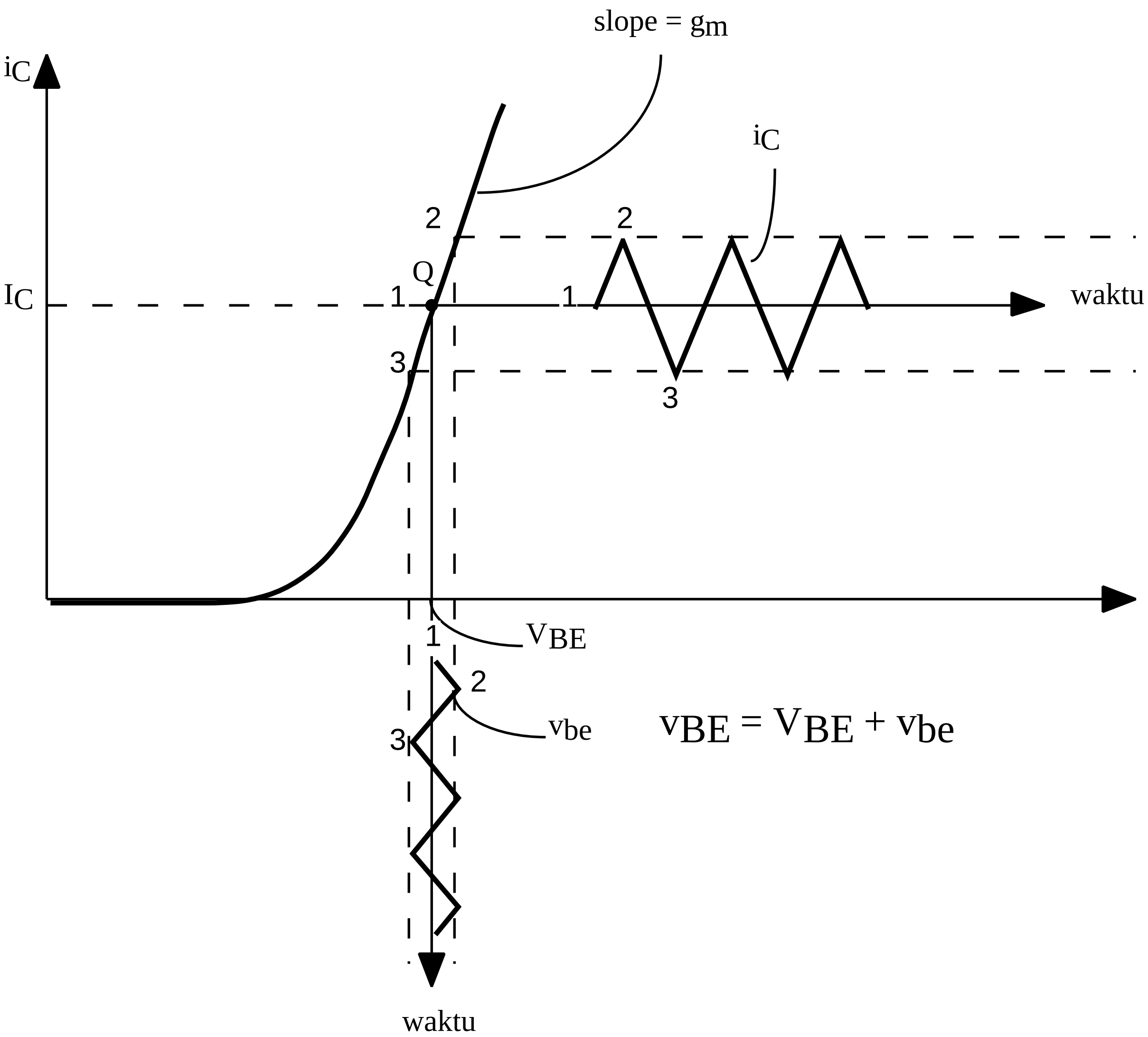
$V_C = V_{CE} = V_{CC} - I_C R_C$

Persamaan Arus Kolektor

$i_C = I_S \exp(v_{BE}/V_T) = I_S \exp((\mathbf{V_{BE} + v_{be}})/V_T)$

$i_C = I_S \exp(V_{BE}/V_T) \exp(v_{be}/V_T) = I_C \exp(v_{be}/V_T)$

Model Sinyal Kecil dan Transkonduktansi



$v_{BE} = V_{BE} + v_{be}$

arus kolektor	$i_C = I_C \exp(v_{be}/V_T)$
bila $v_{be} << V_T$, maka	$i_C \approx I_C (1 + v_{be}/V_T) = I_C + i_c$
aproksimasi sinyal kecil	$i_c = (I_C/V_T)\, v_{be}$
atau	$i_c = g_m v_{be}$
dimana	$g_m = (I_C/V_T)$

Arus dan Resistansi Input Basis

arus basis $i_B = i_C / \beta = (I_C + i_c)/\beta$

$i_B = I_C / \beta + (1/\beta)(I_C/V_T)\, v_{be}$

juga $i_B = I_B + i_b$

sehingga $i_b = (1/\beta)(I_C/V_T)\, v_{be} = (g_m/\beta)\, v_{be}$

atau $i_b = v_{be} / r_\pi$

dimana $r_\pi = \beta/g_m$ atau $r_\pi = V_T/I_B$

Arus dan Resistansi Input Emitor

arus emitor $i_E = i_C / \alpha = (I_C + i_c)/\alpha = I_E + i_e$

dimana $i_e = i_c / \alpha = g_m v_{be} / \alpha = (I_C / \alpha V_T)\, v_{be} = (I_E/V_T)\, v_{be}$

$i_e = v_{be} / r_e$ dimana $r_e = V_T / I_E$

$r_e = \alpha / g_m \approx 1/ g_m$

Hubungan Resistansi Input Basis dan Emitor

tegangan sinyal kecil pada basis $v_{be} = r_\pi i_b = r_e i_e$

sehingga $r_\pi = i_e r_e / i_b$

$$r_\pi = (\beta + 1) r_e$$

Penguatan Tegangan

tegangan sinyal kecil pada kolektor

$$v_C = V_{CC} - i_C R_C$$

$$= V_{CC} - (I_C + i_c) R_C$$

$$= (V_{CC} - I_C R_C) - i_c R_C$$

$$v_C = V_C - i_c R_C$$

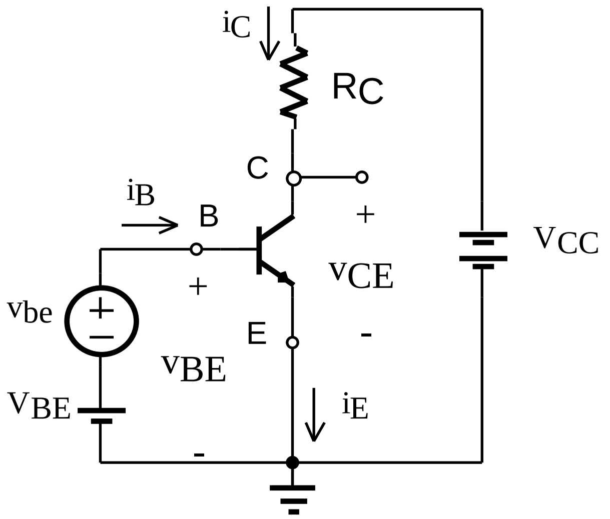
sehingga $v_c = - i_c R_C = - g_m v_{be} R_C$

$$= (- g_m R_C) v_{be}$$

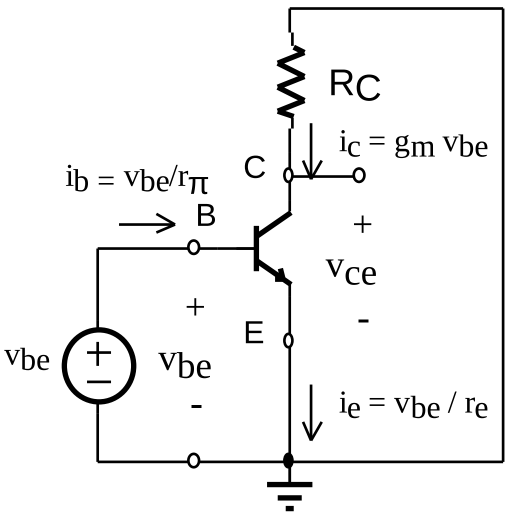
penguatan tegangan

$$v_c / v_{be} = - g_m R_C$$

Rangkaian Pengganti Sinyal Kecil

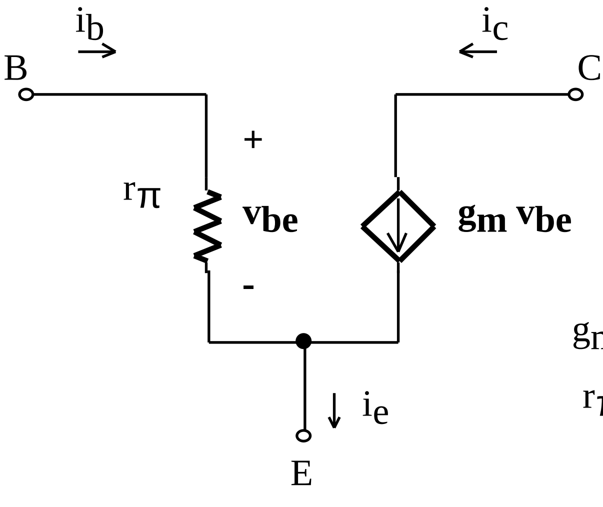


Rangkaian sinyal lengkap



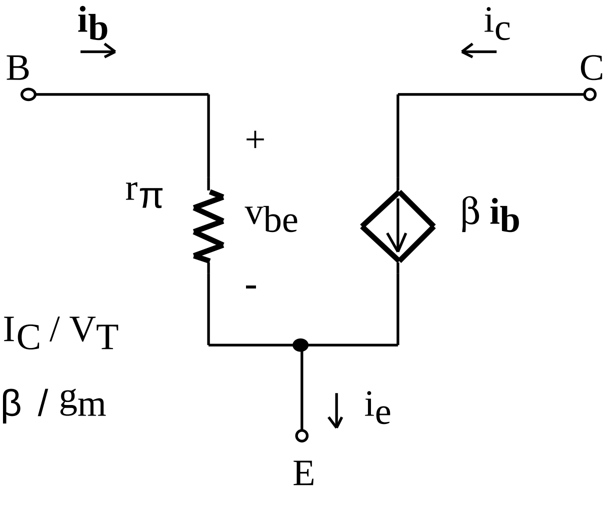
Rangkaian sinyal kecil

Model Hybrid-π



$g_m = I_C / V_T$

$r_\pi = \beta / g_m$



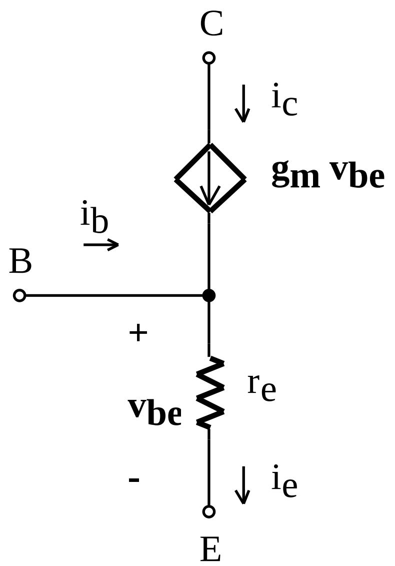
$i_e = v_{be} / r_\pi + g_m v_{be} = v_{be} / r_\pi (1 + g_m r_\pi)$

$= v_{be} / r_\pi (1 + \beta)$

$i_e = v_{be} / r_e$

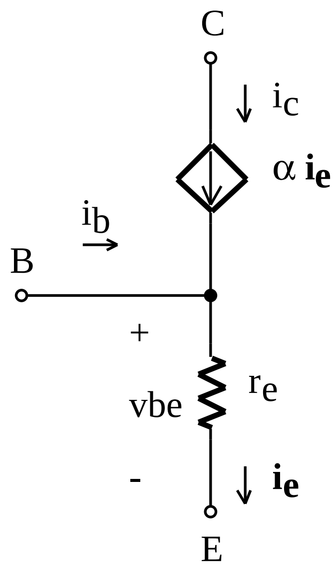
$g_m v_{be} = g_m r_\pi i_b = \beta i_b$

