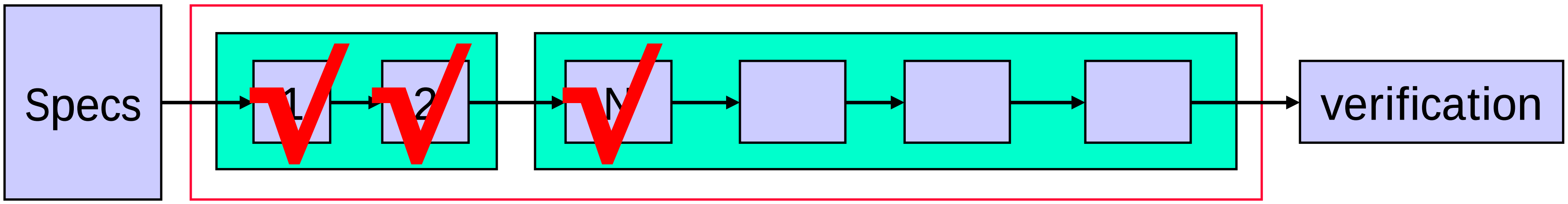
Structured Electronic Design

Building the nullor: **Distortion**



Topology

Best nullor implementation

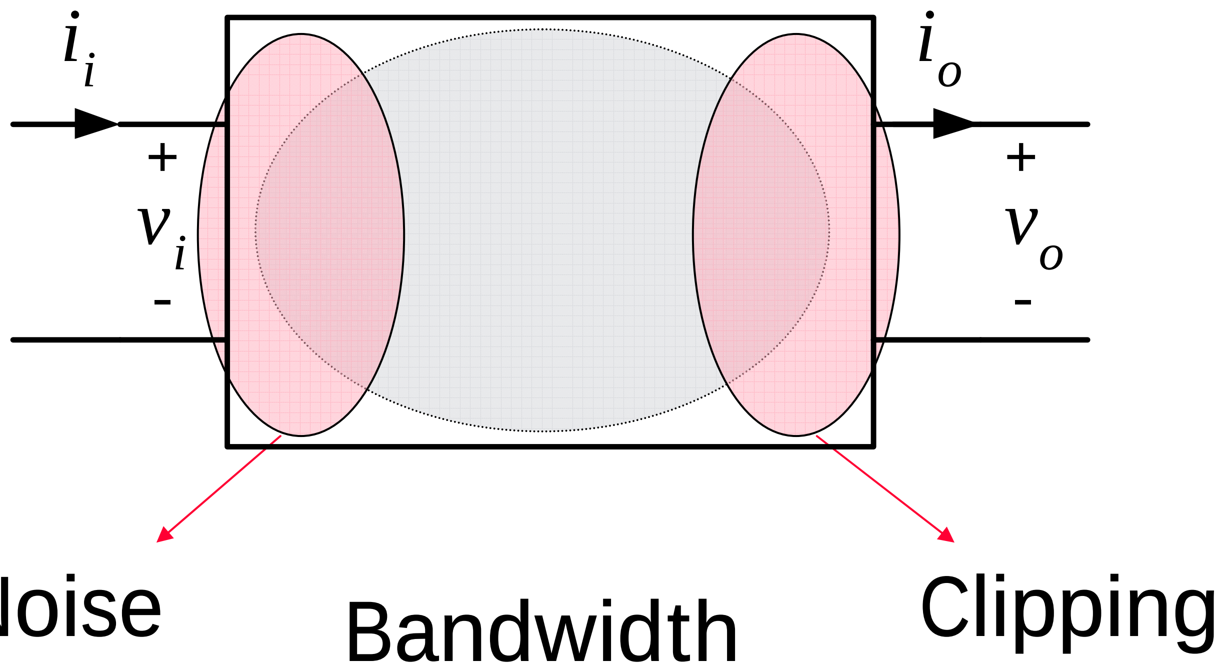
Voltage and current swing

Power consumption

FINAL Noise level

All stages maximal gain (CE CS)

Most orthogonal order: N, D, B



Loopgain

bandwidth – noise – distortion

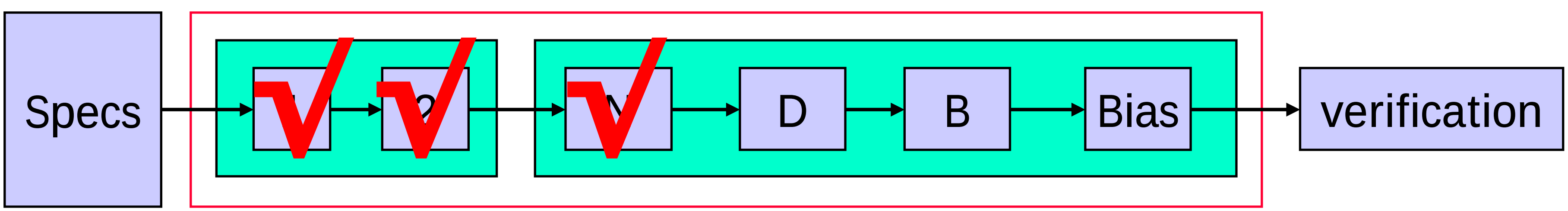
bandwidth – distortion - noise

noise - bandwidth – distortion

noise – **distortion** - bandwidth

distortion - noise – bandwidth

distortion – bandwidth - noise



When optimizing bandwidth:

Small-signal models (no non-linearity)

No noise

When optimizing noise behavior:

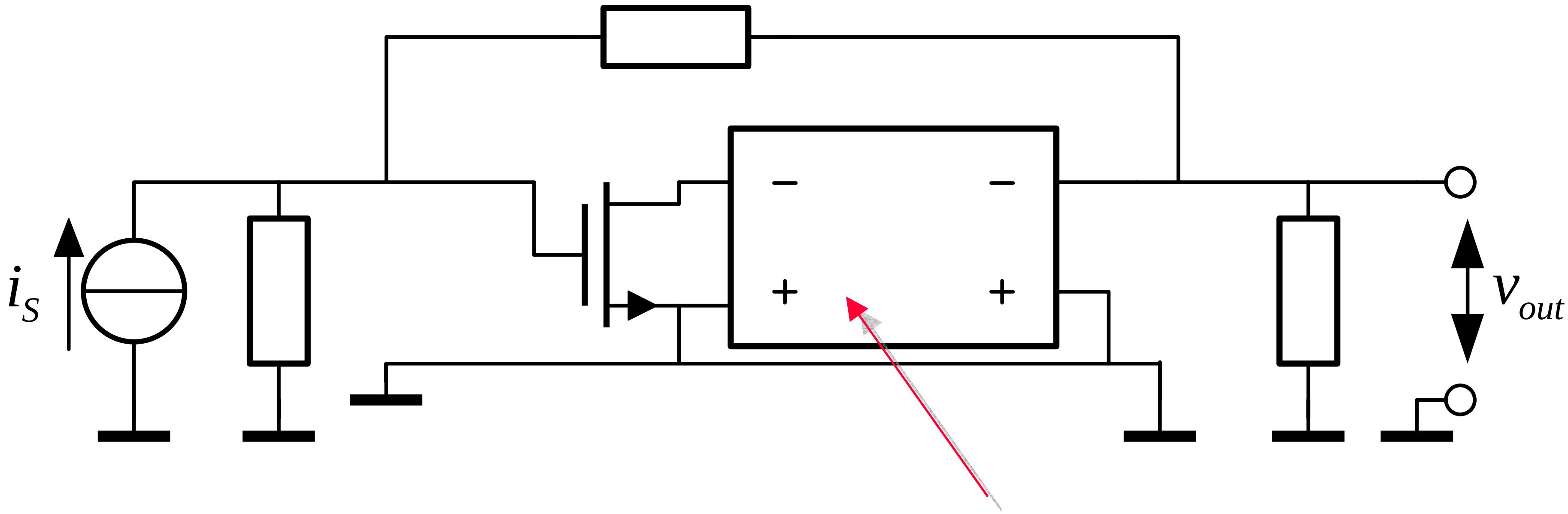
Small-signal models (no non-linearity)

No bandwidth details

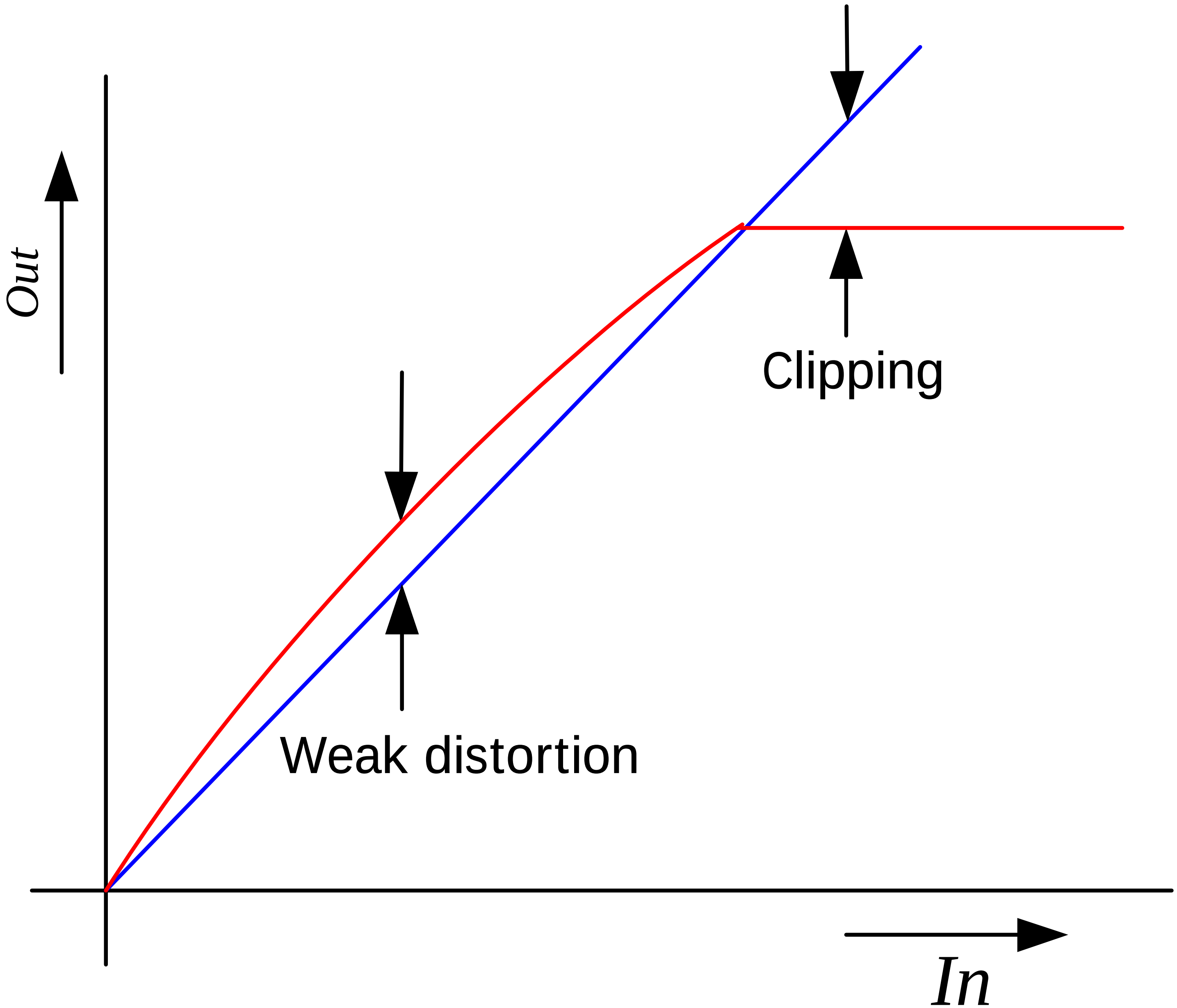
When optimizing non-linear behavior:

No dynamic effects

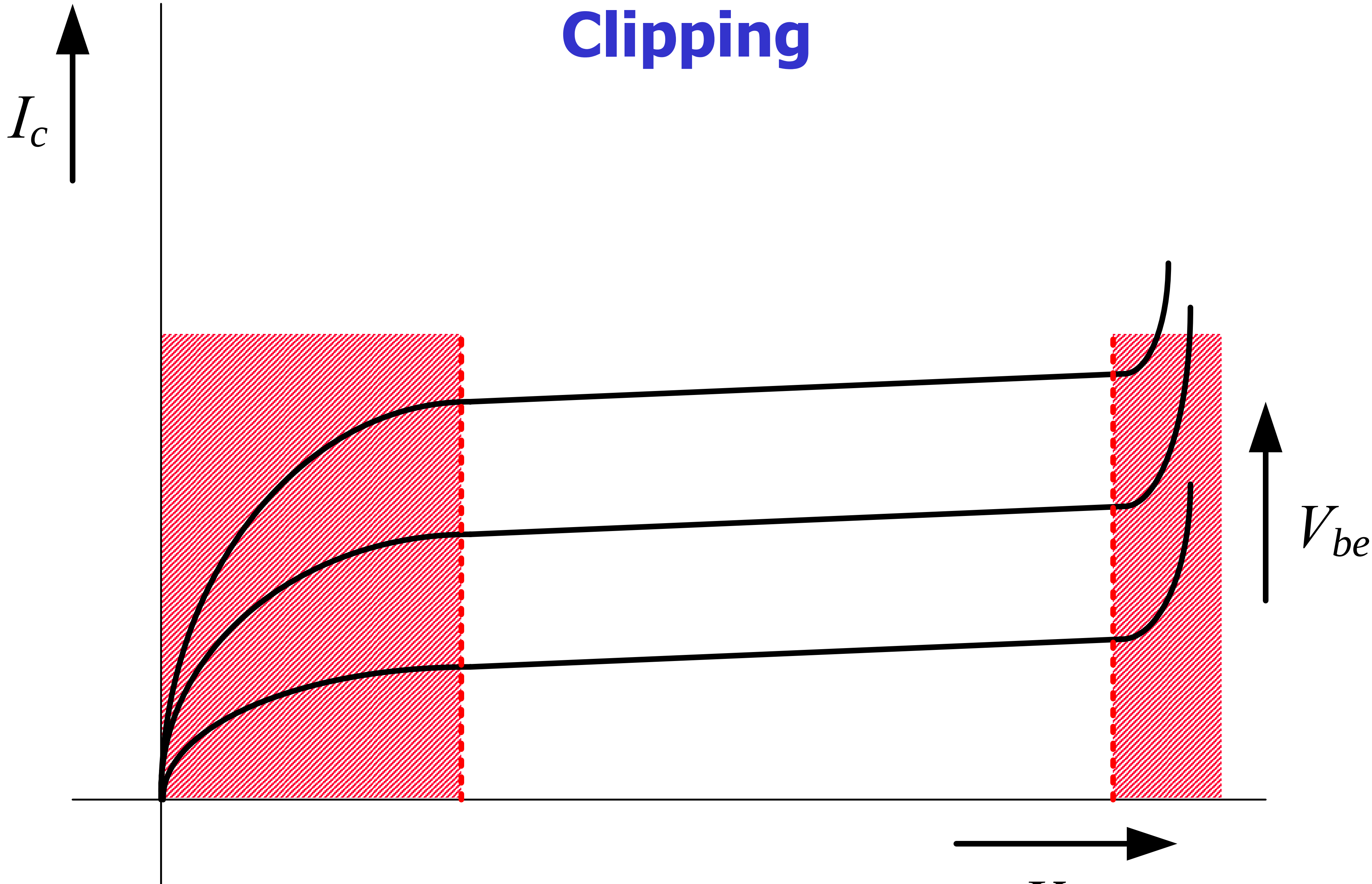
No noise



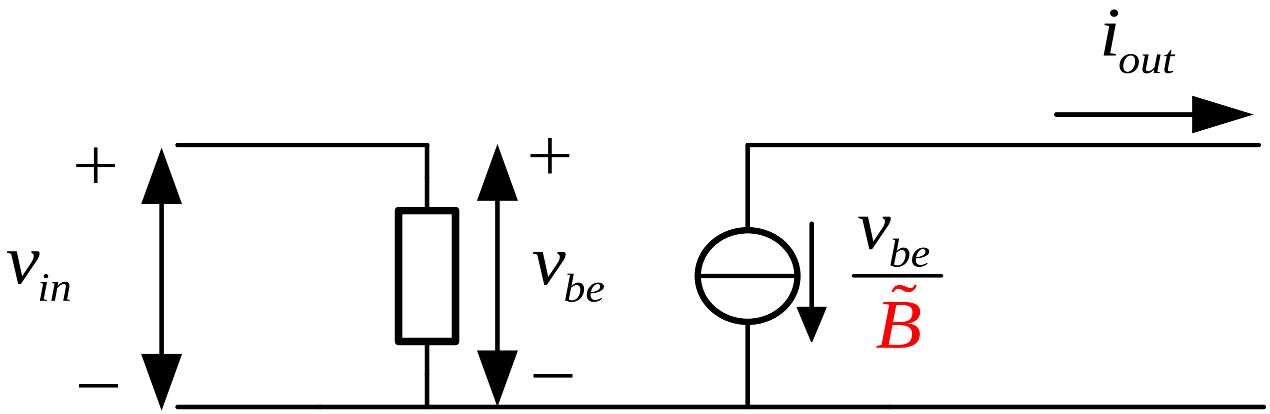
Non-dynamic active circuit
(Not a nullor anymore)