Model T



$g_m = I_C / V_T$

$r_e = \alpha / g_m$



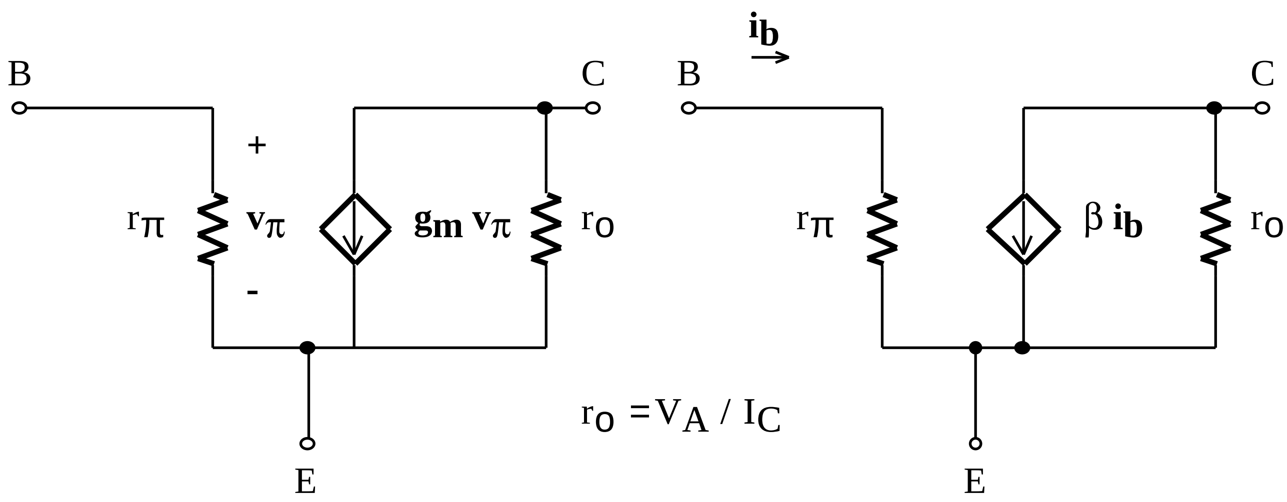
$i_b = v_{be} / r_e - g_m v_{be} = v_{be} / r_e (1 - g_m r_e)$

$= v_{be} / r_e (1 - \alpha) = v_{be} / r_e (1 - \beta/(\beta+1))$

$i_b = v_{be} / (r_e (\beta+1)) = v_{be} / r_\pi$

$g_m v_{be} = g_m r_e i_e = \alpha i_e$

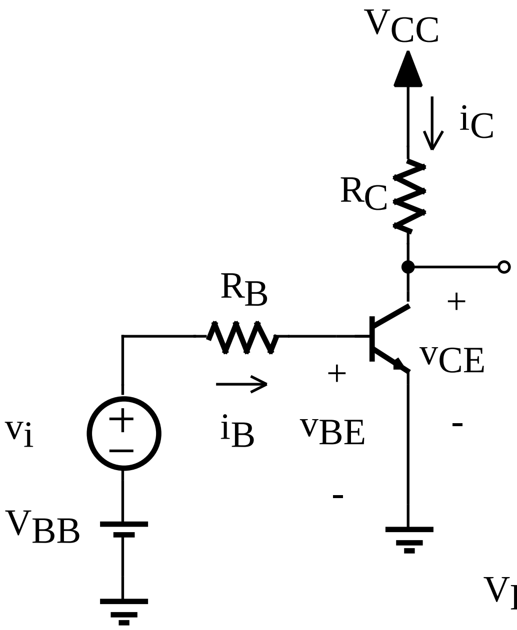
Penambahan Efek Early pada Model Hybrid-π



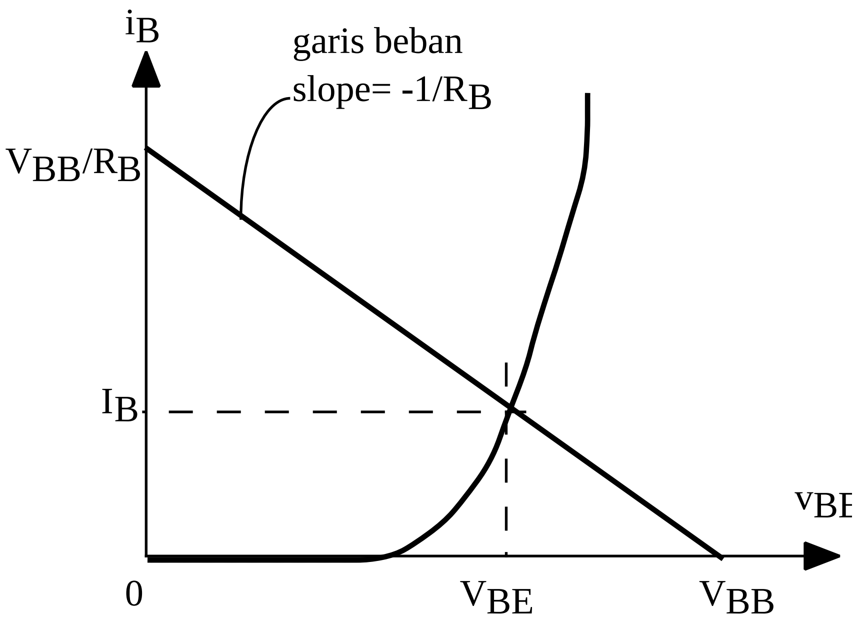
$r_o = V_A / I_C$

$$v_o = -i_c R_C = -g_m v_{be} (R_C // r_o)$$

Analisis Grafis



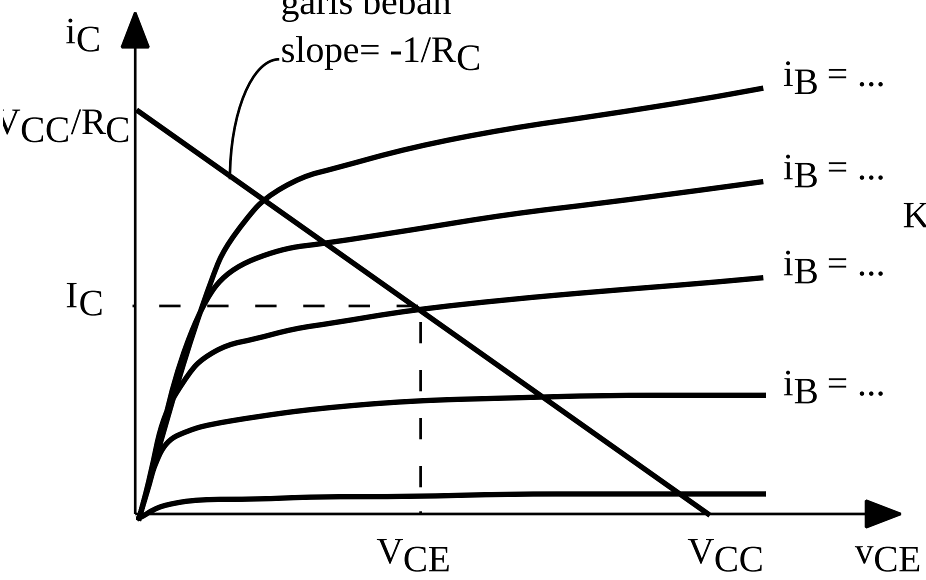
$v_{CE} = V_{CC} - i_C R_C$



Karakteristik Transfer Input

garis beban

$i_B = (V_{BB} - v_{BE}) / R_B$

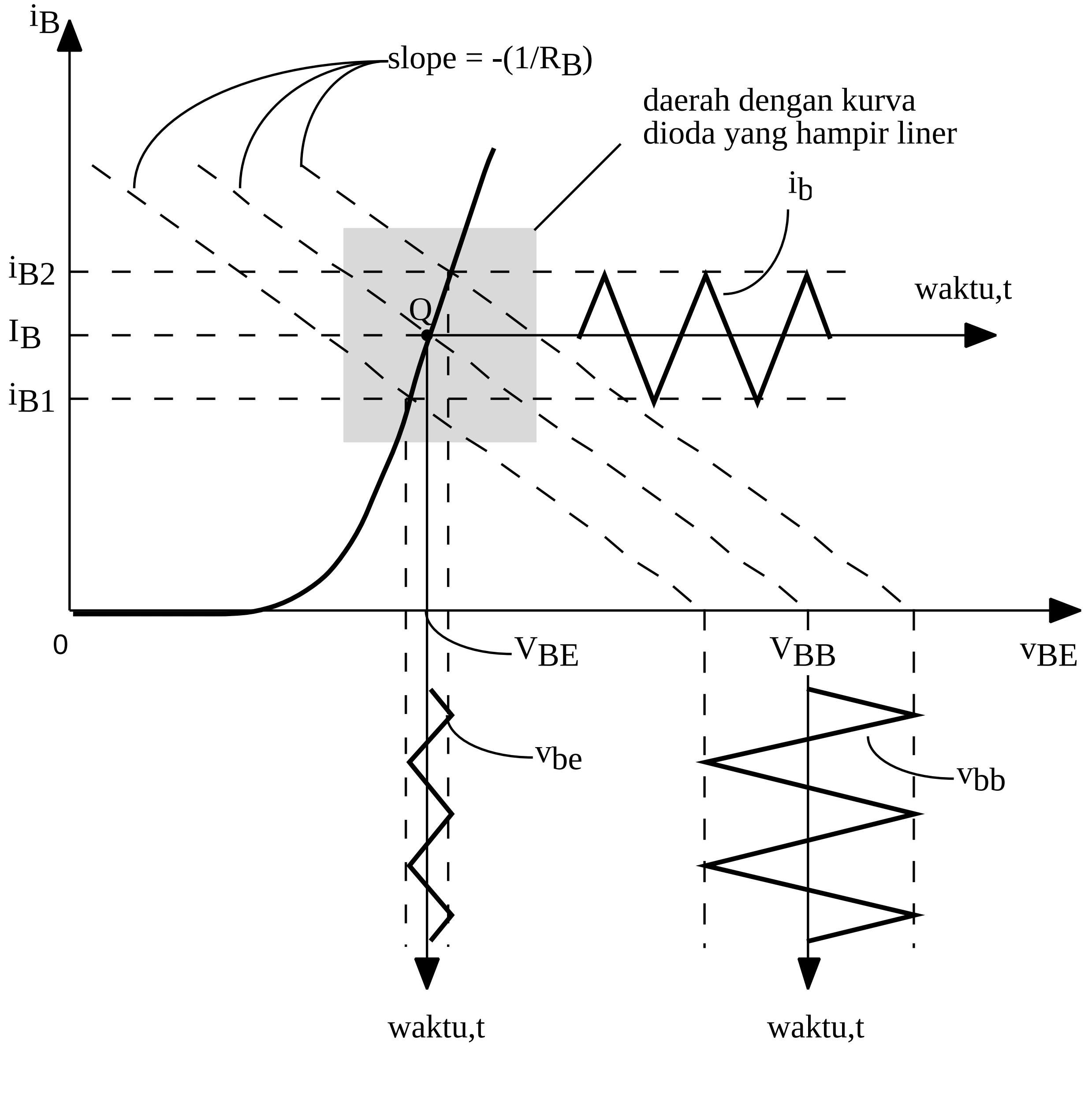


Karakteristik Transfer Output

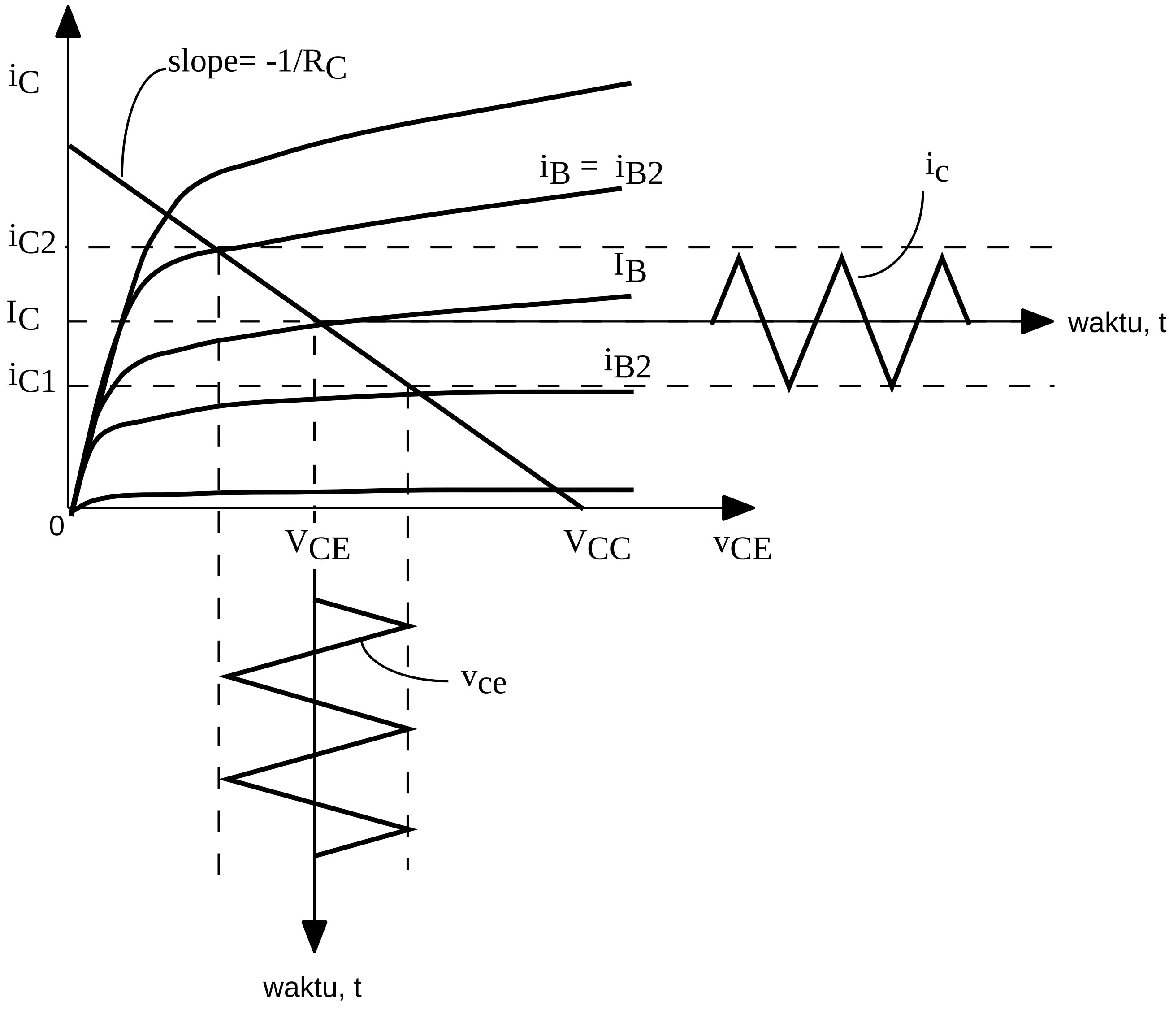
garis beban

$i_C = (V_{CC} - v_{CE}) / R_C$

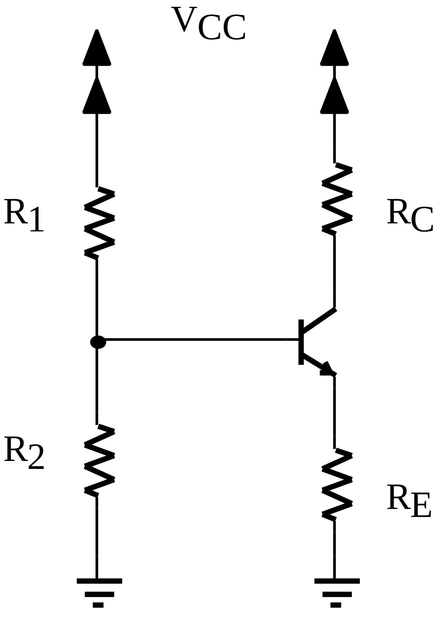
Kurva Transfer Karakteristik Input



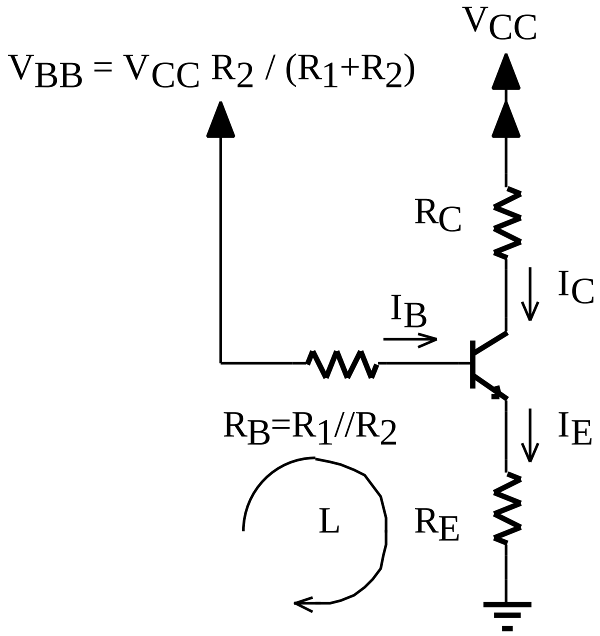
Kurva Transfer Karakteristik Ouput



Rangkaian Bias Catu Daya Tunggal



Rangkaian nyata



Rangkaian untuk/hasil analisis dengan rangkaian basis diubah ke struktur thevenin

$$V_{BB} = I_B R_B + V_{BE} + I_B(\beta+1) R_E$$

$$I_B = (V_{BB}-V_{BE})/(R_B + R_E(\beta+1))$$

$$I_E = (V_{BB}-V_{BE})/(R_E+R_B/(\beta+1))$$

Untuk menurunkan sensitivitas I_E terhadap temperatur

$$V_{BB} >> V_{BE} \quad \text{dan} \quad R_E >> R_B / (\beta+1)$$

Rule of thumb:

$$V_{BB} = (1/3)\, V_{CC}$$

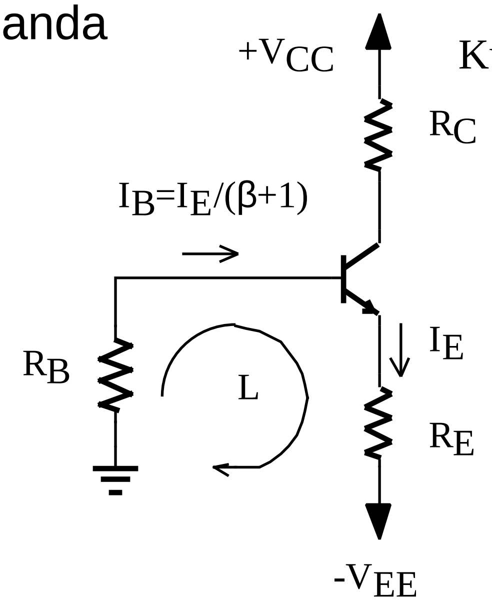
$$V_{CE} = (1/3)\, V_{CC}$$

Rangkaian Bias Catu Daya Ganda

$V_{EE} = I_B R_B + V_{BE} + I_B(\beta+1) R_E$

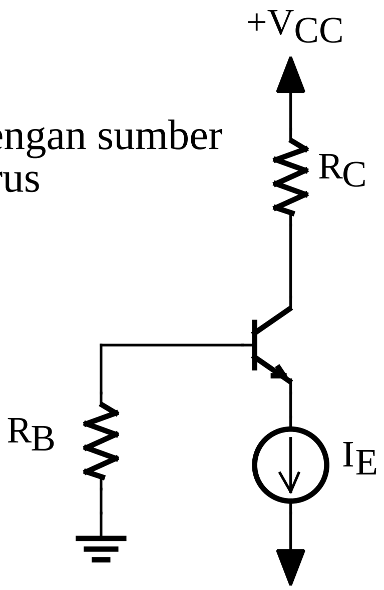
$I_B = (V_{EE}-V_{BE})/(R_B + R_E (\beta+1))$

$I_E = (V_{EE}-V_{BE})/(R_E + R_B/(\beta+1))$

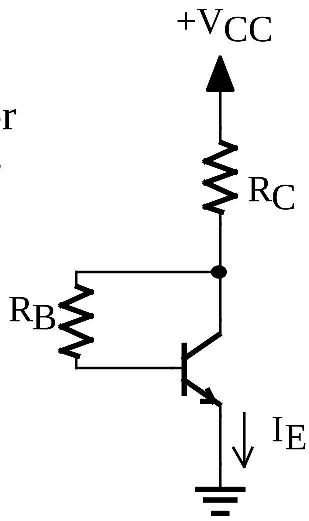


Rangkaian Bias Lain

(a) dengan sumber arus



(b) dengan resistor kolektor-basis

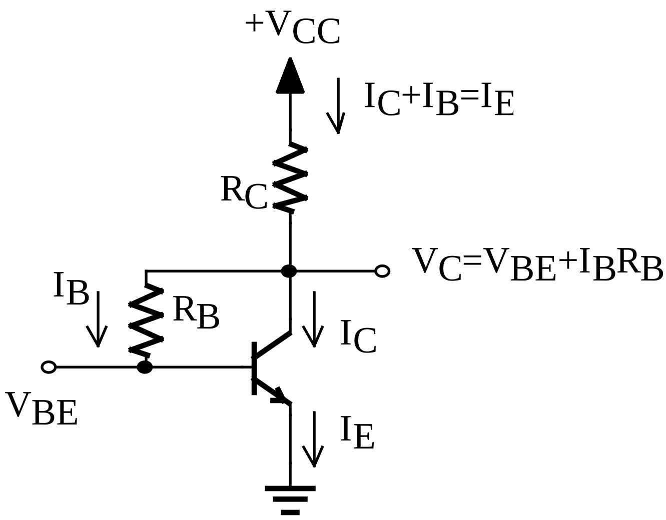


analisis rangkaian (b)

$V_{CC} = I_E R_C + I_B R_B + V_{BE}$

$V_{CC} = I_E R_C + \mathbf{I_E} R_B /\mathbf{(\beta+1)} + V_{BE}$

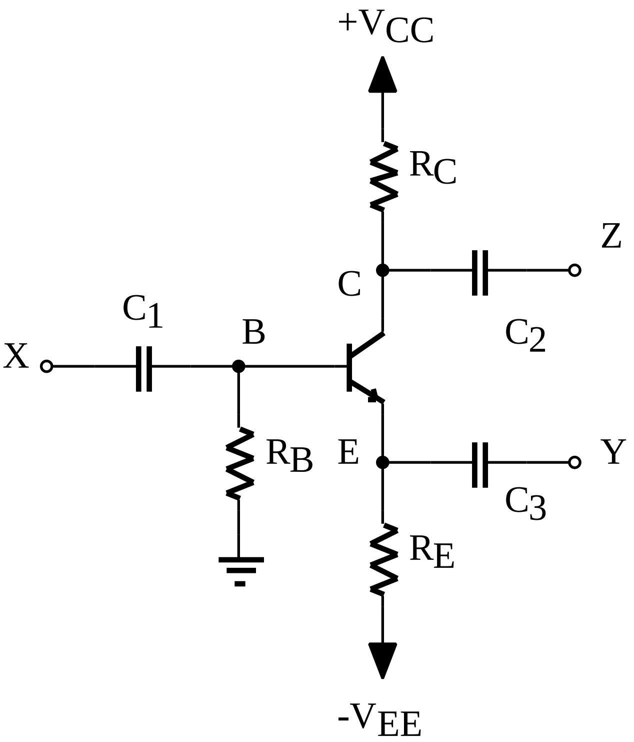
$I_E = (V_{CC}-V_{BE})/(R_C + R_B /(\beta+1))$