Out
Clipping
Weak distortion
In

Clipping



Weak distortion

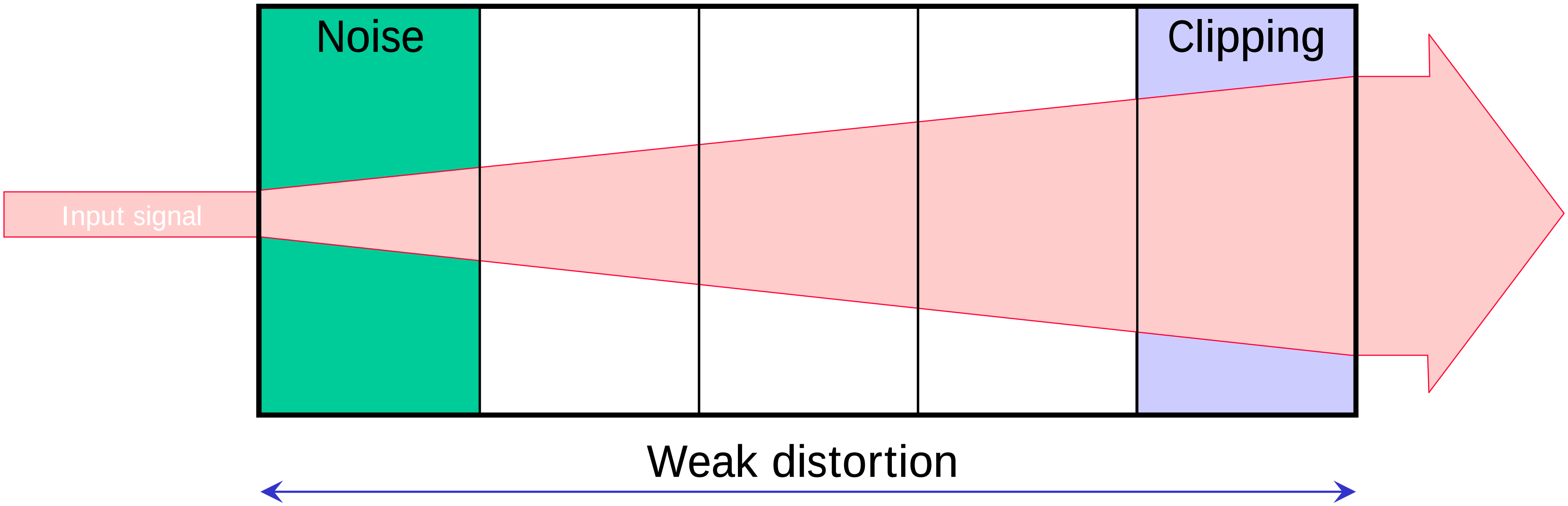


Simplest model that suffices

$$i_{out} = -I_s \left(e^{\frac{v_{in}}{V_T}} - 1 \right)$$

$V_T = \frac{kT}{q}$

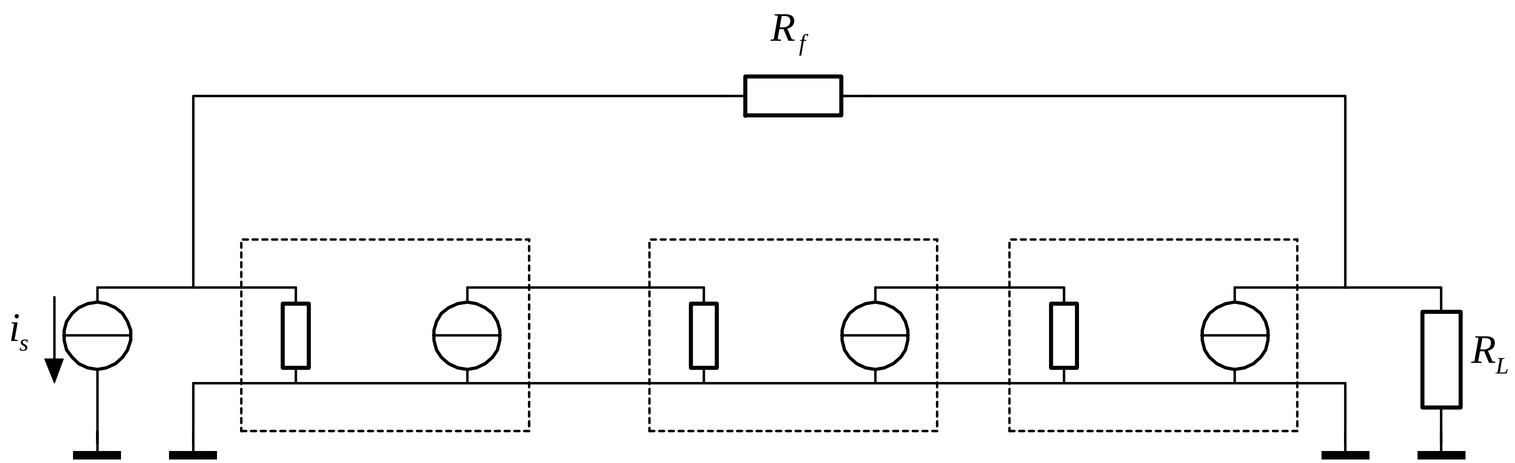
Strategy

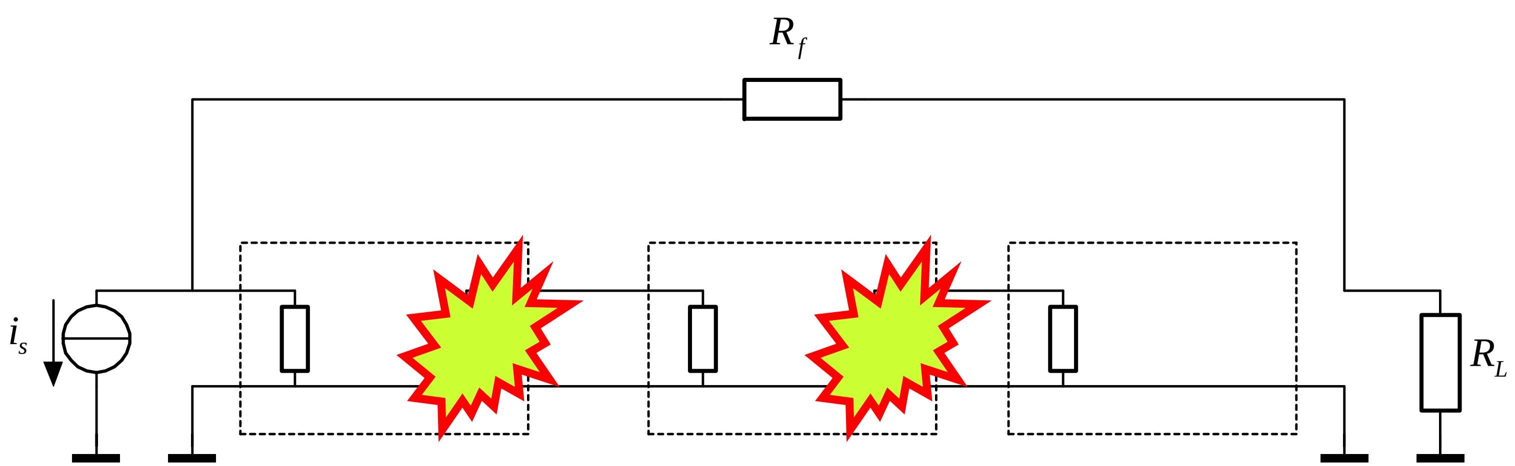


2 distortion types

Completely different approach

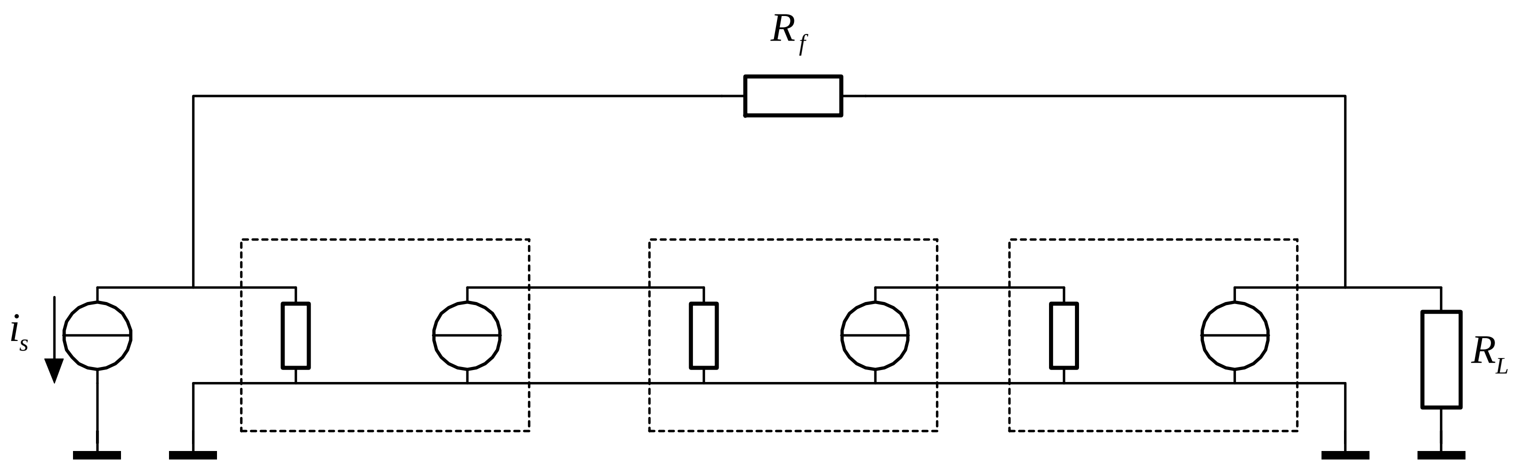
Clipping breaks the loop

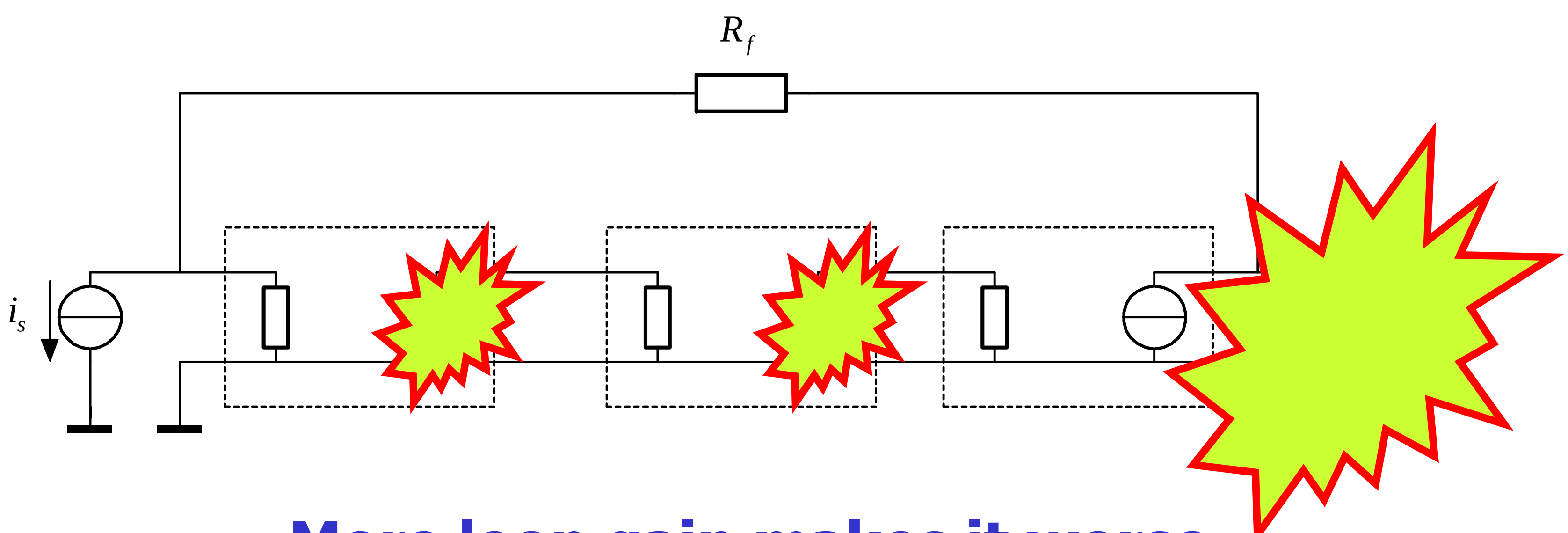




More loop gain does not repair this

Clipping breaks the loop





More loop gain makes it worse

Strategy

Clipping breaks the loop

local problem

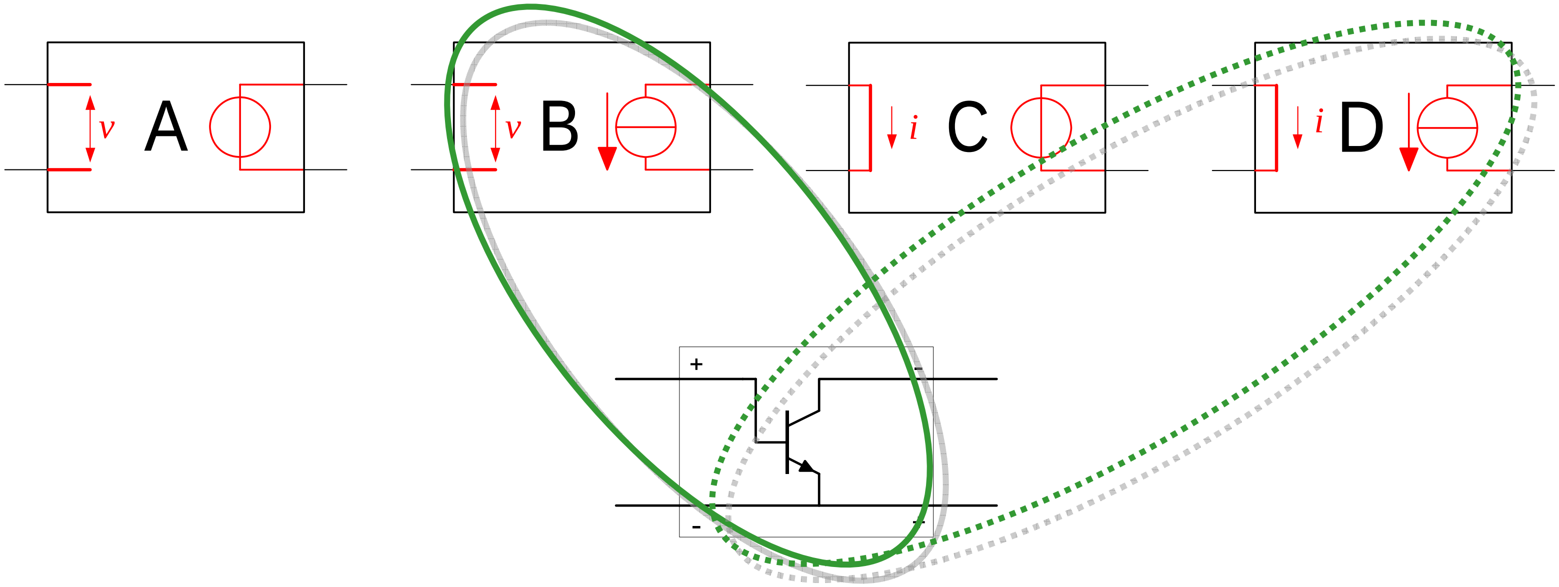
local solution

Weak distortion does not break the loop

can be in **any stage**

reduced by **the loop** (everywhere)

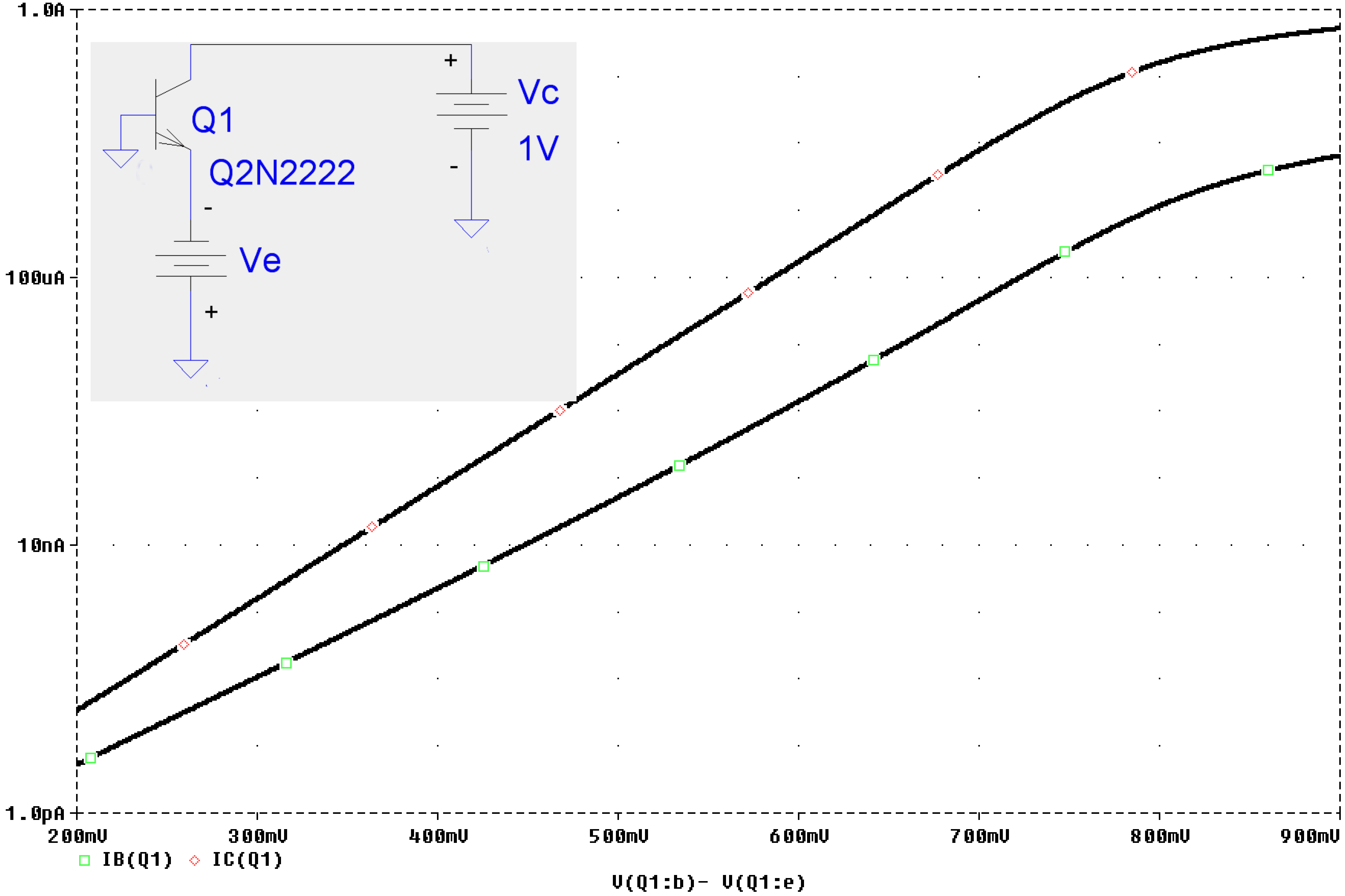
The bipolar transistor model



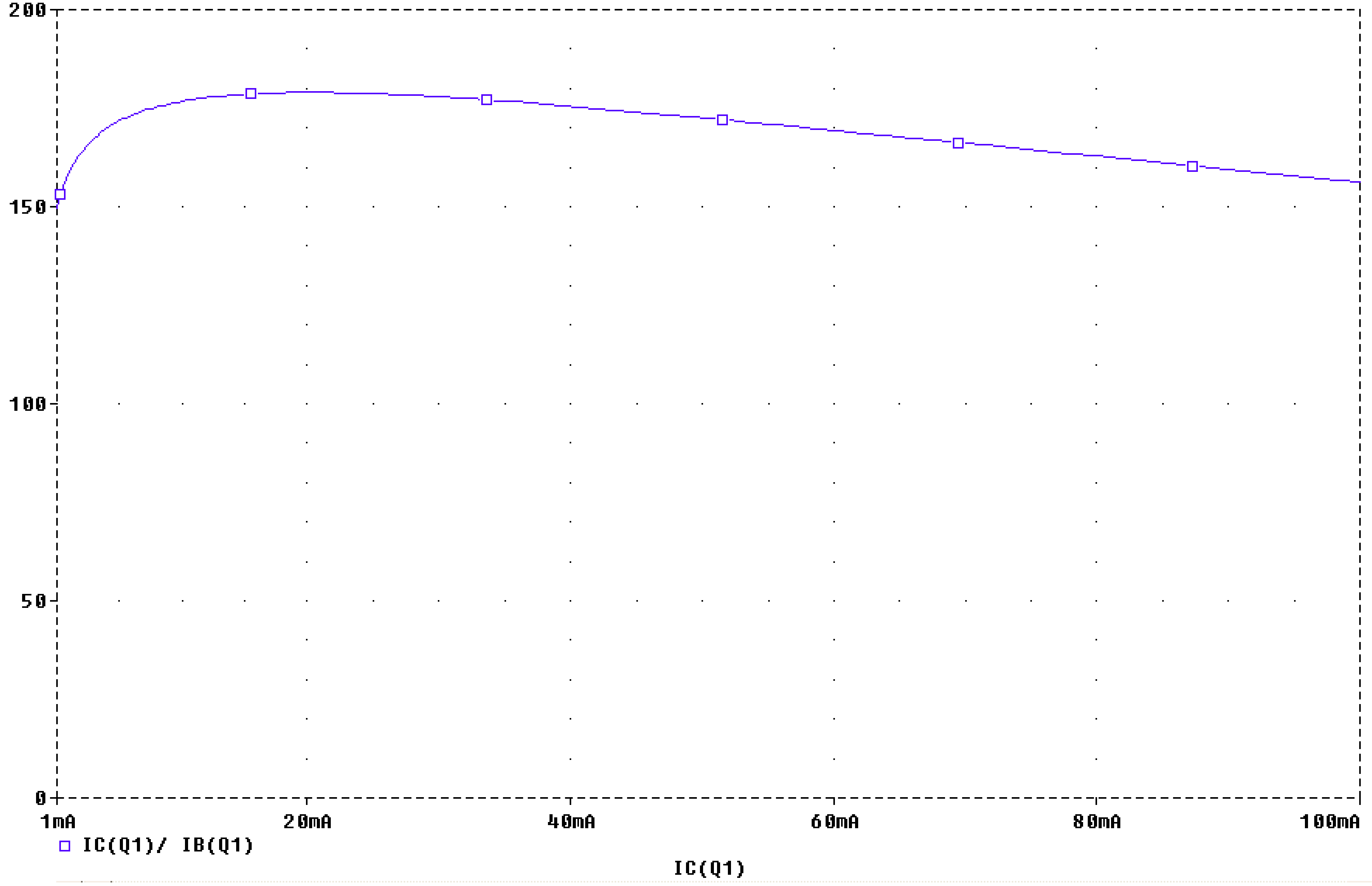
CE-stage

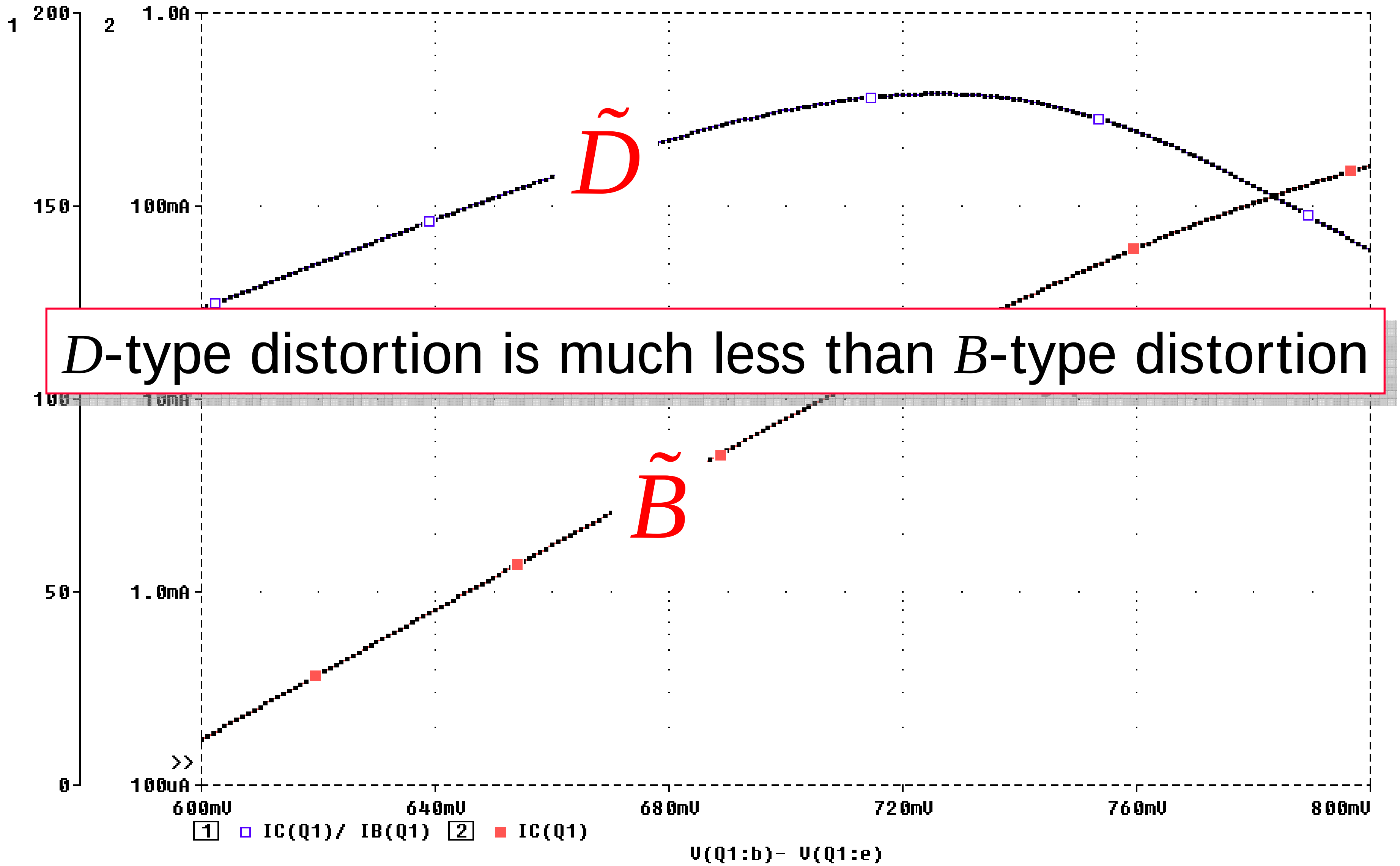
$$\begin{pmatrix} \tilde{A} & \tilde{B} \\ \tilde{C} & \tilde{D} \end{pmatrix}$$