Untuk menurunkan sensitivitas I_E terhadap β

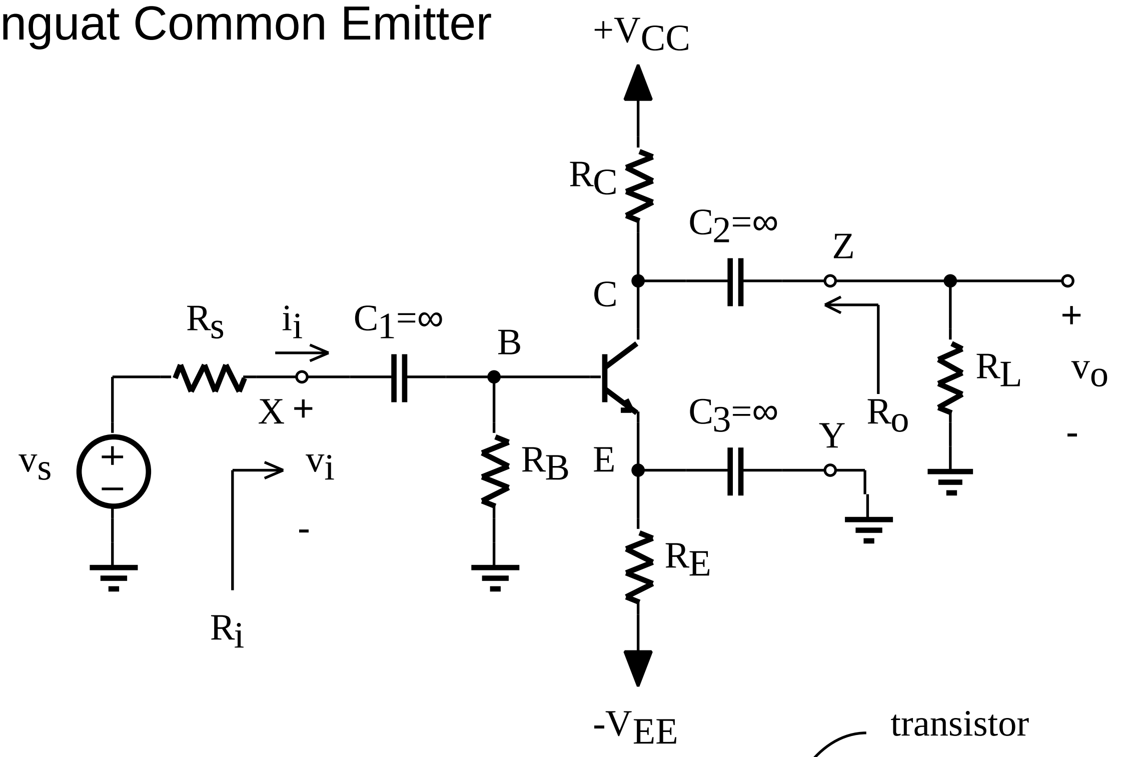
$R_C >> R_B / (\beta+1)$

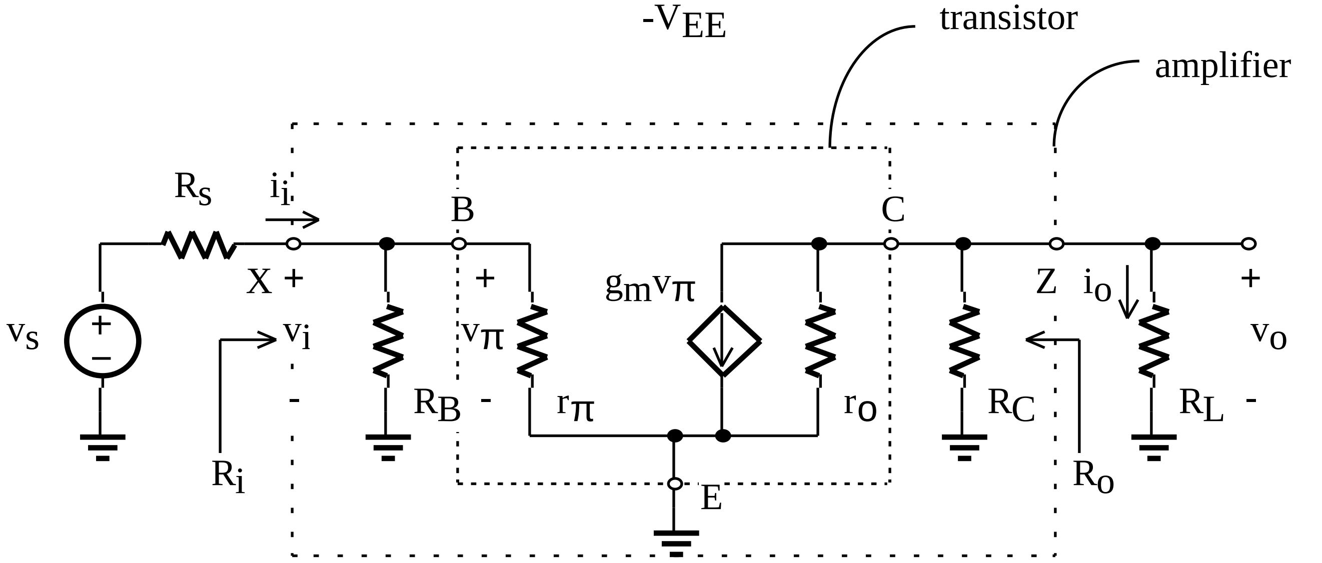
Rangkaian Dasar Penguat Satu Tingkat BJT



Jenis Penguat	Node Common (grounded)	Node Input	Node Output
Common Emitter	Y (emitter)	X (base)	Z (collector)
Common Base	X (base)	Y (emitter)	Z (collector)
Common Collector	Z (collector)	X (base)	Y (emitter)

Penguat Common Emitter

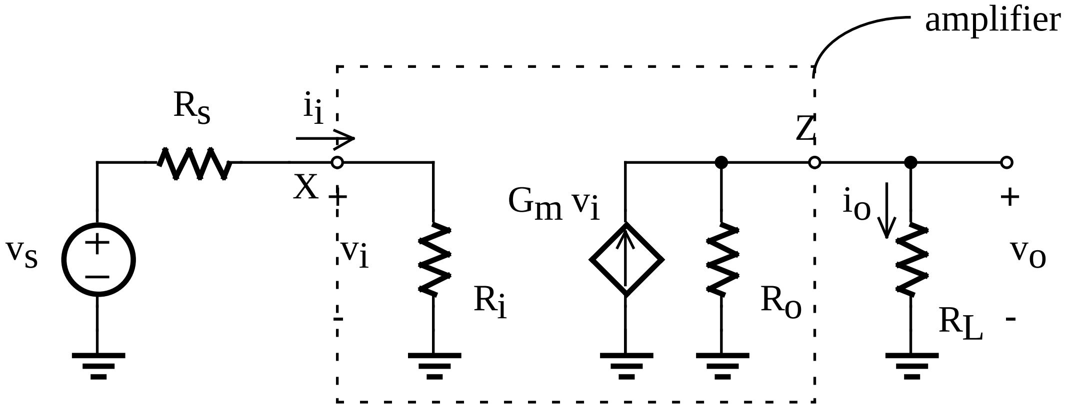




$R_i = R_B \,//\, r_\pi$

$G_m = -g_m$

$R_o = R_C \,//\, r_o$



Analisis Rangkaian Penguat Common Emitter

Kapasitor C_1 dan C_2 sebagai kapasitor kopling

Kapasitor C_3 sebagai kapasitor bypass

Resistansi input

$$R_i \equiv \left.\frac{v_i}{i_i}\right|_{v_o=0} = R_B \,//\, r\pi \approx r\pi \quad \text{bila} \quad R_B >> r\pi$$

Transkonduktasi

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{v_o=0} = \frac{-g_m v\pi}{v\pi} = -g_m$$

Resistansi Output

$$R_o \equiv \left.\frac{v_o}{i_o}\right|_{v_i=0} = R_C \,//\, ro \approx R_C \quad \text{bila} \quad R_C << r\pi$$

Penguatan Tegangan (beban terbuka)

$$A_{vo} \equiv \left.\frac{v_o}{v_i}\right|_{i_o=0 \text{ atau } R_L=\infty} = G_m R_o = -g_m (R_C \,//\, ro)$$

$$A_{vo}\Big|_{max} = -g_m r_o = -(I_C/V_T)(V_A/I_C) = -V_A / V_T$$

Analisis Rangkaian Penguat Common Emitter

Penguatan Arus (beban terhubung singkat)

$$A_{is} \equiv \left.\frac{i_o}{i_i}\right|_{v_o=0} = \frac{G_m v_i}{v_i / R_i} = G_m R_i$$

$$A_{is} = -g_m (R_B \,//\, r_\pi) = -\frac{g_m r_\pi R_B}{R_B + r_\pi}$$

$$= -\beta \frac{1}{1 + r_\pi / R_B}$$

Penguatan Tegangan

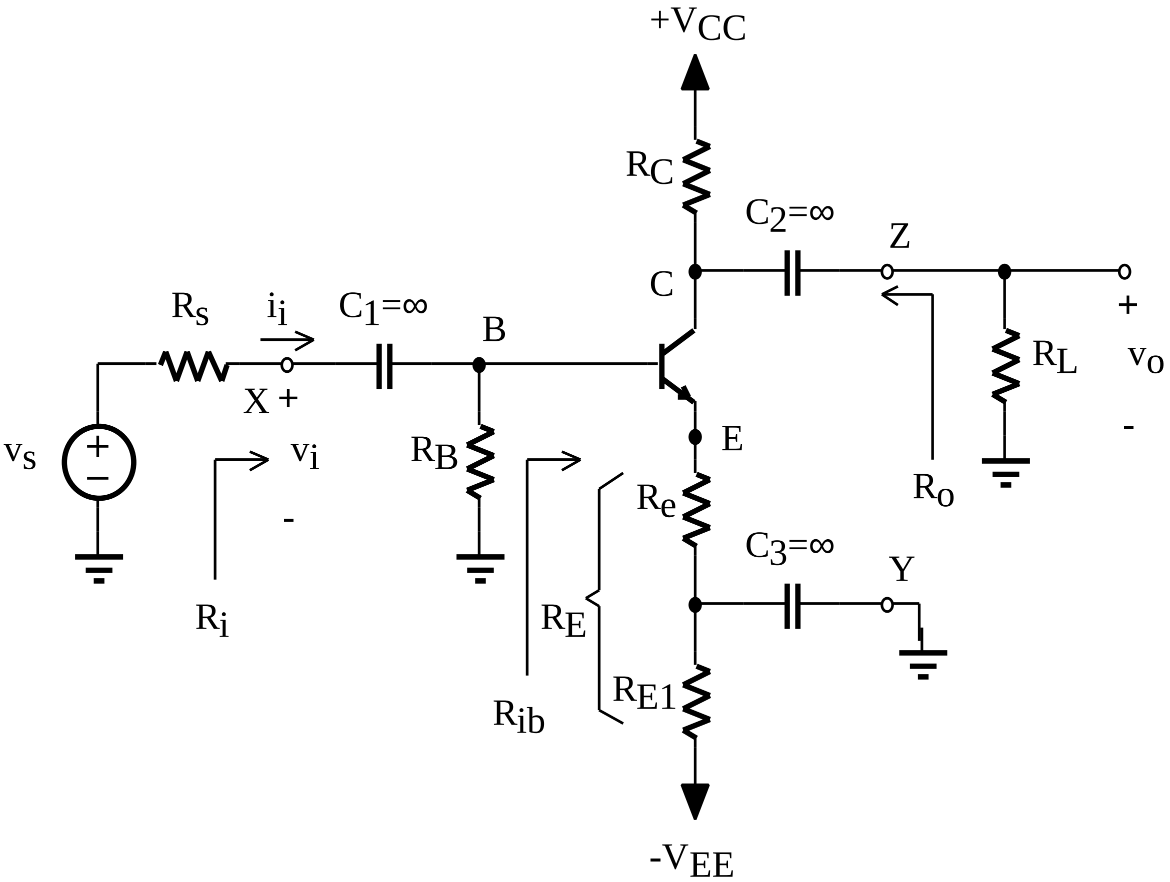
$$A_v = \frac{v_i}{v_s} \frac{v_o}{v_i} = \frac{R_i}{R_i + R_s} G_m (R_o \,//\, R_L)$$

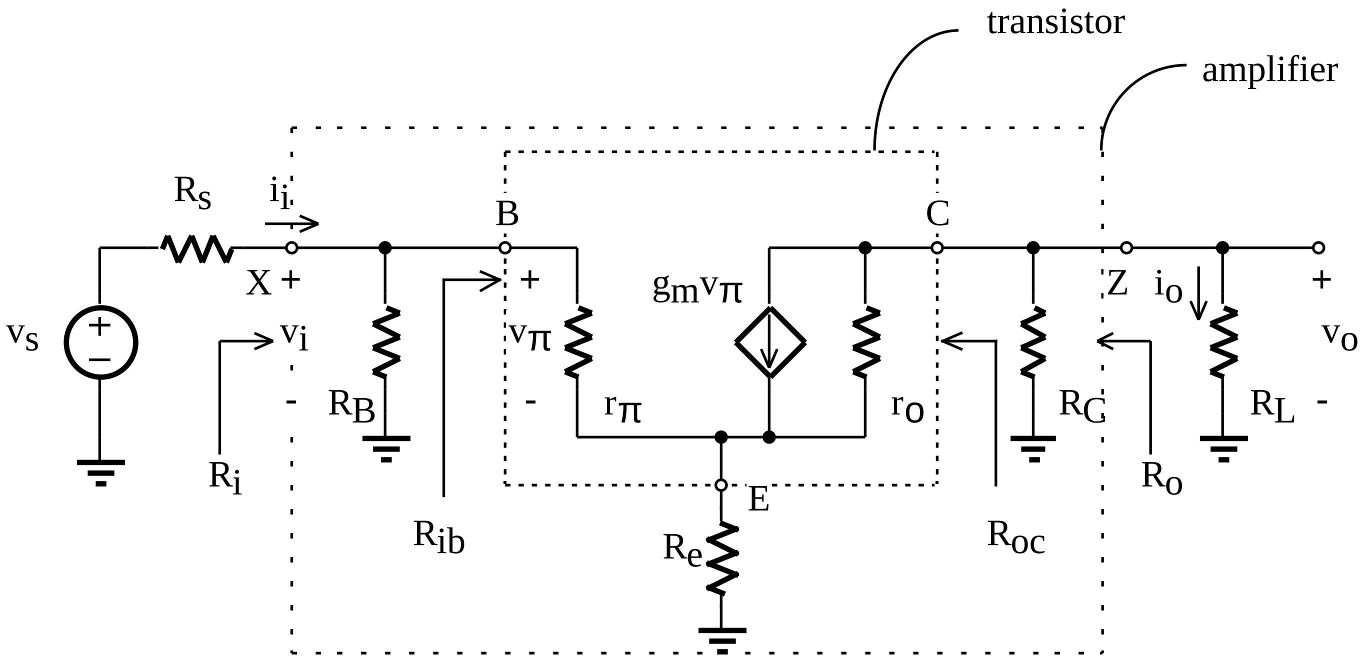
$$= -\frac{(R_B \,//\, R\pi)}{(R_B \,//\, R\pi) + R_s} g_m (R_C \,//\, r_o \,//\, R_L)$$

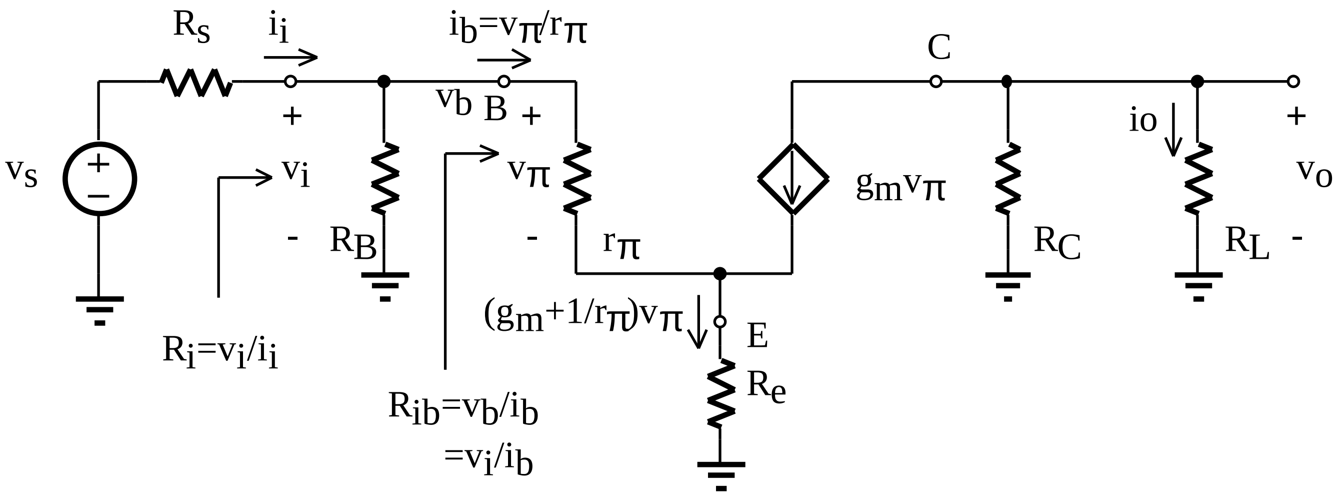
$$\approx -\frac{r\pi}{r\pi + R_s} g_m (R_C \,//\, r_o \,//\, R_L) \quad \text{bila} \quad R_B >> r\pi$$

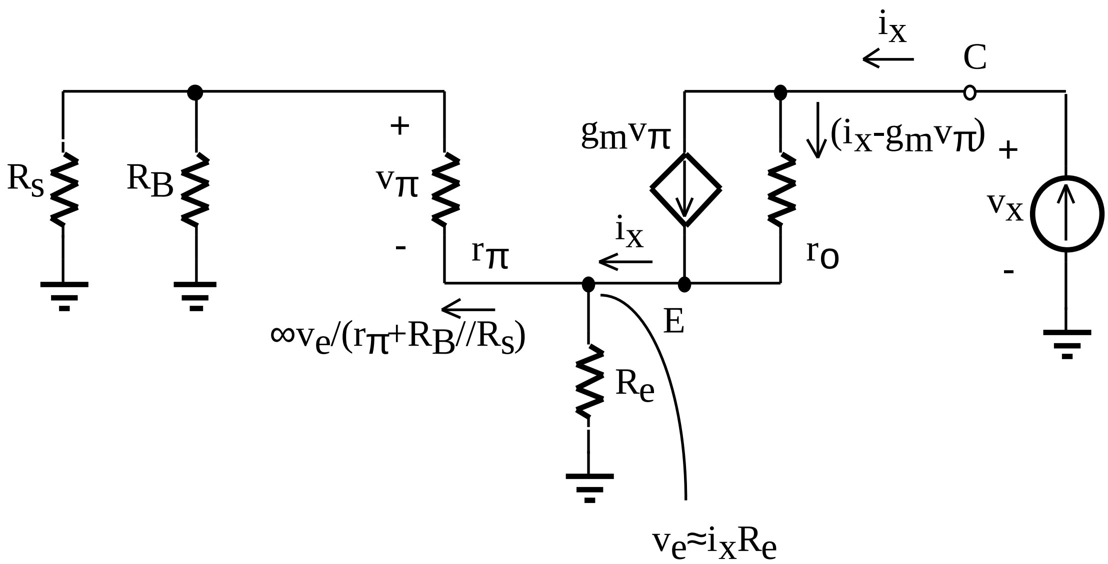
$$A_v = -\frac{\beta(R_C \,//\, r_o \,//\, R_L)}{r\pi + R_s}$$

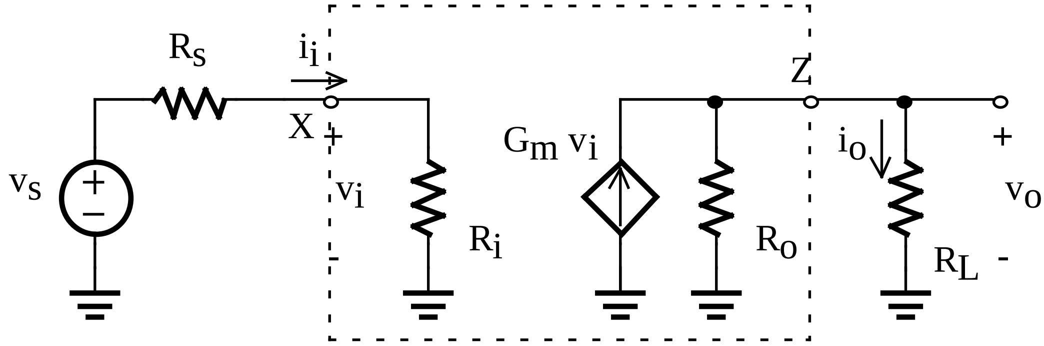
Penguat Common Emitter dengan Resistor Emitter











$R_i = R_B \,//\, r_\pi(1+g_m R_e)$ $\quad$ $G_m = -g_m/(1+g_m R_e)$ $\quad$ $R_o \approx R_C$

Analisis Rangkaian Penguat Common Emitter dengan Resistansi Emitter

Kapasitor C_1 dan C_2 sebagai kapasitor kopling

Kapasitor C_3 sebagai kapasitor bypass

Resistansi input

$$R_i \equiv \frac{v_i}{i_i} = R_B \,//\, R_{ib}$$

$$R_{ib} \equiv \frac{v_b}{i_b}$$

$i_b = v_\pi / r_\pi$

$v_b = v_\pi + (g_m + 1/r_\pi)\, v_\pi\, R_e$

dengan $(g_m + 1/r_\pi) = r_e$ maka

$v_b = (1 + R_e/r_e)\, v_\pi$

$R_{ib} = r_\pi\, (1 + R_e/r_e)$ dengan $r_e \approx 1/g_m$ maka

$R_{ib} \approx r_\pi\, (1 + g_m R_e)$

$R_i = R_B \,//\, r_\pi\, (1 + g_m R_e)$

Perhatikan $R_{ib} = r_\pi\, (1 + R_e/r_e) = (\beta + 1) r_e\, (1 + R_e/r_e)$

$$R_{ib} = (\beta + 1)\, (r_e + R_e)$$

Resistansi emitter “dirasakan” $(\beta + 1)$ kali di base (*reflection rule*)

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{R_L=0} = \frac{-g_m v_\pi}{v_\pi}$$

sebelumnya telah didapat

$v_b = (1 + R_e / r_e)\ v_\pi$

$$G_m = -\frac{g_m}{1 + R_e / r_e}$$

dengan $r_e \approx 1/g_m$ maka

$$G_m \approx -\frac{g_m}{1 + g_m R_e}$$

Perhatikan

R_{ib} naik sebesar $(1+g_m R_e)$ kali dan G_m turun $(1+g_m R_e)$ kali.

Resistansi Output

$R_o = R_C \,//\, R_{oc}$ dengan $R_{oc} = v_x / i_x$

$$v_x = (i_x - g_m v_\pi)\, r_o + v_e \qquad v_e \approx i_x R_e$$

$$v_\pi = -\frac{i_x R_e r_\pi}{r_\pi + (R_S \,//\, R_B)}$$

$$R_{oc} = r_o \left(1 + \frac{g_m R_e r_\pi}{r_\pi + (R_S \,//\, R_B)}\right) + R_e$$

untuk $R_e << r_o$ maka

$$R_{oc} \approx r_o \left(1 + \frac{g_m R_e r_\pi}{r_\pi + (R_S \,//\, R_B)}\right)$$

sehingga

$$R_o = R_C \,//\, r_o \left(1 + \frac{g_m R_e r_\pi}{r_\pi + (R_S \,//\, R_B)}\right)$$

$$R_o \approx R_C$$

Penguatan Tegangan

$$A_v \equiv \frac{v_o}{v_s} = \frac{v_o}{v_s} \quad \frac{v_o}{v_s}$$

$$= \frac{R_i}{R_i + R_s} G_m (R_o // R_L)$$

$$= - \frac{(R_B // r_\pi (1+g_m R_e)}{(R_B // r_\pi (1 + g_m R_e)) + R_s} \quad \frac{g_m}{1 + g_m R_e} (R_C // R_L)$$