Simulation of *B*



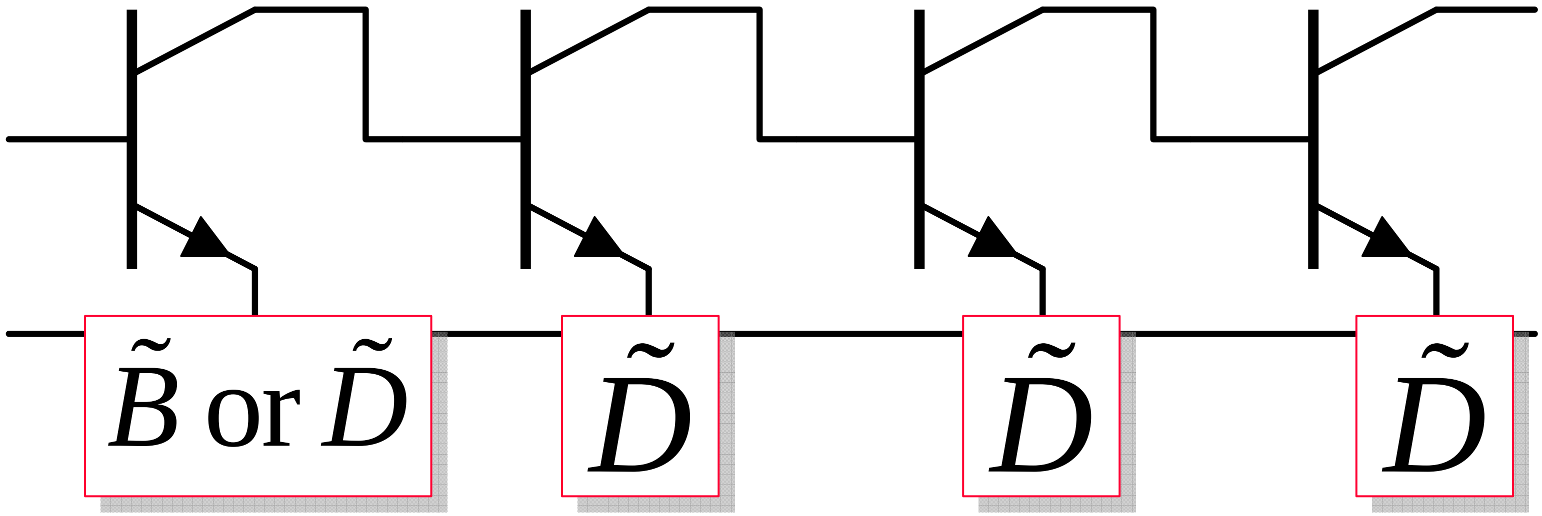
Simulation of *D*



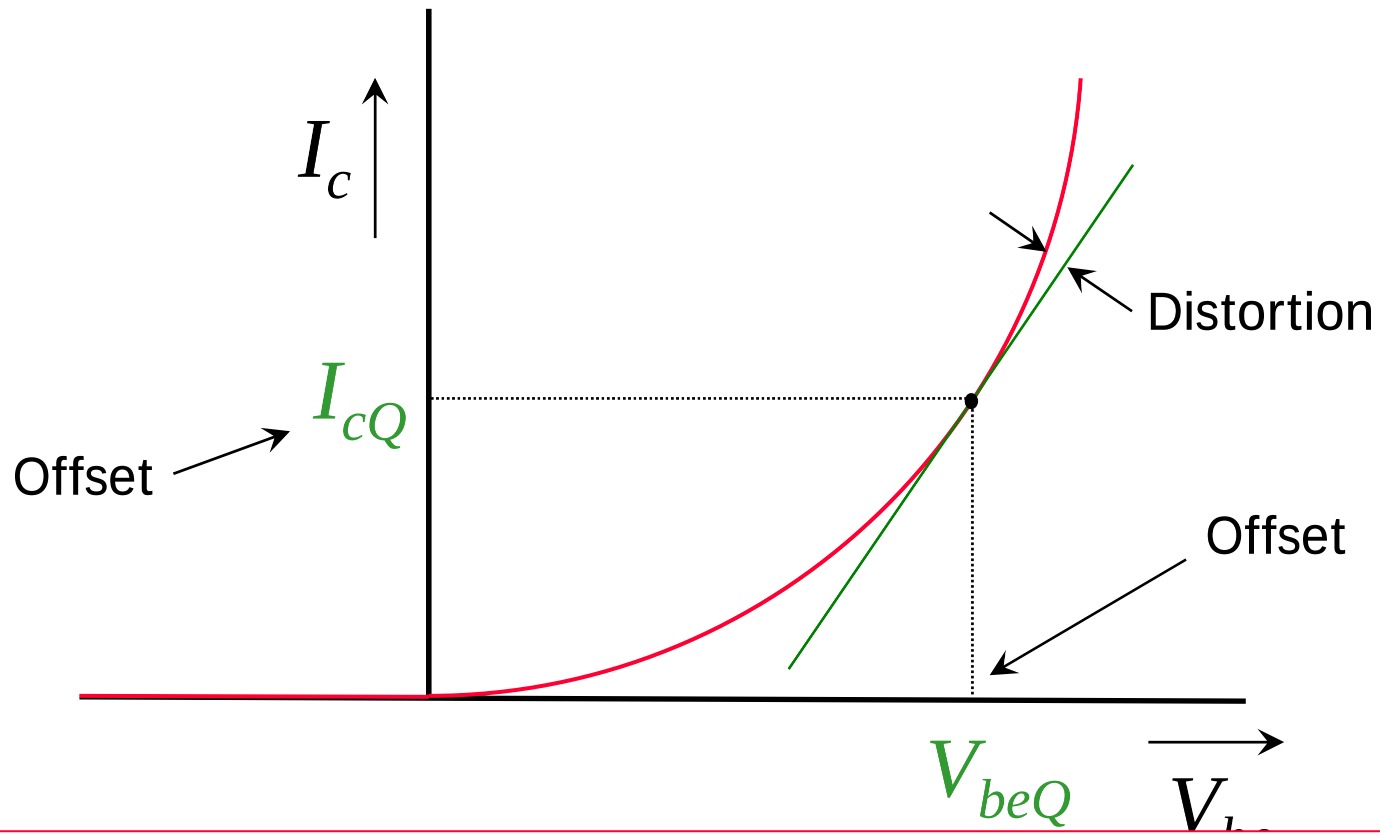


D-type distortion is much less than *B*-type distortion

Location

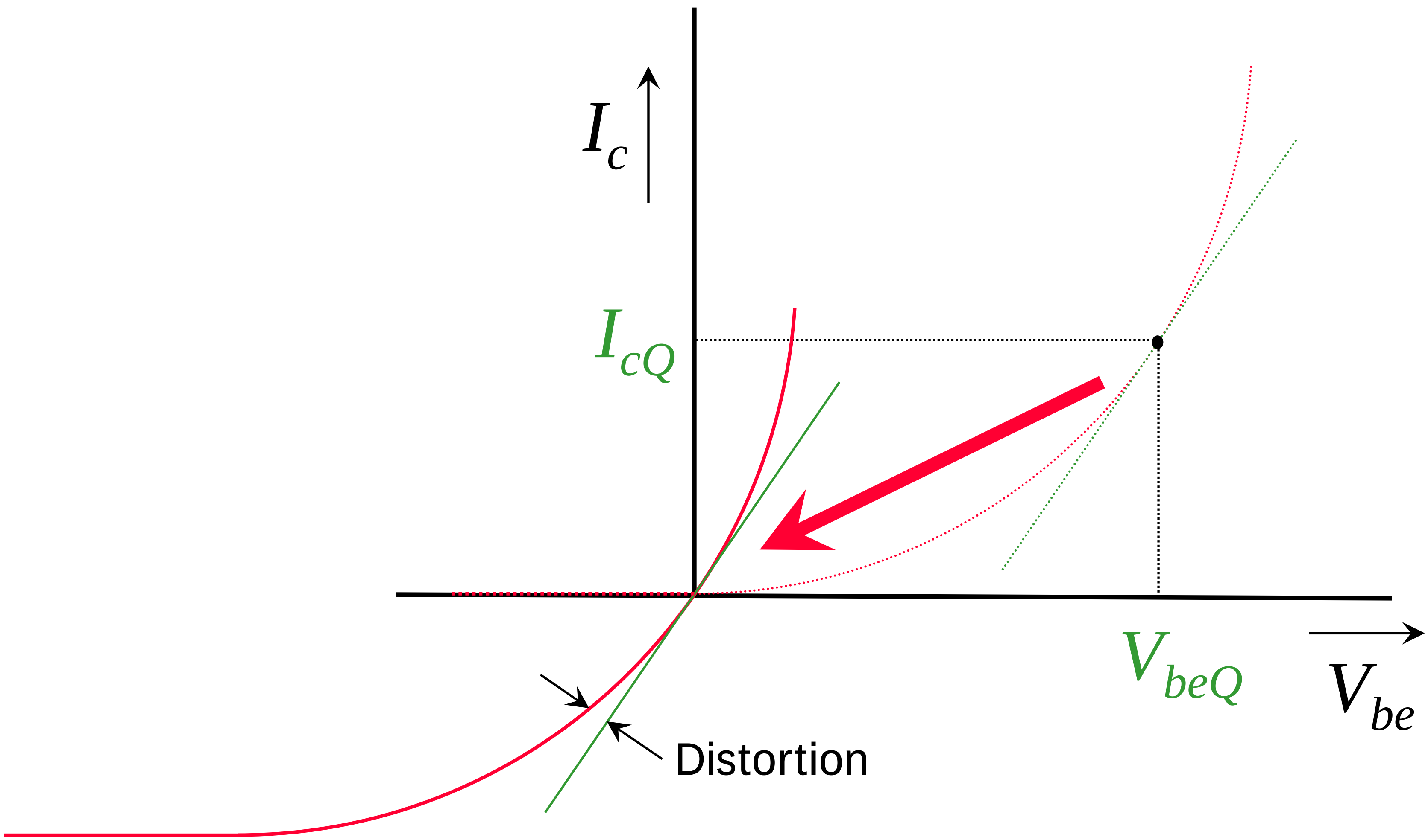


Select a suitable tangent



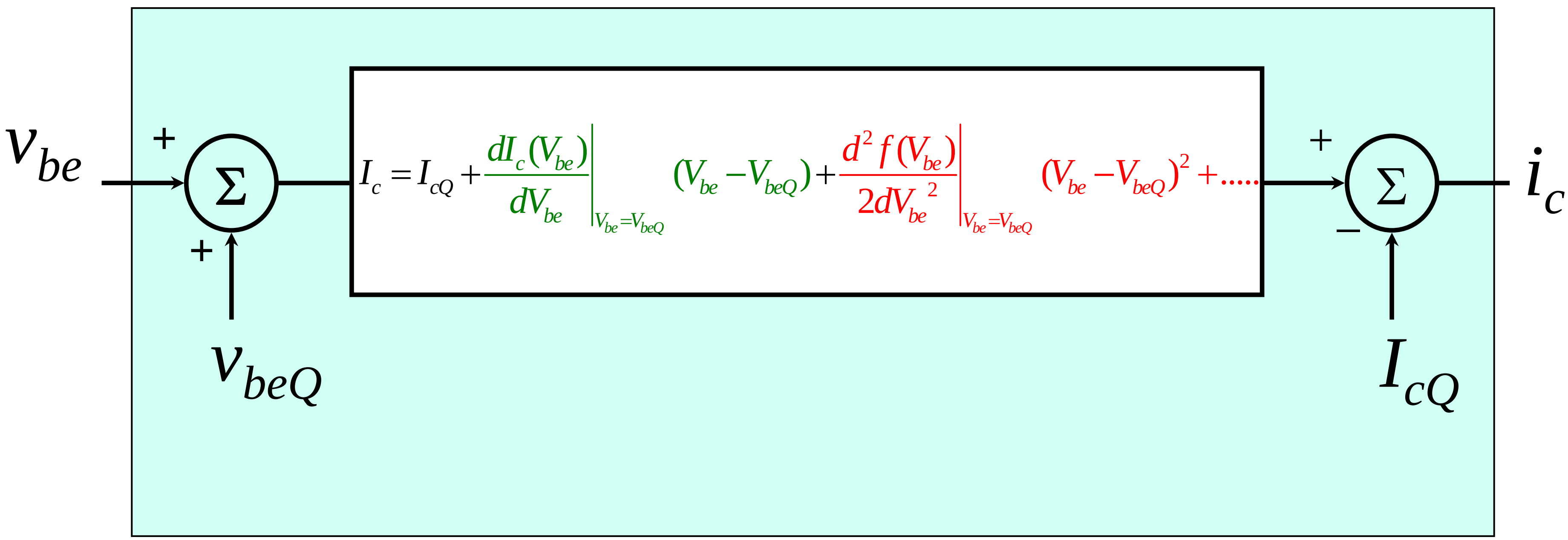
$$I_c = I_{cQ} + \left.\frac{dI_c(V_{be})}{dV_{be}}\right|_{V_{be}=V_{beQ}} (V_{be} - V_{beQ}) + \left.\frac{d^2 f(V_{be})}{2dV_{be}^{\ 2}}\right|_{V_{be}=V_{beQ}} (V_{be} - V_{beQ})^2 + \ldots..$$

Translation to the origin (Biasing)



Adding and subtracting offsets = Biasing

$$i_c = \frac{1}{B_{V_{beQ}}} v_{in} + \left.\frac{d^2 f(V_{be})}{2dV_{be}^{\ 2}}\right|_{V_{be}=V_{beQ}} v_{be}^{\ 2} + ...$$



Bias parameters for transfer B

IF:

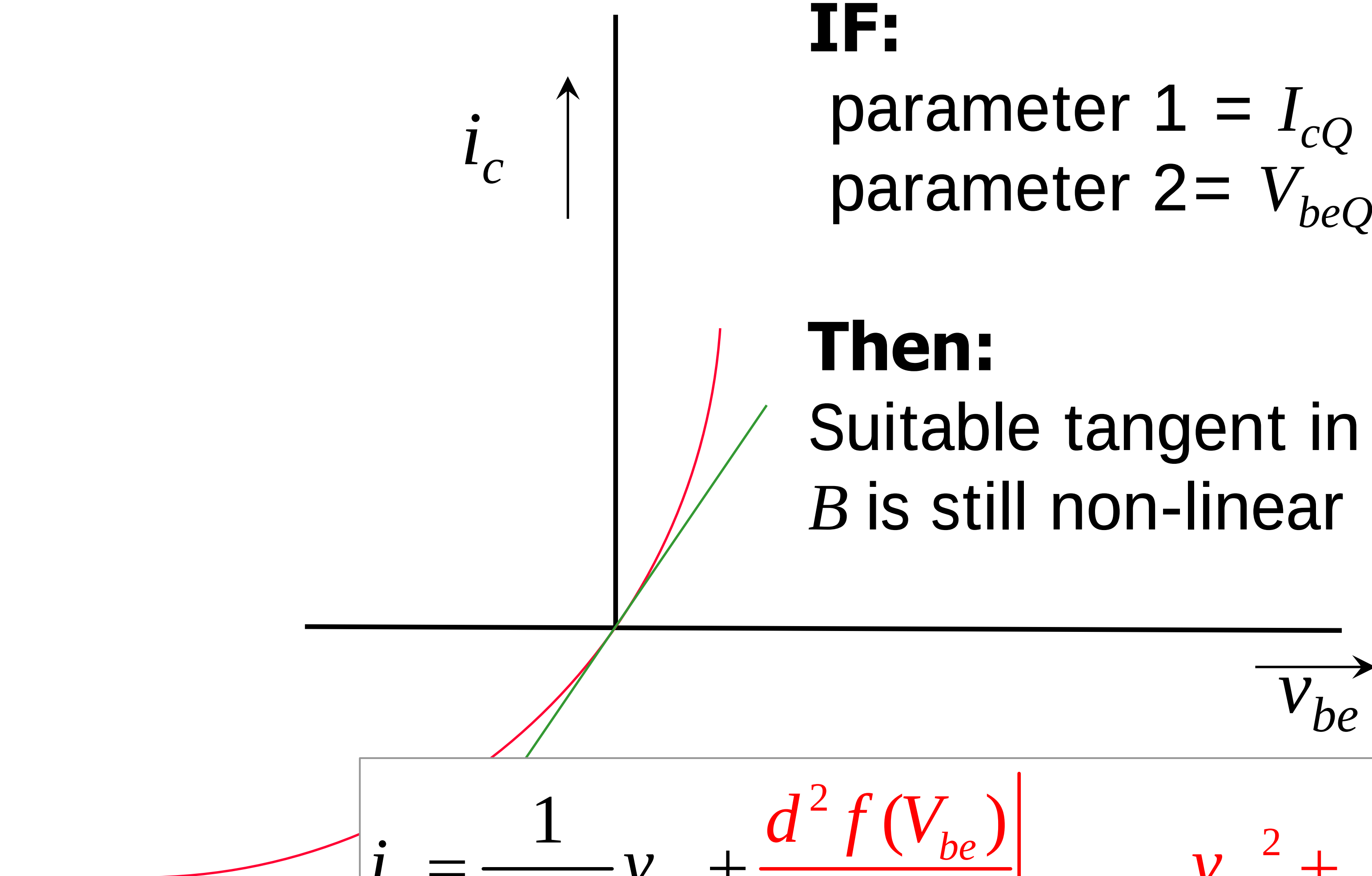
parameter 1 = I_{cQ}

parameter 2= V_{beQ}

Then:

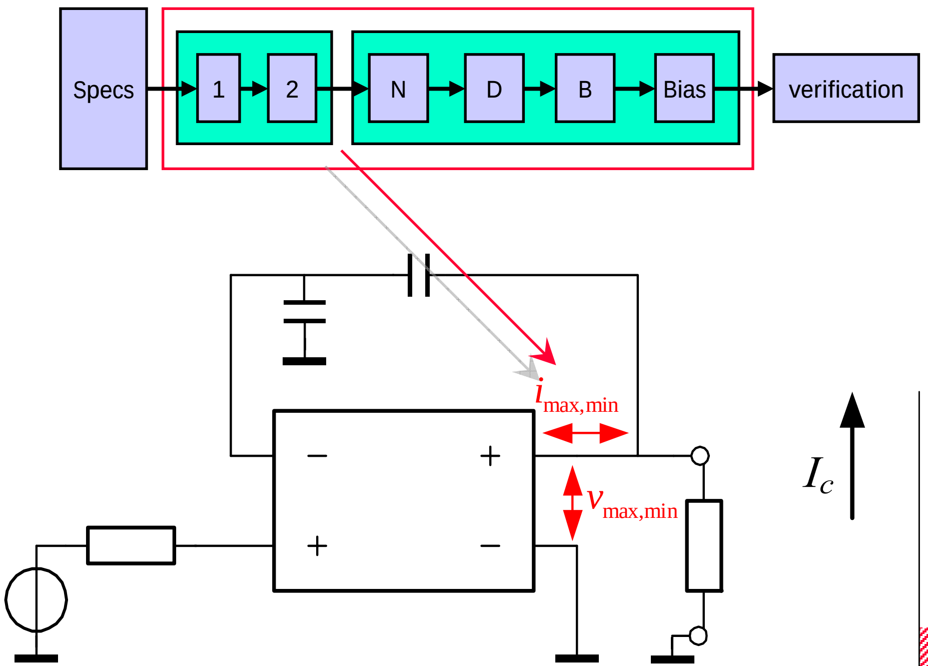
Suitable tangent in origin

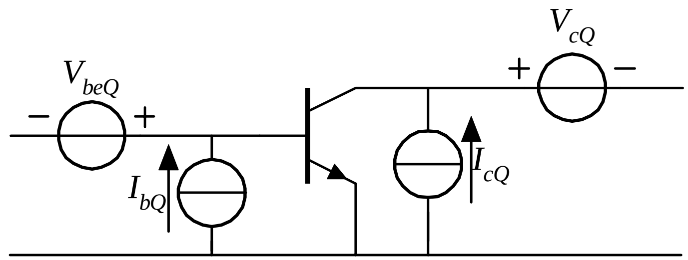
B is still non-linear

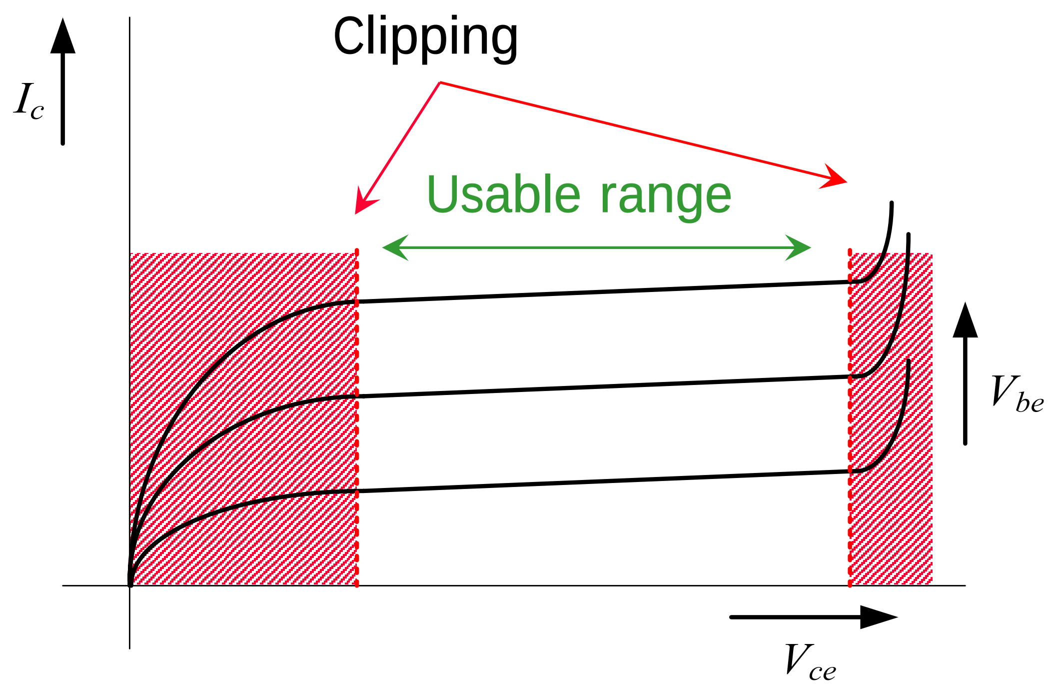


$$i_c = \frac{1}{B_{V_{beQ}}} v_{be} + \left. \frac{d^2 f(V_{be})}{2dV_{be}^2} \right|_{V_{be}=V_{beQ}} v_{be}^2 + ...$$

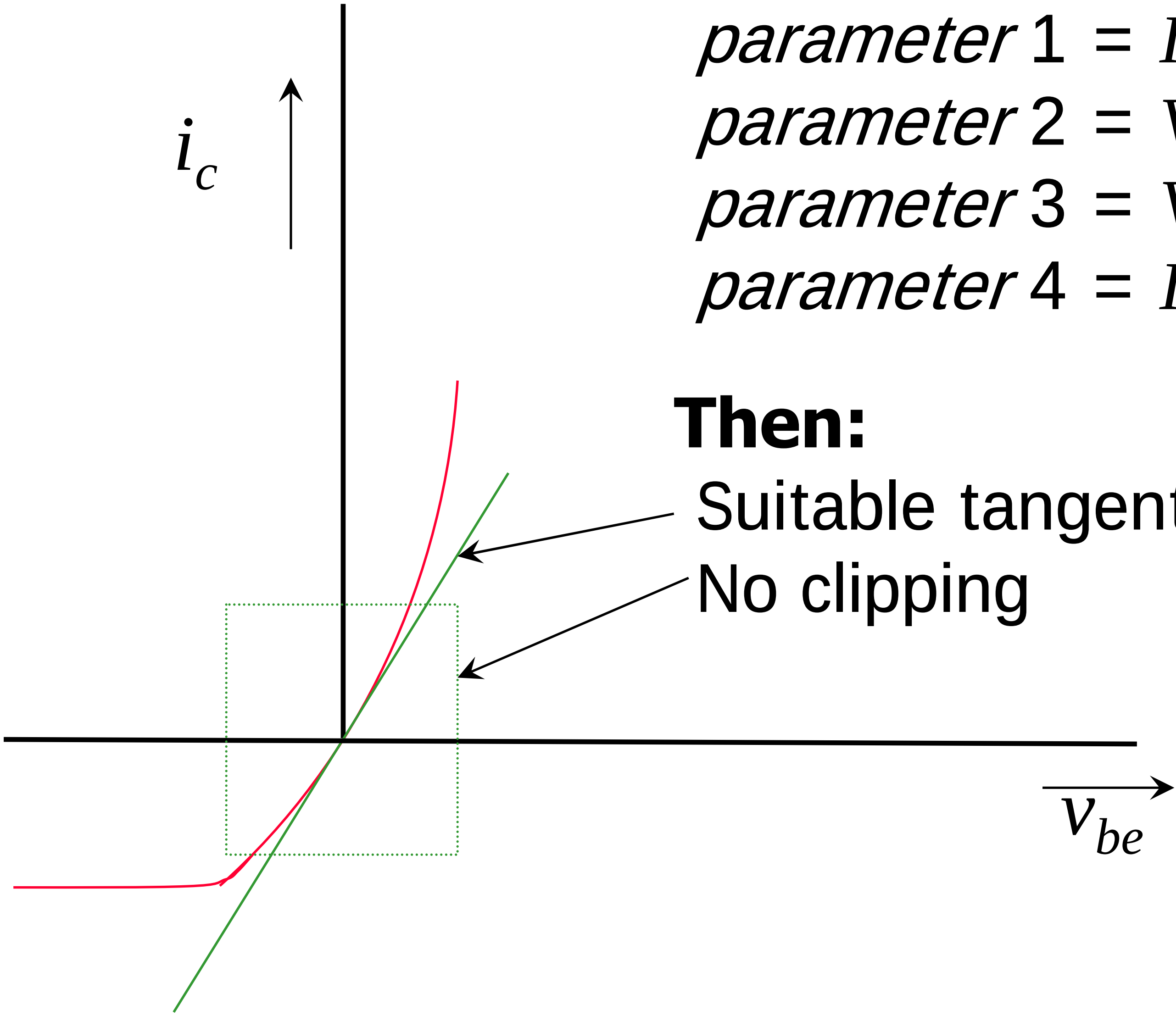
More bias parameters







4 bias parameters



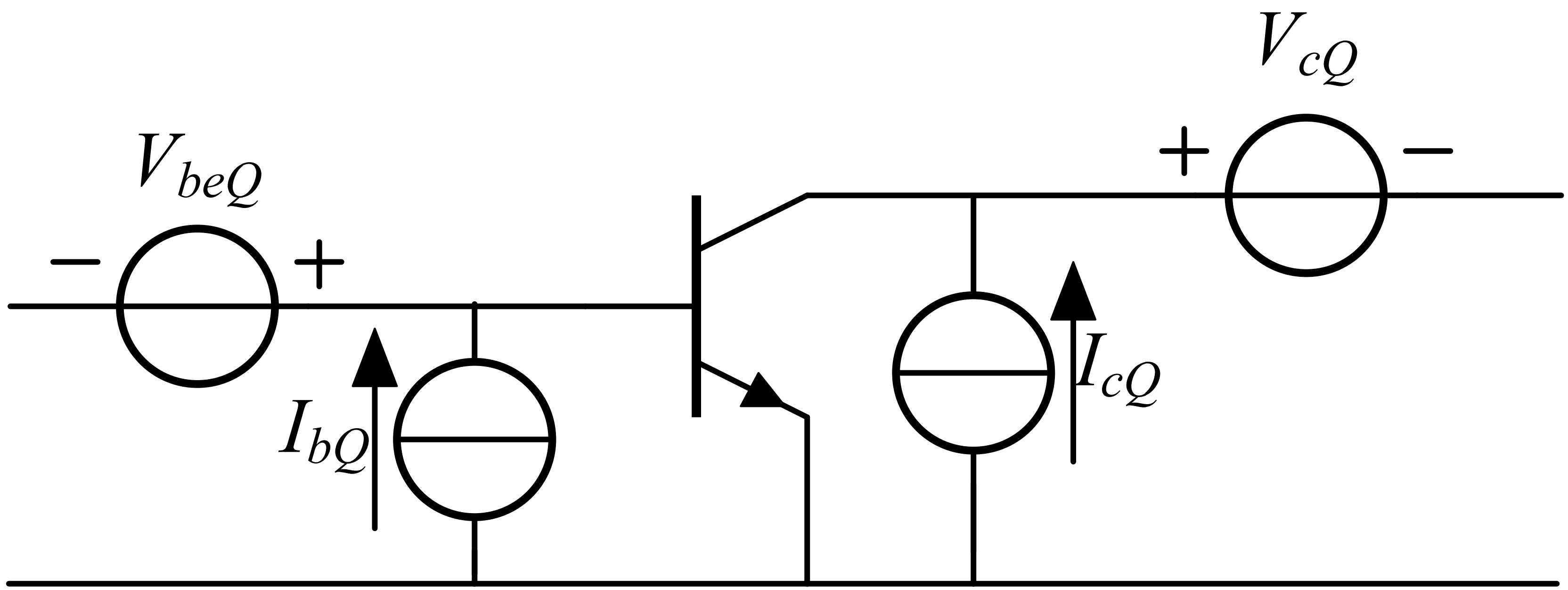
IF:

$parameter\,1 = I_{cQ}$
$parameter\,2 = V_{beQ}$
$parameter\,3 = V_{cQ}$
$parameter\,4 = I_{bQ}$

Then:

Suitable tangent in origin
No clipping

4 bias sources needed for the translations



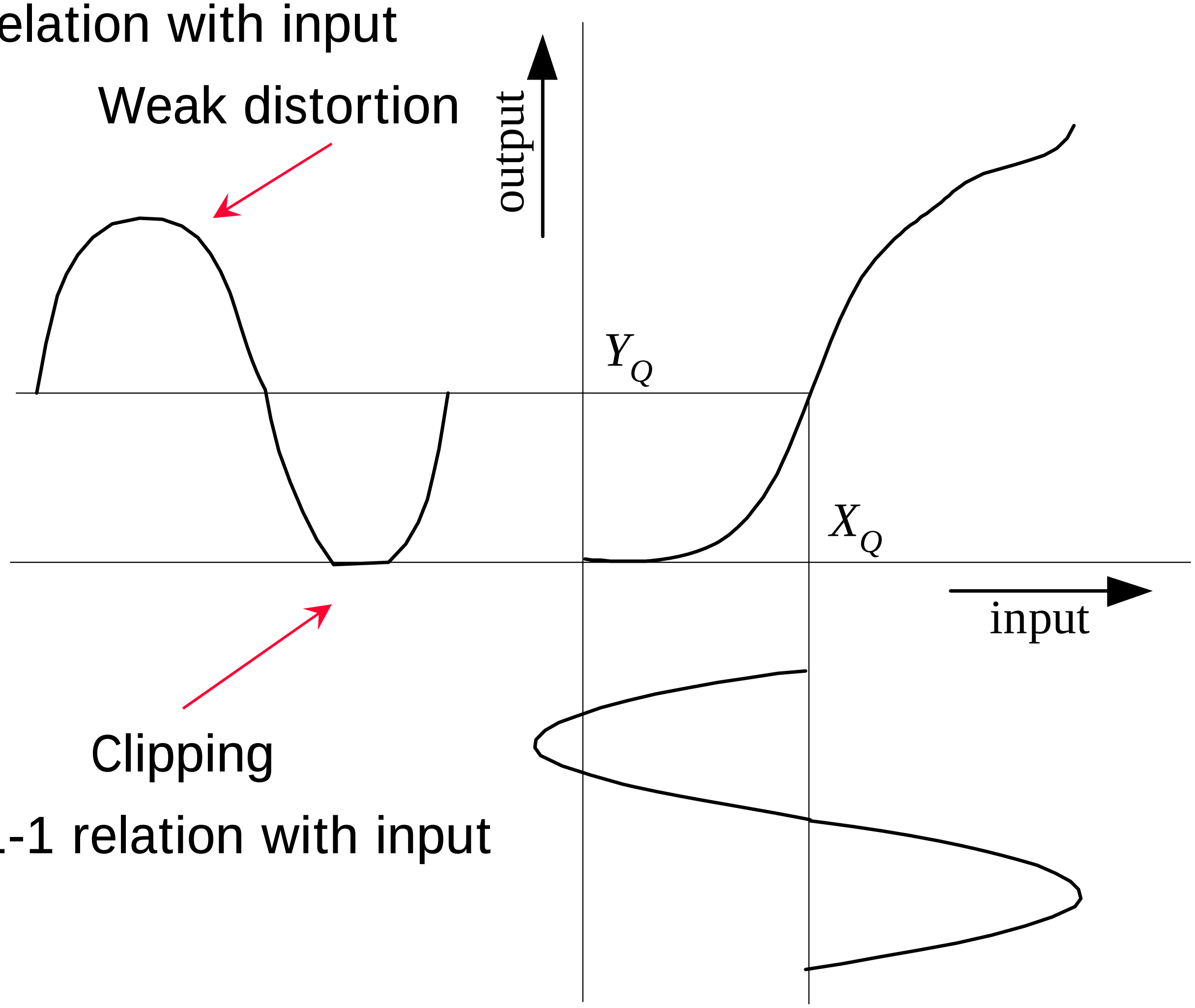
Implementation will be **done later** in the biasing step

Now biasing quantities are **just parameters**

Biasing does **not** make the circuit linear

Summary : Clipping and weak distortion

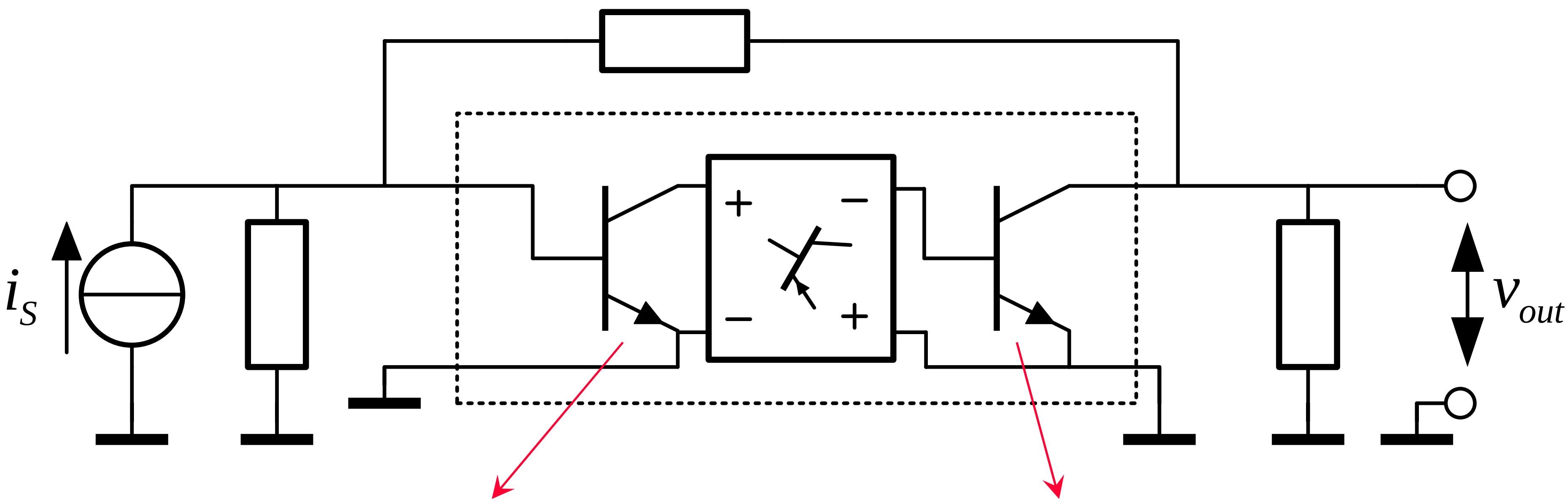
Still 1-1 relation with input



No 1-1 relation with input

Design the last stage: clipping

V_{beQ} and I_{bQ} not independent

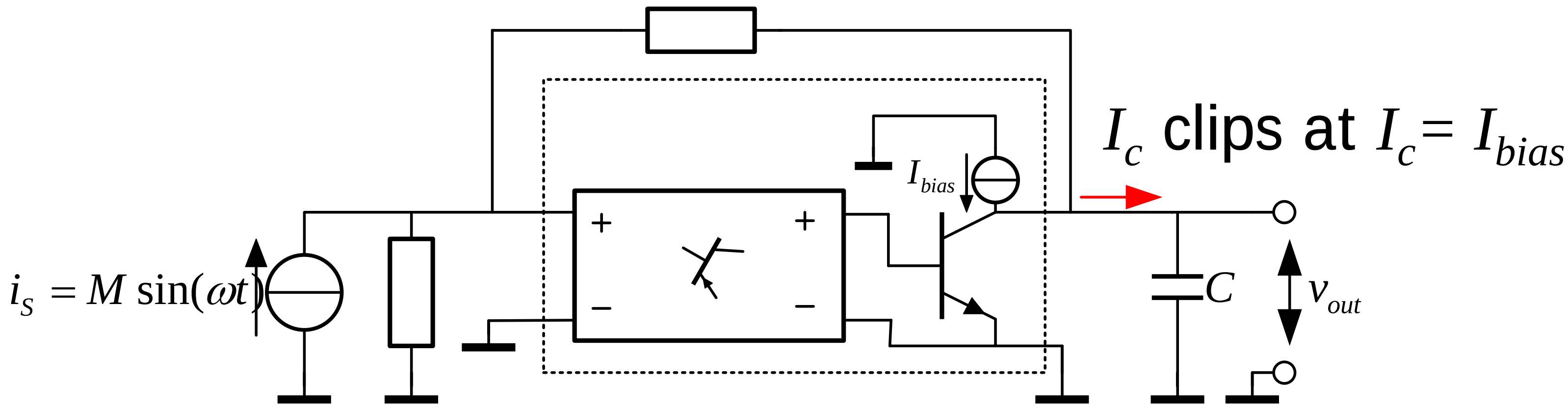


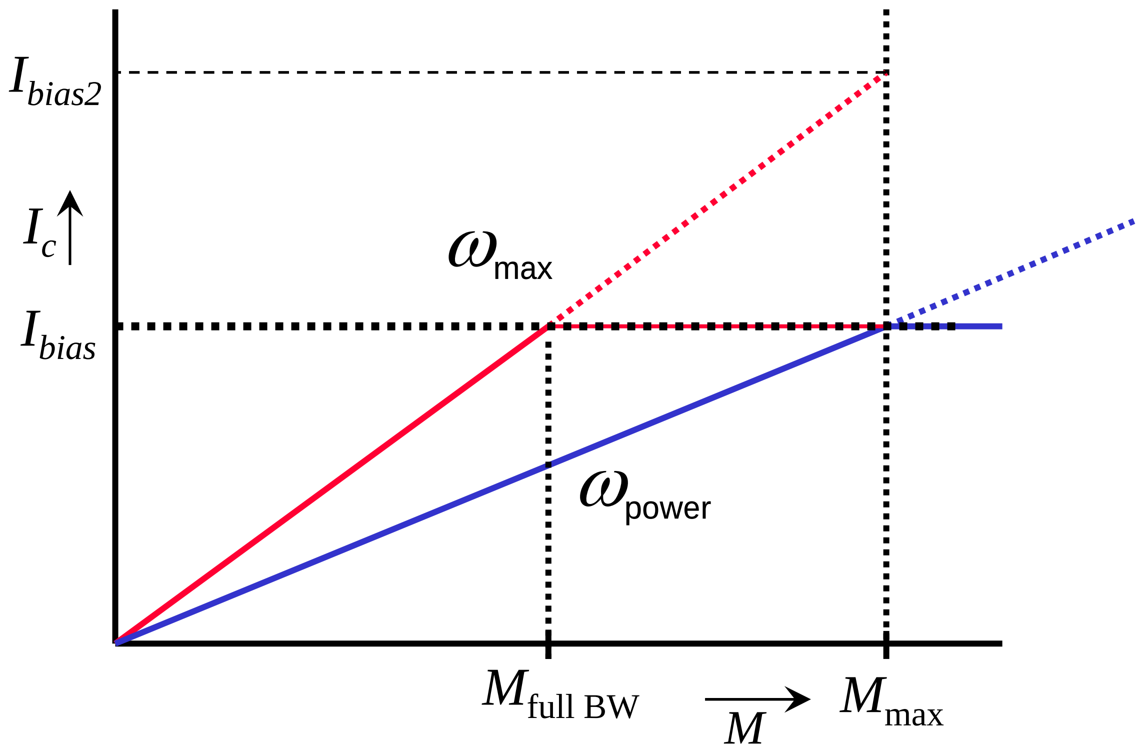
$$V_{cQ} \Rightarrow V_{\min} < v_c < V_{\max}$$
$$I_{cQ} \Rightarrow I_{\min} < i_c < I_{\max}$$

Slewing

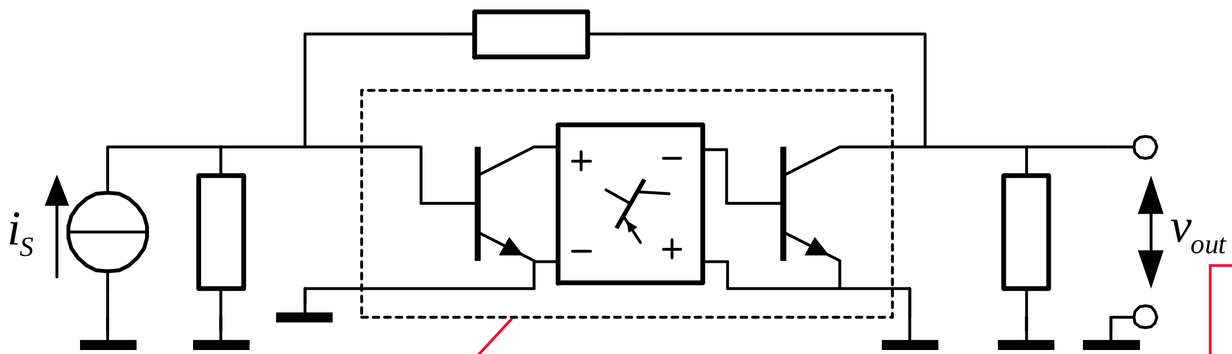
$$V_{cQ} \Rightarrow V_{\min} < v_c < V_{\max}$$
$$I_{cQ} \Rightarrow I_{\min} < i_c < I_{\max}$$

Power bandwidth $\omega_{max} > \omega_{power}$





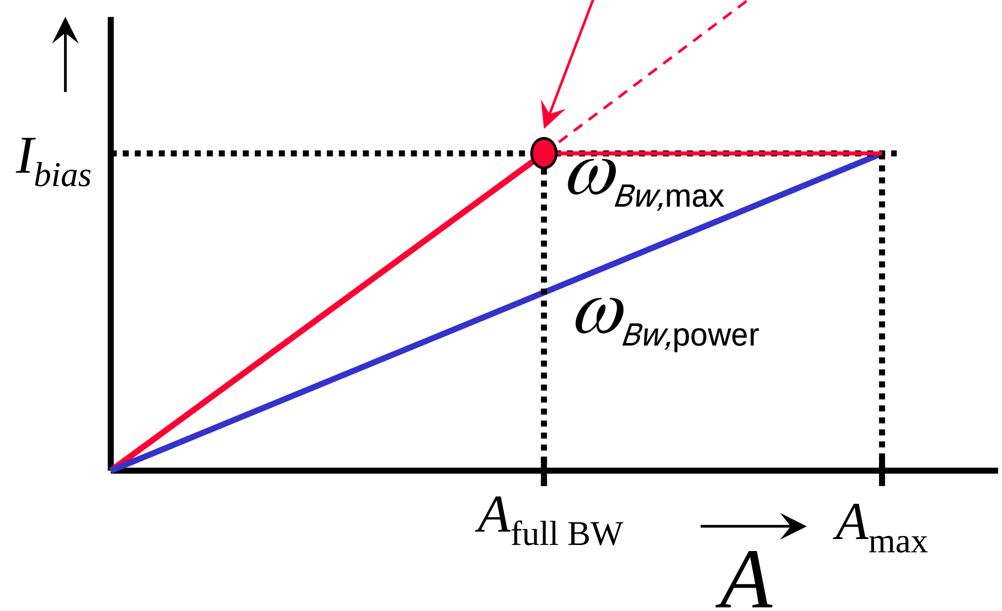
Check all stages



$$V_{cQ} \Rightarrow V_{\min} < v_c < V_{\max}$$

$$I_{cQ} \Rightarrow I_{\min} < i_c < I_{\max}$$

Can be verified with small-signal models (AC analysis)



Conclusions: Clipping

The loop is broken!