Perhatikan

1. Penguatan A_v menjadi lebih bebas dari nilai β.

   Bila R_B cukup besar maka

$$A_v \approx - \frac{g_m r_\pi}{r_\pi (1 + g_m R_e) + R_s} \quad (R_C // R_L)$$

   Bila $r_\pi (1 + g_m R_e) >> R_s$ maka

$$A_v \approx - \frac{g_m}{1 + g_m R_e} \quad (R_C // R_L)$$

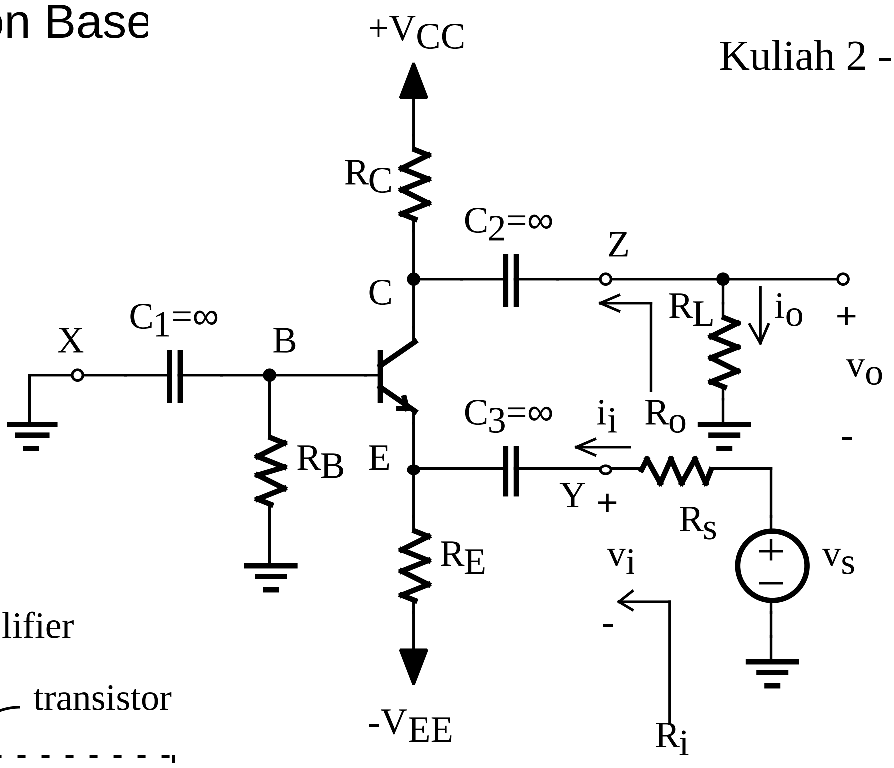
   atau dalam bentuk lain

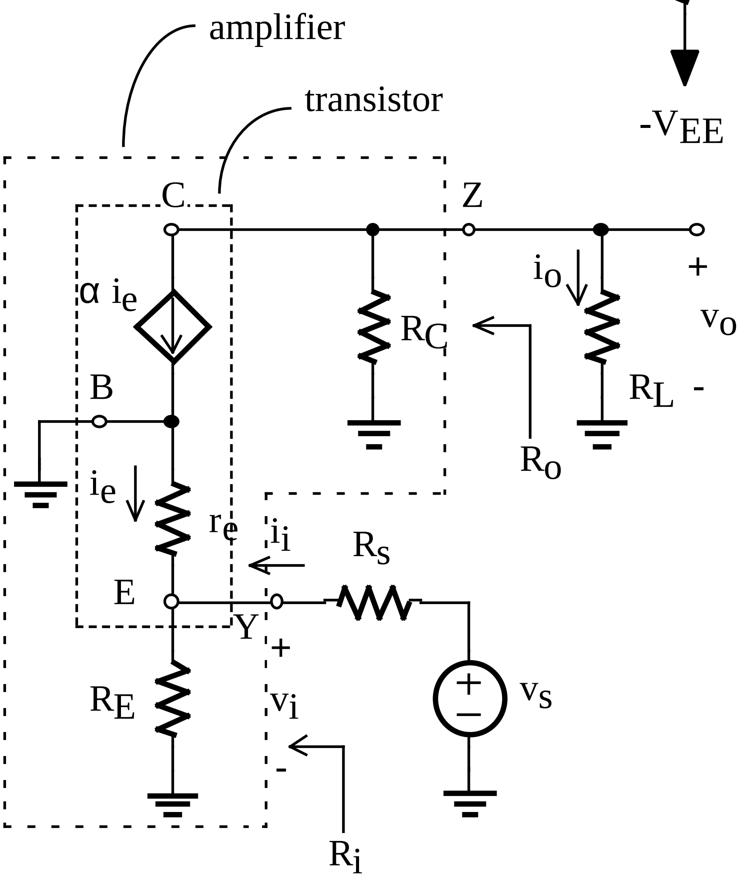
$$A_v \approx - \frac{1}{r_e + R_e} \quad (R_C // R_L)$$

2. Penguat lebih tahan distorsi nonlinear pada sinyal besar karena dengan v_π yang sama v_i dapat dinaikan dengan faktor $1 + R_e/r_e$

3. Penguat mempunyai respons frekuensi yang lebih baik (Bab 7)

Penguat Common Base

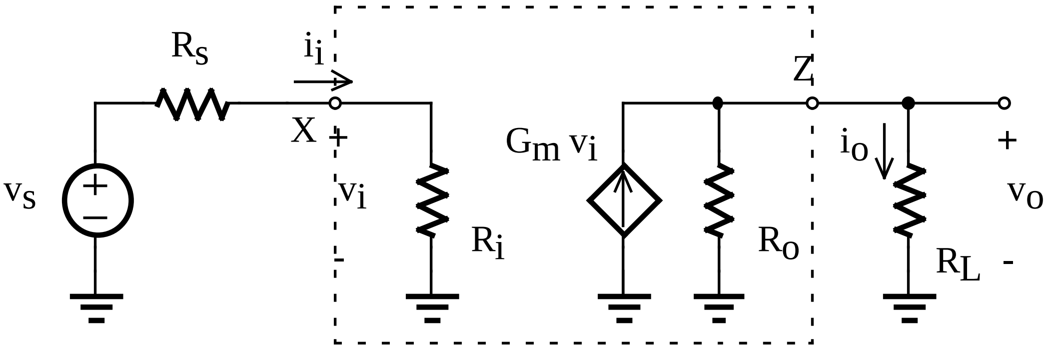




$R_i = R_B \,//\, r_\pi$

$G_m = -g_m$

$R_o = R_C \,//\, r_o$



Analisis Rangkaian Penguat Common Base

Kapasitor C_2 dan C_3 sebagai kapasitor kopling

Kapasitor C_1 sebagai kapasitor bypass

Resistansi input

$$R_i \equiv \left.\frac{v_i}{i_i}\right|_{v_o=0} = R_E \,//\, r_e$$

$$\approx r_e \quad \text{untuk} \quad R_E >> r_e$$

Transkonduktasi

$$G_m \equiv \left.\frac{i_o}{v_i}\right|_{v_o=0} = \frac{-\alpha\, i_e}{v_i} = -g_m \quad \text{karena } i_e = -(v_i / r_e)$$

Resistansi Output

$$R_o \equiv \left.\frac{v_o}{i_o}\right|_{v_i=0} = R_C$$

Penguatan Tegangan (beban terbuka)

$$A_{vo} \equiv \left.\frac{v_o}{v_i}\right|_{i_o=0 \text{ atau } R_L=\infty} = G_m R_o = -g_m R_C$$

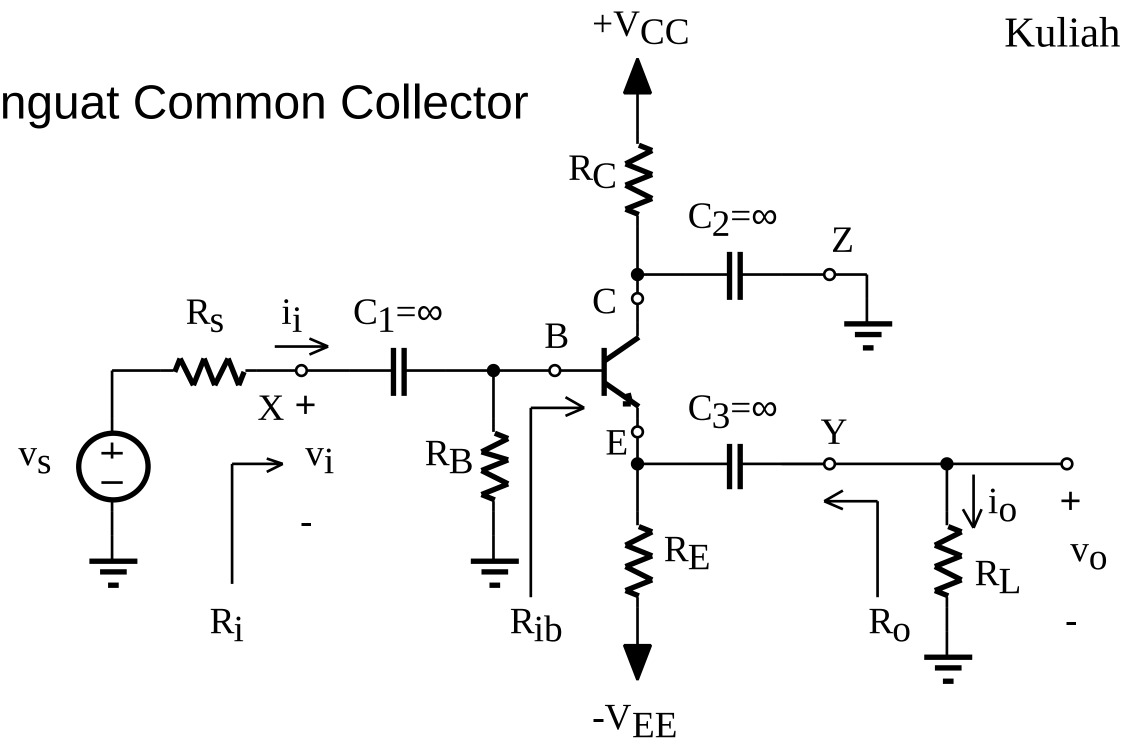
Penguatan Arus

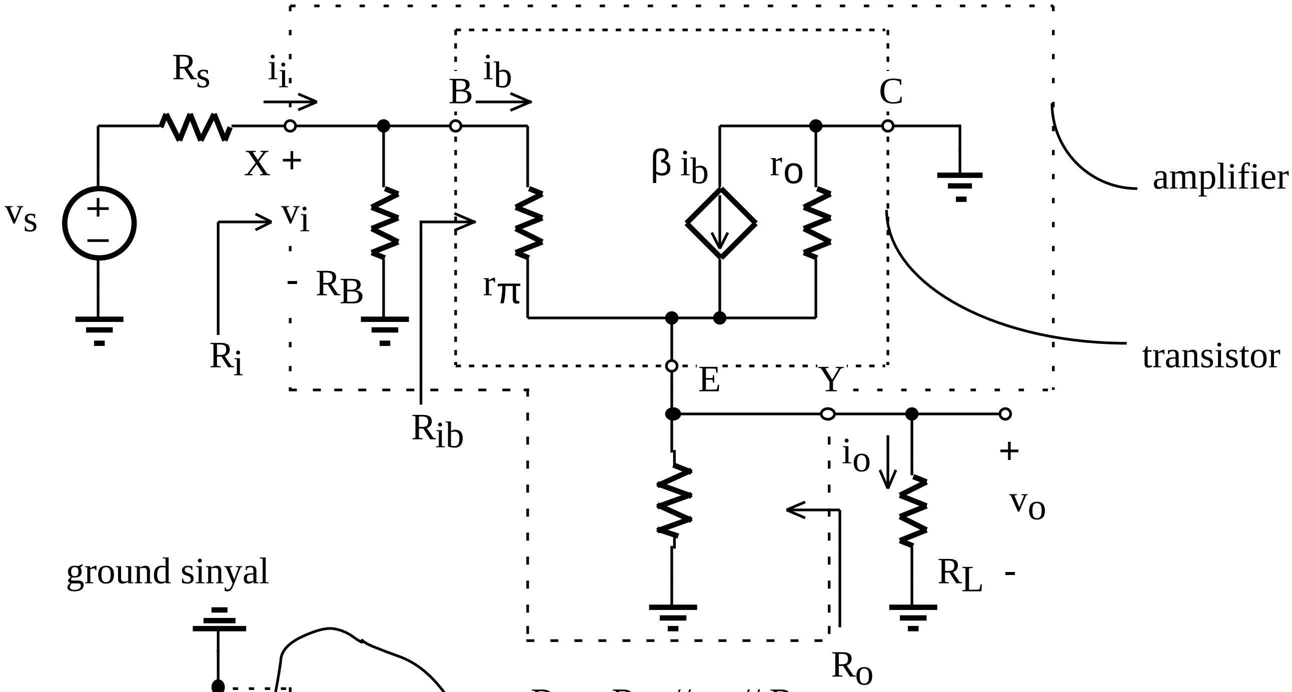
$$A_{is} \equiv \left.\frac{i_o}{i_i}\right|_{v_o=0 \text{ atau } R_L=0} = \frac{G_m v_i}{v_i / R_i} = G_m R_i = g_m r_e = \alpha$$