Loop gain does not help (Disaster)

Can only be prevented locally

Last stage large gain

Clipping in last stage

Dominant criterion for last stage

Dominant influence on power consumption

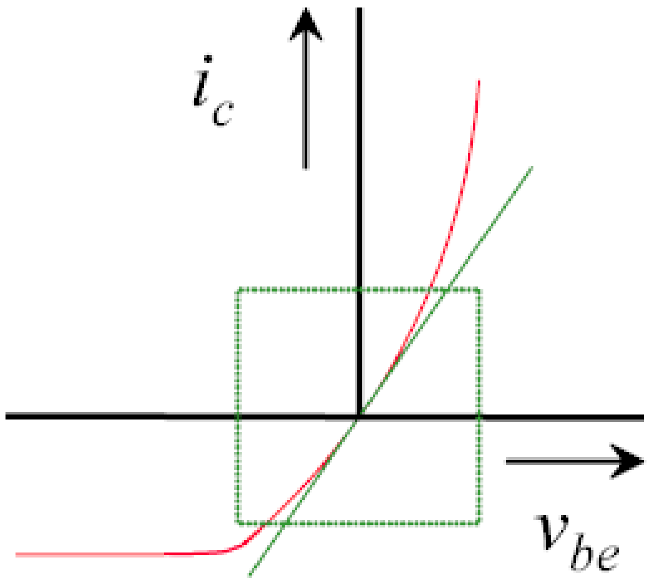
Clipping of other stages should not be a problem

Weak distortion

Proper bias signals added (no offsets)

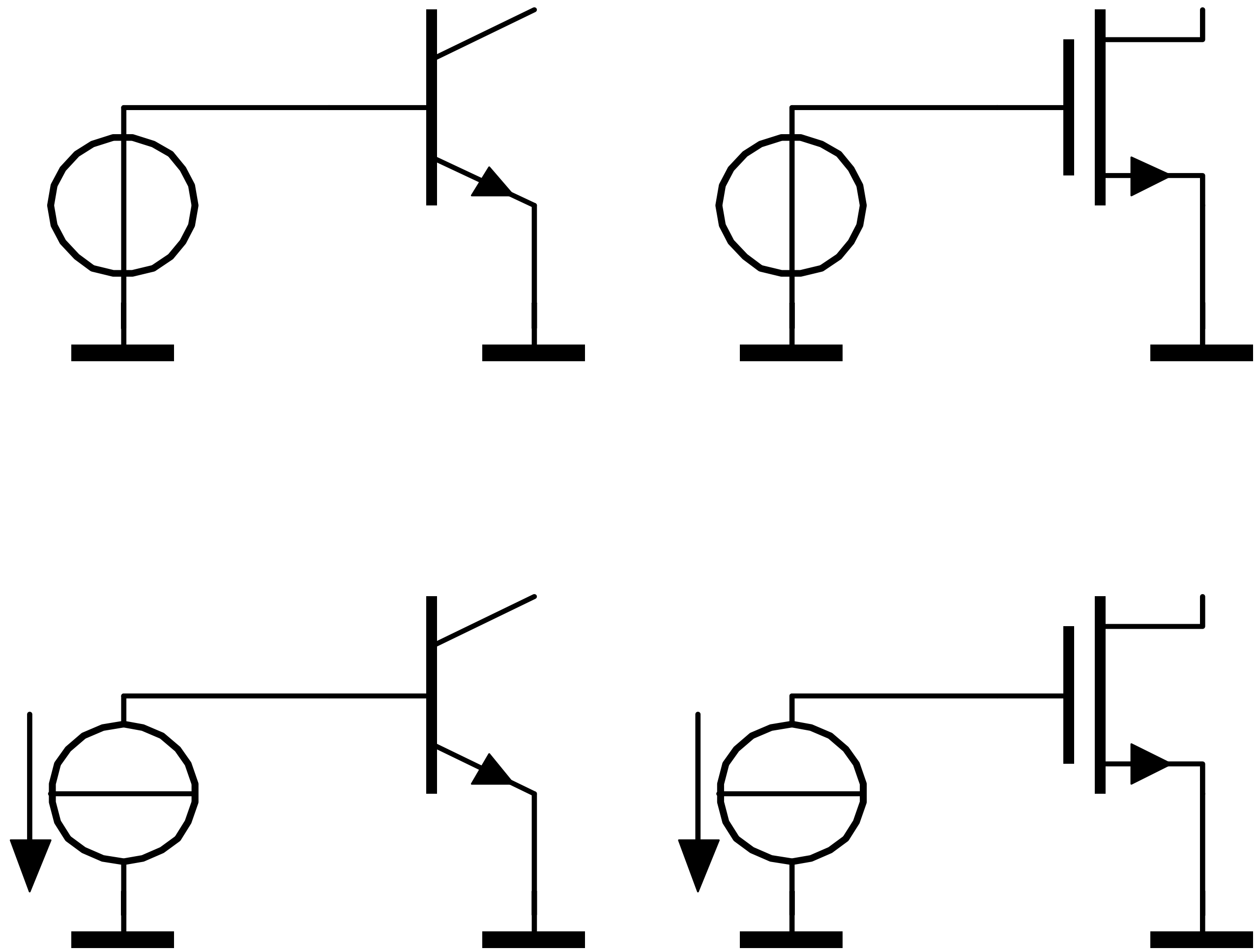
No clipping

Small distortion components → Third order is enough

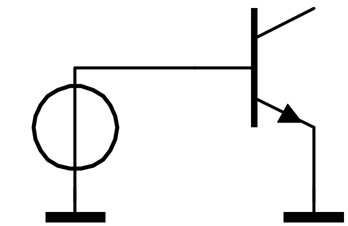


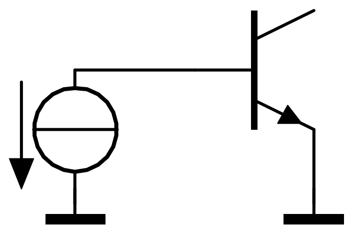
$$i_c = G_t v_{be} + G_{t2} v_{be}^2 + G_{t3} v_{be}^3$$

Weak distortion, 4 cases



Weak distortion, Bipolar transistor



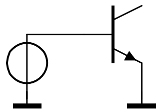


$$\begin{pmatrix} -\dfrac{1}{g_m r_o} & -\dfrac{1}{g_m} \\ -\dfrac{1}{\beta_F r_o} & -\dfrac{1}{\beta_F} \end{pmatrix}$$

g_m or B –type distortion

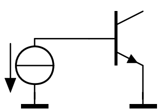
β or D –type distortion

Weak distortion, bipolar transistor



g_m or B –type distortion

$$i_c = \frac{1}{B} v_{be} + \left. \frac{d^2 f(V_{be})}{2dV_{be}^{\ 2}} \right|_{V_{be}=V_{beQ}} v_{be}^{\ 2} + \left. \frac{d^3 f(V_{be})}{6dV_{be}^{\ 3}} \right|_{V_{be}=V_{beQ}} v_{be}^{\ 3}$$

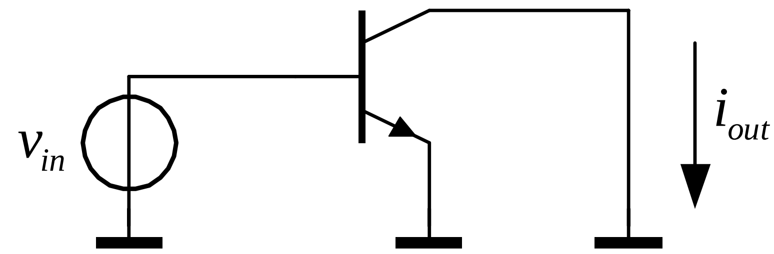


β or D –type distortion

$$i_c = \frac{1}{D} i_b + \left. \frac{d^2 f(I_b)}{2dI_b^{\ 2}} \right|_{I_b=I_{bQ}} i_b^{\ 2} + \left. \frac{d^3 f(I_b)}{6dI_b^{\ 3}} \right|_{I_b=I_{bQ}} i_b^{\ 3}$$

B –type distortion

$$I_c = I_s\left(e^{\frac{V_{be}}{V_T}} - 1\right)$$



$$\frac{dI_c}{dV_{be}} = \frac{1}{V_T} I_s e^{\frac{kT}{q}V_{be}} = \frac{I_c}{V_T} = \frac{1}{B}$$

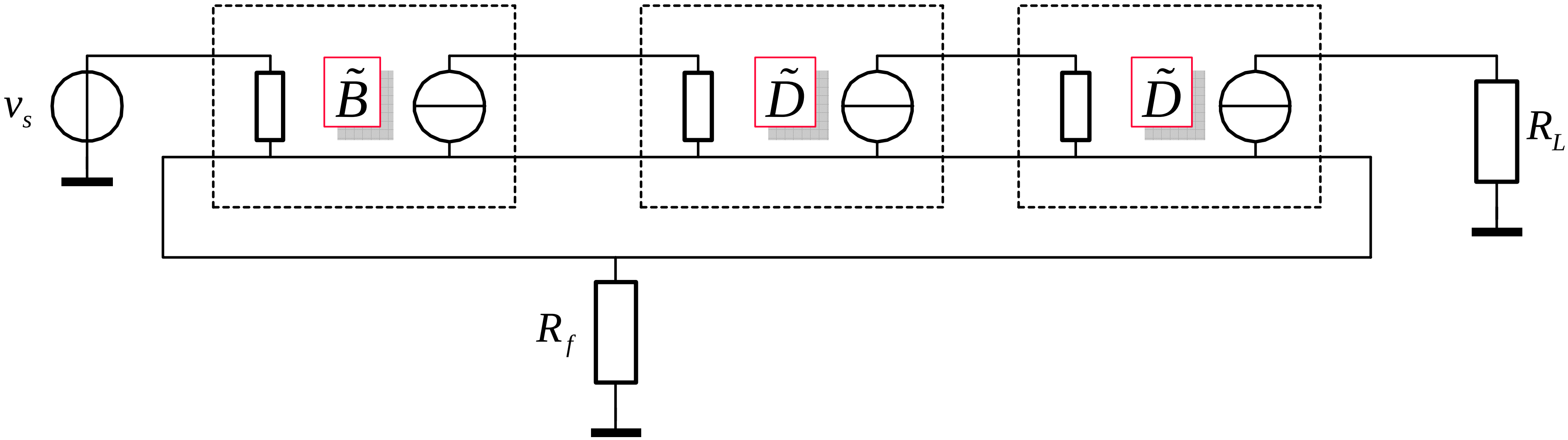
$$\frac{d^2I_c}{dV_{be}^2} = \frac{1}{V_T^2} I_s e^{\frac{kT}{q}V_{be}} = \frac{I_c}{V_T^2} = \frac{1}{BV_T}$$

$$\frac{d^3I_c}{dV_{be}^3} = \frac{1}{V_T^3} I_s e^{\frac{kT}{q}V_{be}} = \frac{I_c}{V_T^3} = \frac{1}{BV_T^2}$$

$$i_{out} = -\frac{1}{B}\left(v_{in} + \frac{v_{in}^2}{2V_T} + \frac{v_{in}^3}{6V_T^2}\right)$$

B –type distortion is bias independent

$$i_{out} = -\frac{1}{B}\left(v_{in} + \frac{v_{in}^2}{2V_T} + \frac{v_{in}^3}{6V_T^2} \right)$$

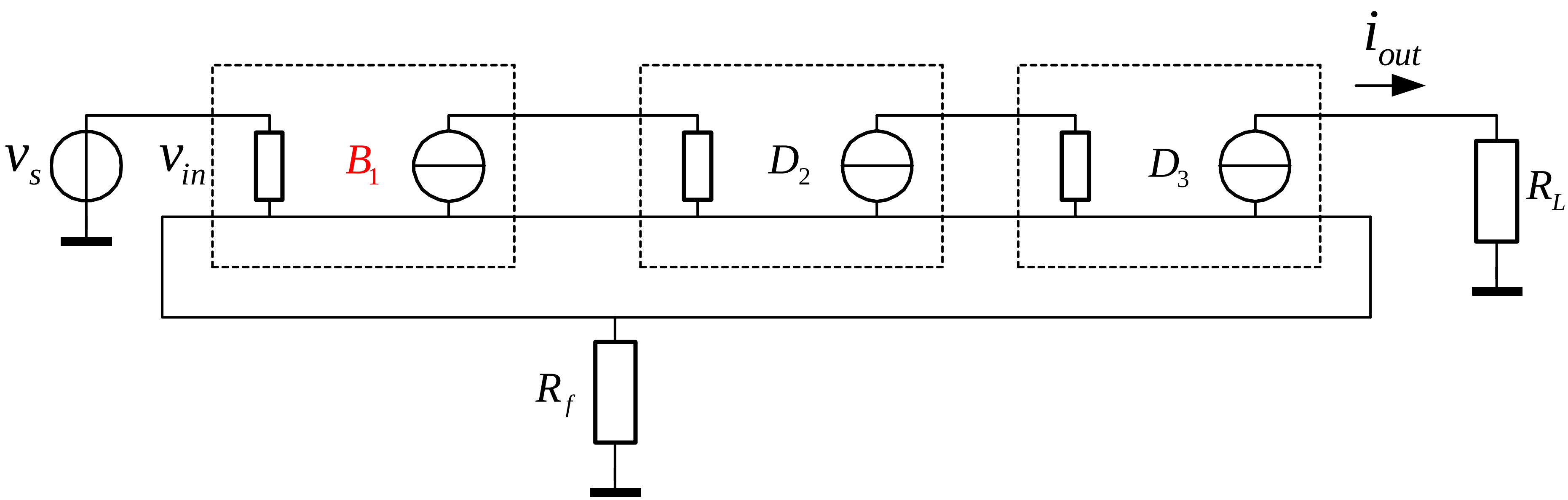


B –type at the **input**, when the nullator is a voltage sensor

Reduce via loopgain (no interference with noise optimum)