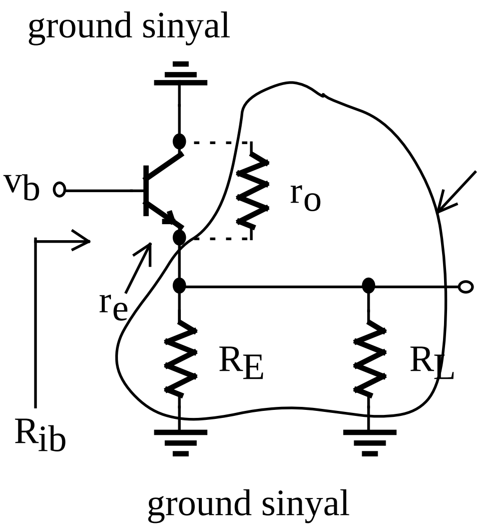
Penguatan Tegangan

$$A_v = \frac{R_i}{R_i + R_s} G_m (R_C \,//\, R_L) = \frac{r_e}{r_e + R_s} G_m (R_C \,//\, R_L)$$

Penguat Common Collector







$R_e = R_E \: // \: r_o \: // \: R_L$:

$v_e/v_b = R_E \: / \: (r_e + R_E)$:

Analisis Rangkaian Penguat Common Collector

Kapasitor C_1 dan C_2 sebagai kapasitor kopling

Kapasitor C_3 sebagai kapasitor bypass

Resistansi input

$R_i = R_B \,//\, R_{ib}$

$$R_{ib} = (\beta + 1)\,(r_e + R_e) \quad \text{dan} \quad R_e = R_E \,//\, r_o \,//\, R_L$$

$R_i = R_B \,//\, (\beta + 1)\,(r_e + (R_E \,//\, r_o \,//\, R_L))$

Jika R_B cukup besar maka $R_i \approx (\beta + 1)\,(r_e + (R_E \,//\, r_o \,//\, R_L))$

dan bila $R_L \ll (R_E \,//\, r_o)$ maka $R_i \approx (\beta + 1)\,(r_e + R_L)$

$$= r_\pi + (\beta + 1)\,R_L$$

Penguatan tegangan

$A_v = v_o/v_s = v_o/v_i \;\; v_i/v_s$

$$v_i/v_s = \frac{R_i}{R_i + R_s}$$ dengan Ri besar maka $v_i/v_s \approx 1$

$$v_o/v_i = \frac{(R_E \,//\, r_o \,//\, R_L)}{r_e + (R_E \,//\, r_o \,//\, R_L)}$$

$$A_v = \frac{R_i}{R_i + R_s} \; \frac{(R_E \,//\, r_o \,//\, R_L)}{r_e + (R_E \,//\, r_o \,//\, R_L)}$$

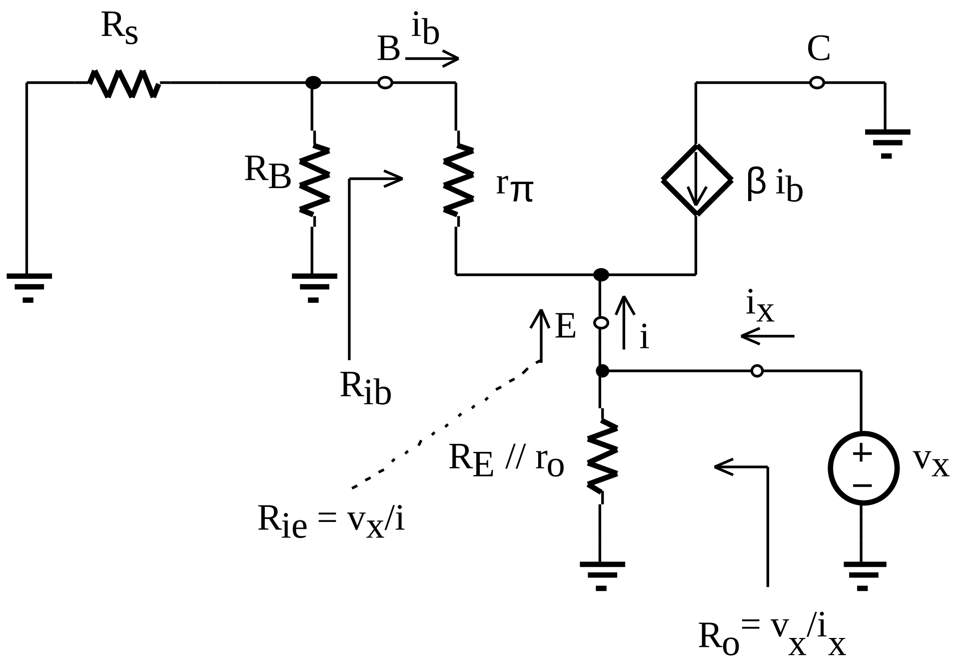
$$\approx \frac{(\beta + 1)\,R_L}{(\beta + 1)\,R_L + r_\pi + R_s}$$ bila R_B besar dan $R_L \ll R_E / r_o$

Penguatan Arus

$$A_i \equiv i_o/i_i = \frac{v_o/R_L}{v_s/(R_i + R_s)} = \frac{R_i}{R_L} \; \frac{R_E // r_o // R_L}{(R_E // r_o // R_L) + r_e} \approx \frac{R_i}{R_L}$$

Jika $R_L << (R_E // r_o)$ serta $R_B >> R_{ib}$ maka $A_i \approx \beta + 1$

Resistansi Output



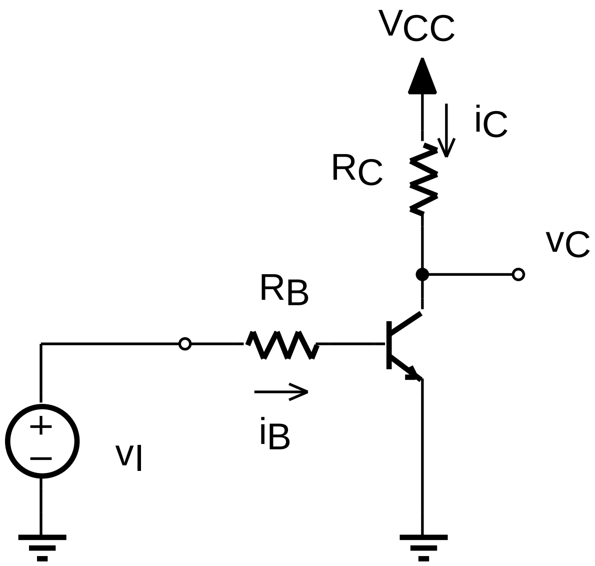
$$R_o \equiv v_x / i_x = R_{ie} // R_E // r_o \qquad R_{ie} \equiv v_x / i \qquad i = -(\beta + 1)\, i_b$$

$$i_b = \frac{v_x}{r_\pi + (R_S // R_B)} \qquad R_{ie} = \frac{r_\pi + (R_S // R_B)}{(\beta + 1)}$$

$$R_o = R_E // r_o // \frac{r_\pi + (R_S // R_B)}{(\beta + 1)} \approx \frac{r_\pi + (R_S // R_B)}{(\beta + 1)}$$

$$= re + \frac{R_S // R_B}{(\beta + 1)} \approx \frac{R_S}{(\beta + 1)}$$ bila R_B cukup besar

Transistor sebagai Switch



Daerah Cutoff

$i_B = 0 \quad i_E = 0 \quad i_C = 0$

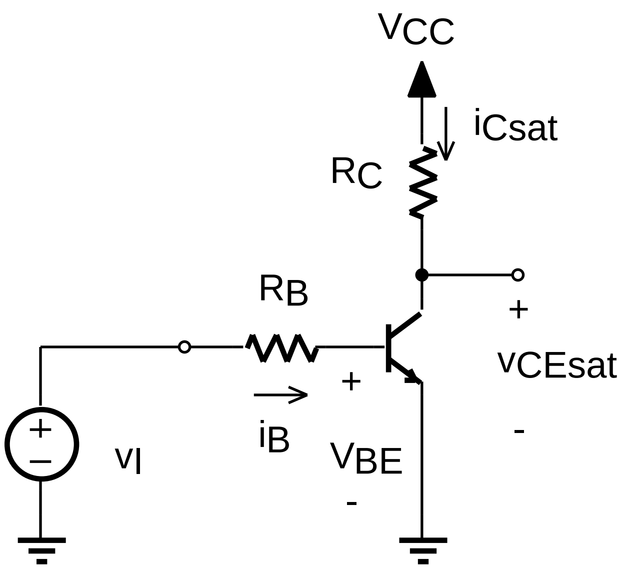
$v_C = V_{CC}$

Daerah Aktif

$$i_B = (v_I - V_{BE}) / R_B \approx (v_I - 0.7) / R_B$$

$$i_C = \beta \, i_B \qquad v_C = V_{CC} - R_C \, i_C$$

Daerah Saturasi



$i_{Csat} = (V_{CC} - V_{CEsat}) / R_C$

$I_{Bsat} = i_{Csat}) / \beta$

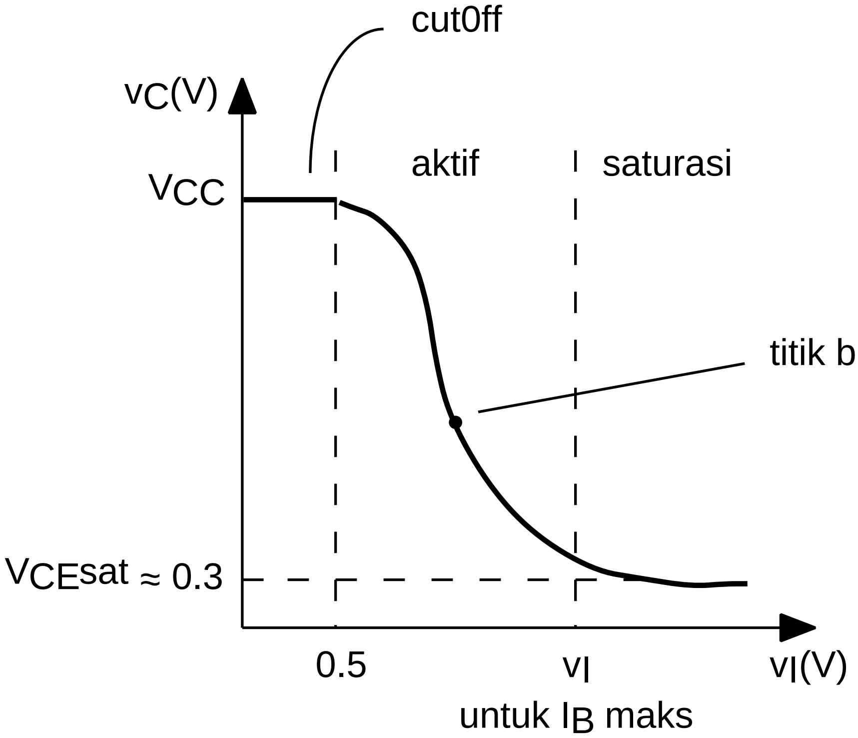
dalam desain $I_B > I_{Bsat}$

(faktor 2 - 10 kali)

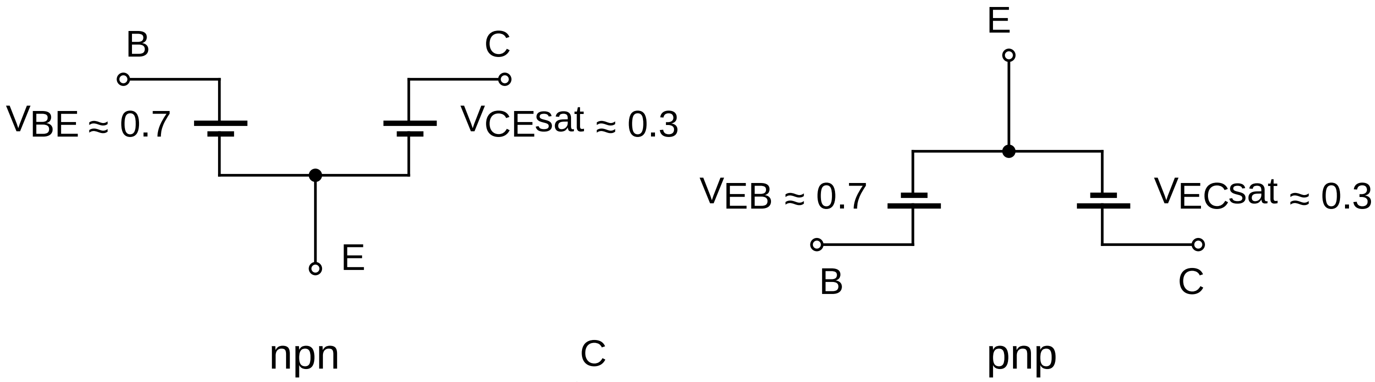
$\beta_{forced} = i_{Csat}) / I_B$

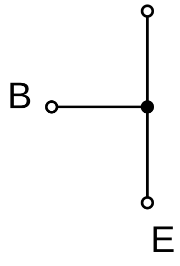
Transistor sebagai Switch

Inverter Transistor



Model Transistor dalam keadaan saturasi

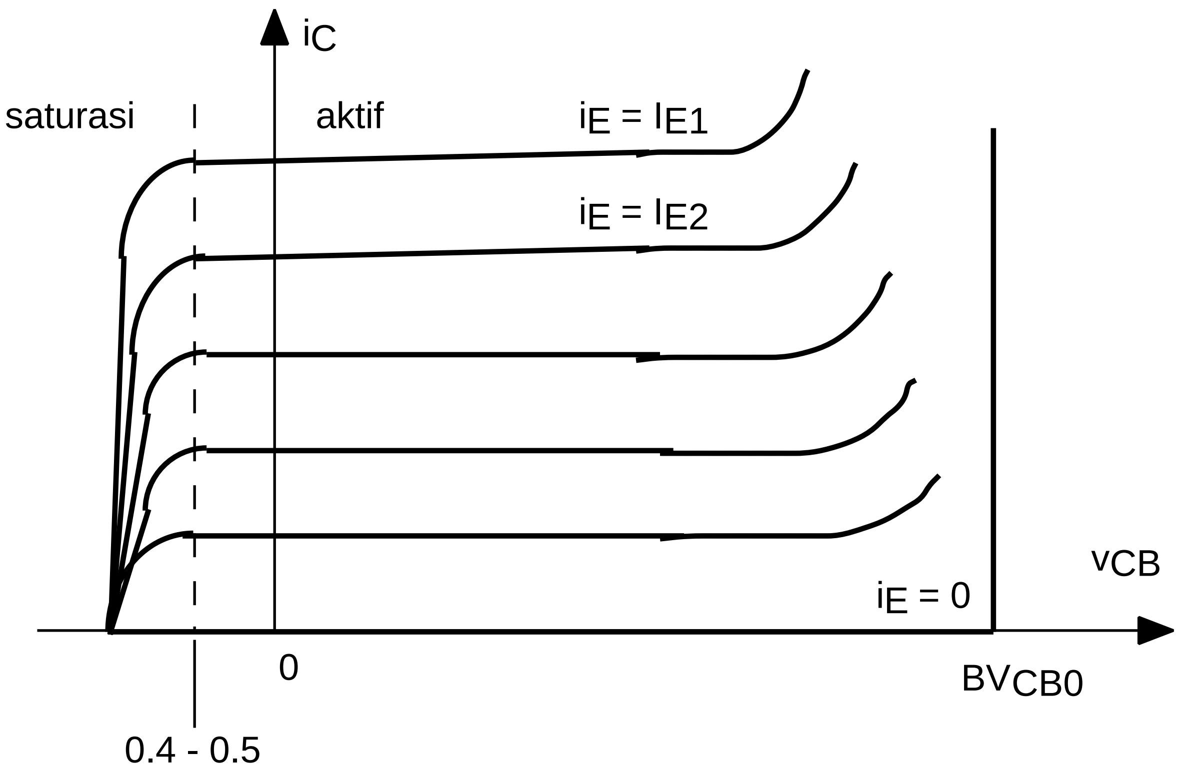


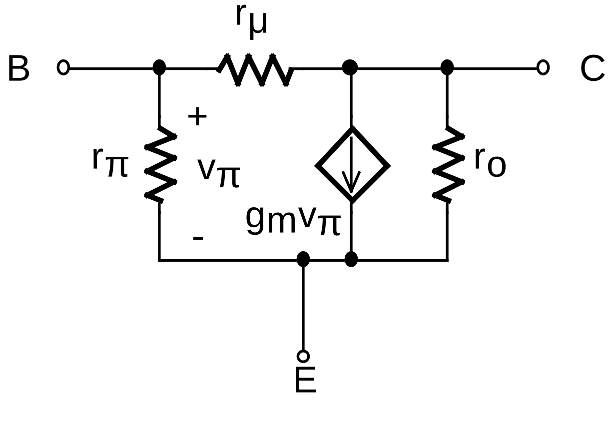


model sangat disederhanakan

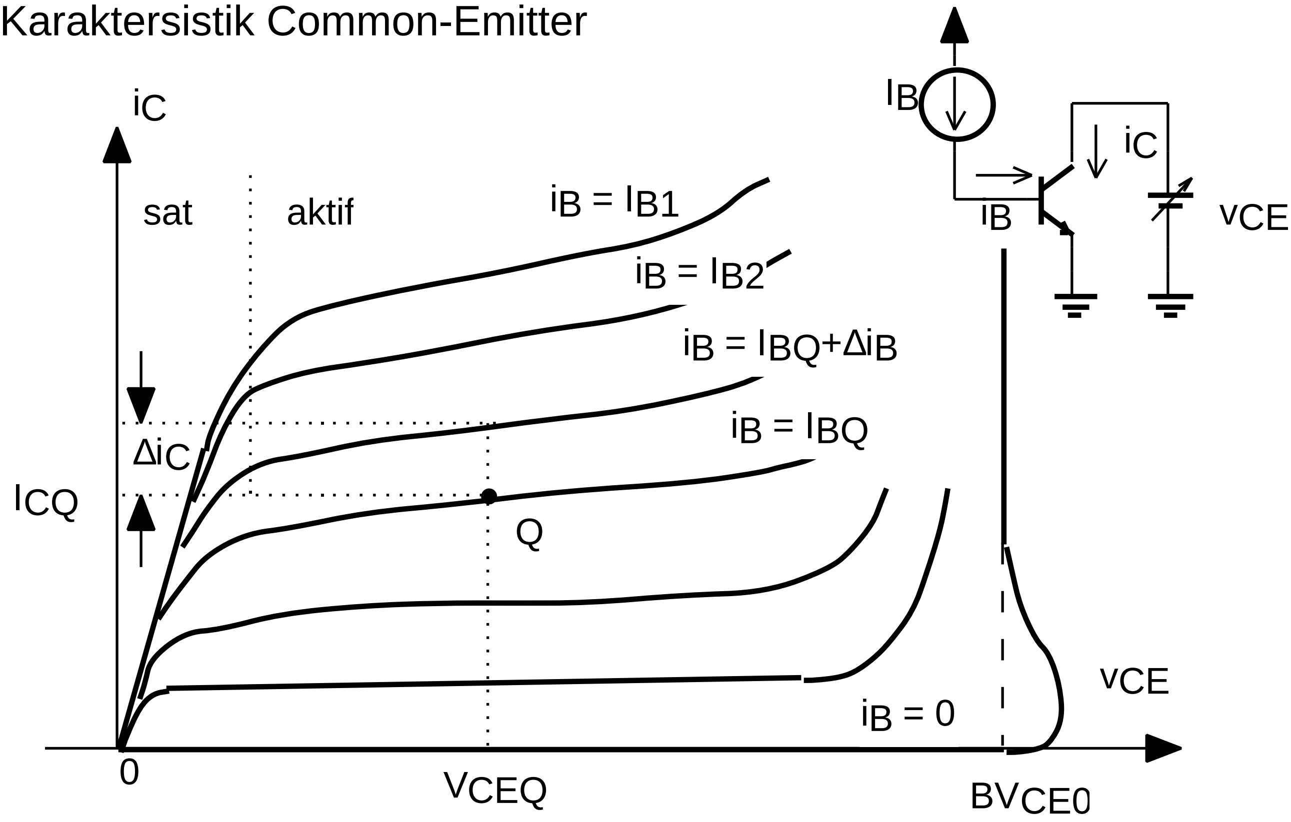
Karakteristik Statis Lengkap dan Efek Orde Dua

Karaktersisistik Common-Base

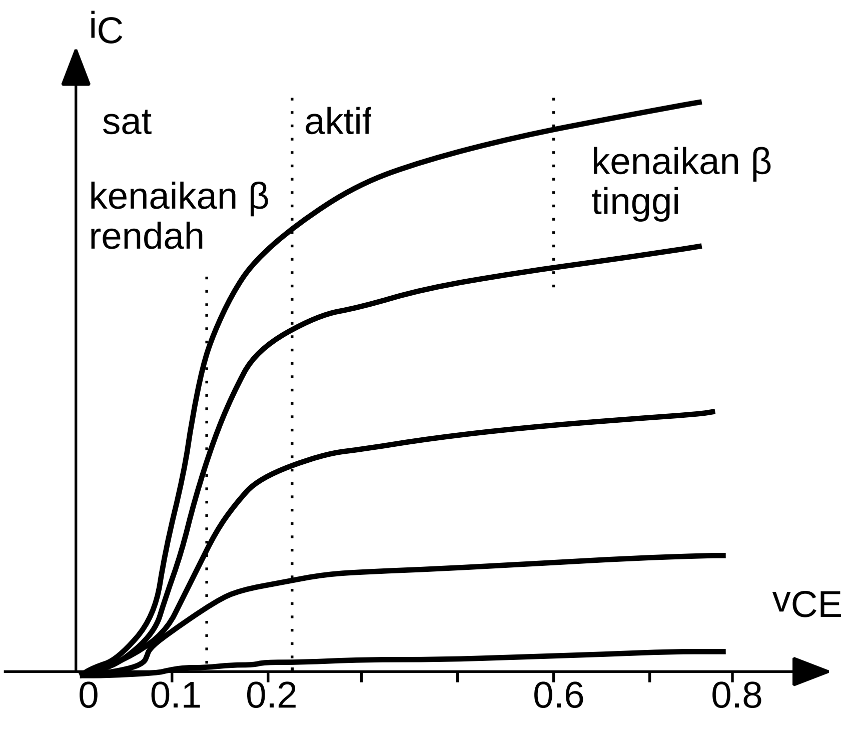


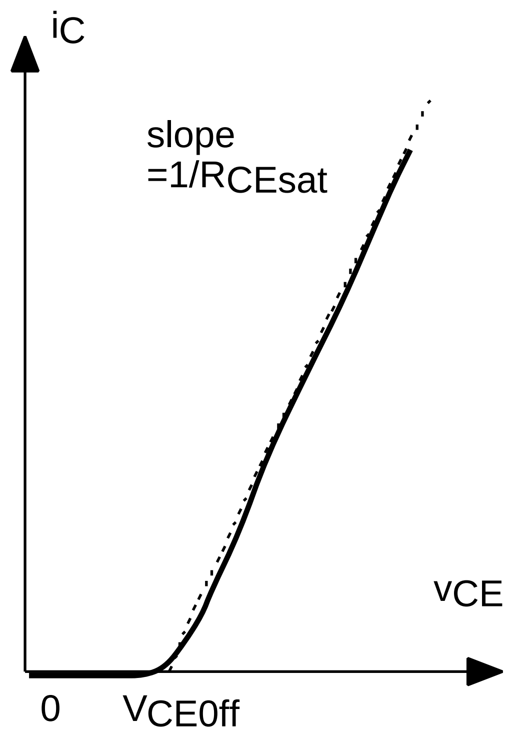


Karaktersistik Common-Emitter



$h_{FE} \equiv \beta_{dc} \equiv I_{CQ}/I_{BQ}$ $h_{fe} \equiv \beta_{ac} \equiv \Delta i_C/\Delta i_B$ = konstan





β transistor