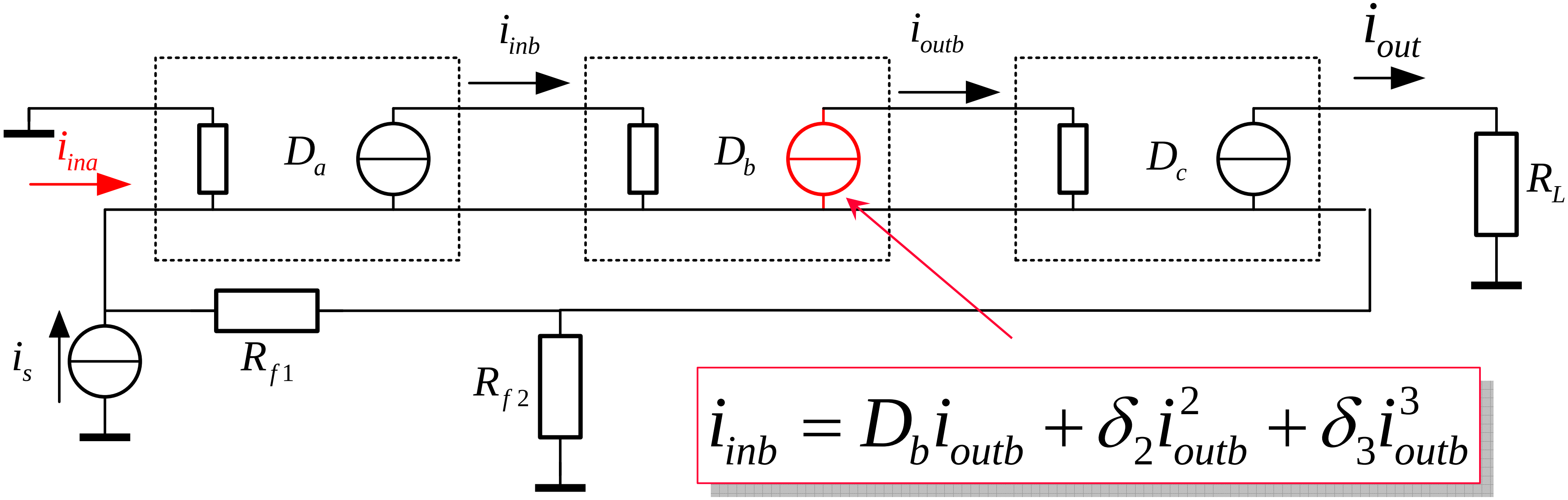
Reduction of B –type distortion

$$i_{out} = -\frac{1}{B_1 D_2 D_3}\left(v_{in} + \frac{v_{in}^2}{2V_T} + \frac{v_{in}^3}{6V_T^2} \right)$$



Secondary effect : Increase bias first stage → B_1 smaller → more loopgain
Without feedback, increasing bias first stage does not help

Influence of location of distortion



$$i_{inb} = D_b i_{outb} + \delta_2 i_{outb}^2 + \delta_3 i_{outb}^3$$

$$i_{ina} = D_a \left[D_b D_c i_{out} + \delta_2 \left(D_c i_{out} \right)^2 + \delta_3 \left(D_c i_{out} \right)^3 \right]$$

D_a has a linear effect on distortion

D_c has a **quadratic** and **cubic** effect on distortion

Gain after non-linear stage is best

$$i_{ina} = D_a \left[D_b D_c i_{out} + \delta_2 \left(D_c i_{out} \right)^2 + \delta_3 \left(D_c i_{out} \right)^3 \right]$$

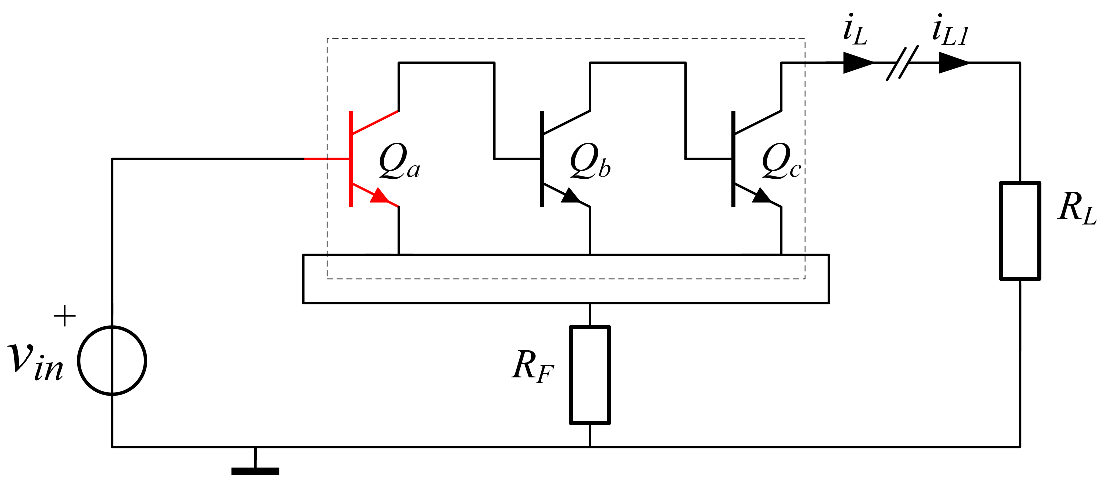
Gain **last stage** important!

Insert **extra gain after** distorting stage

Maximum gain all stages

Worst distortion often at input (B –type)

Distortion caused by first transistor



$$i_L = L i_{L1} + l_2 i_{L1}^2 + l_3 i_{L1}^3$$

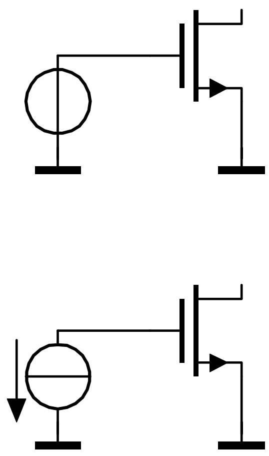
$$L = \frac{R_F}{B_a D_b D_c}$$

$$l_2 = -\frac{1}{2V_T}\frac{B_a^2 D_b^2 D_c^2}{R_F} = \frac{1}{2V_T}\frac{1}{L} B_a D_b D_c$$

$$l_3 = -\frac{1}{3V_T^2}\frac{B_a^3 D_b^3 D_c^3}{R_F} = \frac{1}{3V_T^2}\frac{1}{L} B_a^2 D_b^2 D_c^2$$

Gain of stage itself works as if it's after its non-linearity

Weak distortion, FET

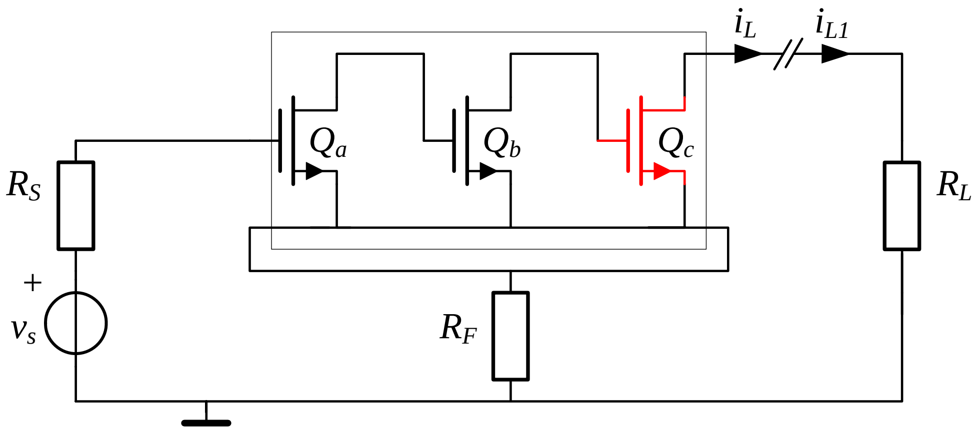


$$\begin{pmatrix} -\frac{1}{g_m r_d} & -\frac{1}{g_m} \\ -\frac{j\omega C_{gs}}{g_m r_d} & -\frac{j\omega C_{gs}}{g_m} \end{pmatrix}$$

Always g_m distortion

$$\begin{pmatrix} -\frac{1}{g_m r_o} & -\frac{1}{g_m} \\ -\frac{1}{\beta_F r_o} & -\frac{1}{\beta_F} \end{pmatrix}$$

Distortion caused by last transistor



$$i_L = L i_{L1} + l_2 i_{L1}^2 + l_3 i_{L1}^3$$

$$L = \frac{R_F}{A_a A_b B_c}$$

$$l_2 = -\frac{1}{4}\frac{A_a A_b B_c}{R_F I_{dQc}} = \frac{1}{4}\frac{1}{L}\frac{1}{I_{dQc}}$$

$$l_3 = -\frac{1}{8}\frac{A_a A_b B_c}{R_F I_{dQc}^2} = \frac{1}{8}\frac{1}{L}\frac{1}{I_{dQc}^2}$$

$$A \propto (\text{Channel length})^{-1}$$

Longer transistor $\Rightarrow$ lower distortion

Bipolar versus FET

$$l_2 = -\frac{1}{2V_T}\frac{B_a^2 D_b^2 D_c^2}{R_F} = \frac{1}{2V_T}\frac{1}{L}B_a D_b D_c$$

$$l_3 = -\frac{1}{3V_T^2}\frac{B_a^3 D_b^3 D_c^3}{R_F} = \frac{1}{3V_T^2}\frac{1}{L}B_a^2 D_b^2 D_c^2$$

Distortion from first stage

Reduce via bias, loopgain

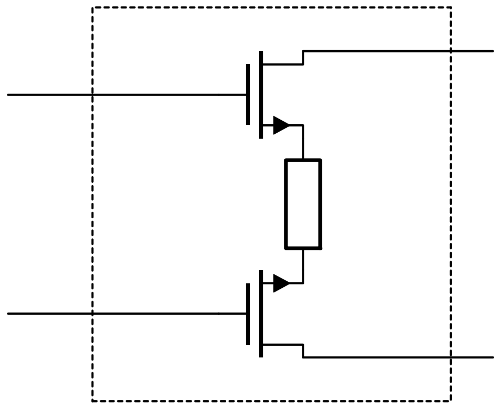
$$l_2 = -\frac{1}{4}\frac{A_a A_b B_c}{R_F I_{dQc}} = \frac{1}{4}\frac{1}{L}\frac{1}{I_{dQc}}$$

$$l_3 = -\frac{1}{8}\frac{A_a A_b B_c}{R_F I_{dQc}^2} = \frac{1}{8}\frac{1}{L}\frac{1}{I_{dQc}^2}$$

Distortion from last stage

Reduce via bias, loopgain, **layout**

Local feedback



Reduces non-linearity of stage

Impedance in active part ☠
Reduces the overall loopgain
Never better than overall loop
Increases distortion other stages
Especially for last stage not a good idea

Only when non-linearity makes variation of loopgain too large

Conclusions weak distortion

B –type distortion (only at nullor input)

D–type distortion (for bipolar)

Increase the loopgain

Via biasing ($B(I_Q)$)

Via Layout (FET)

Extra stage (preferably after distortion source)

No local feedback

Use high gain last stage (also reduces clipping preceding stage)

Dynamic distortion

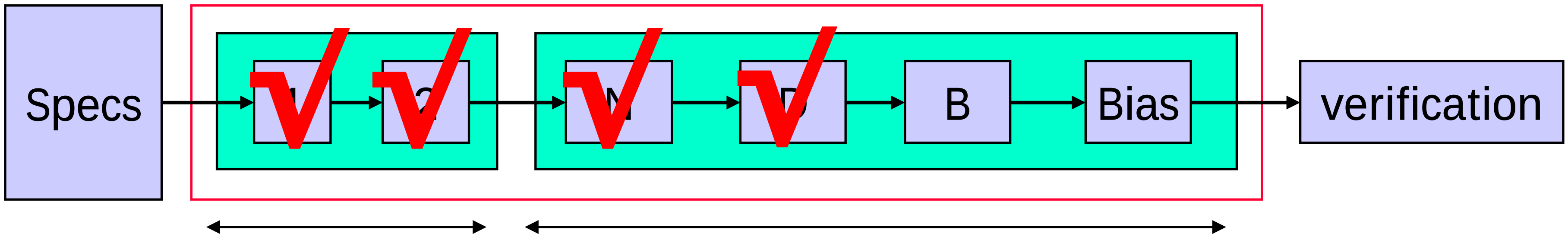
Volterra series

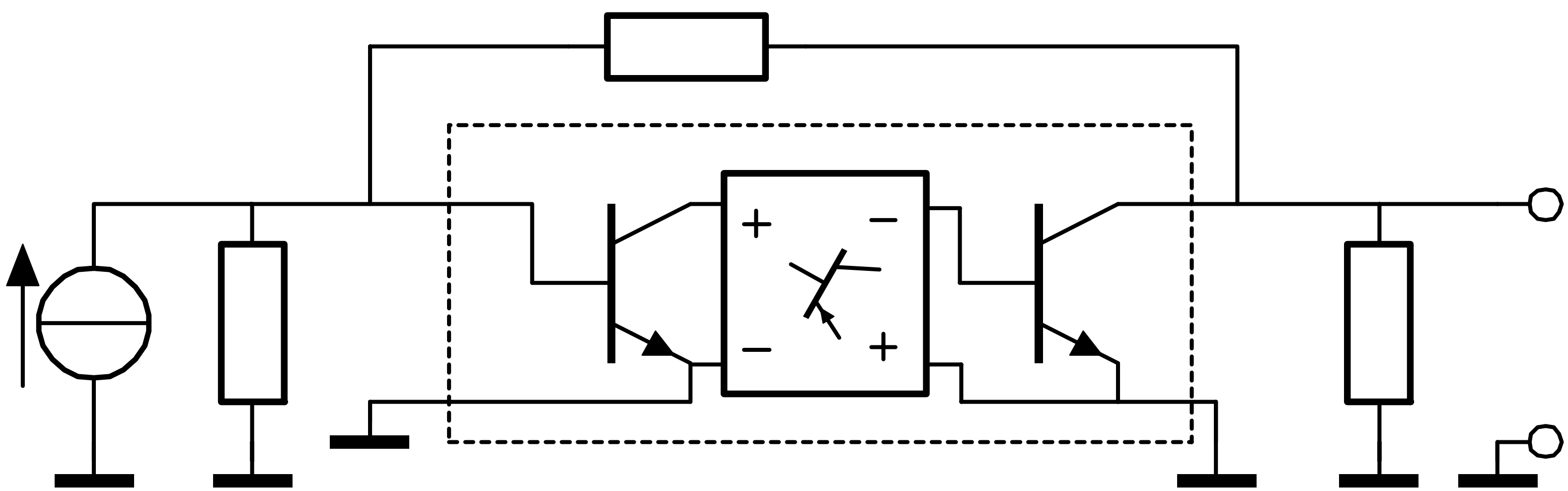
Dynamic eigenvalues

Loopgain helps

Still research

Conclusions





Specifications

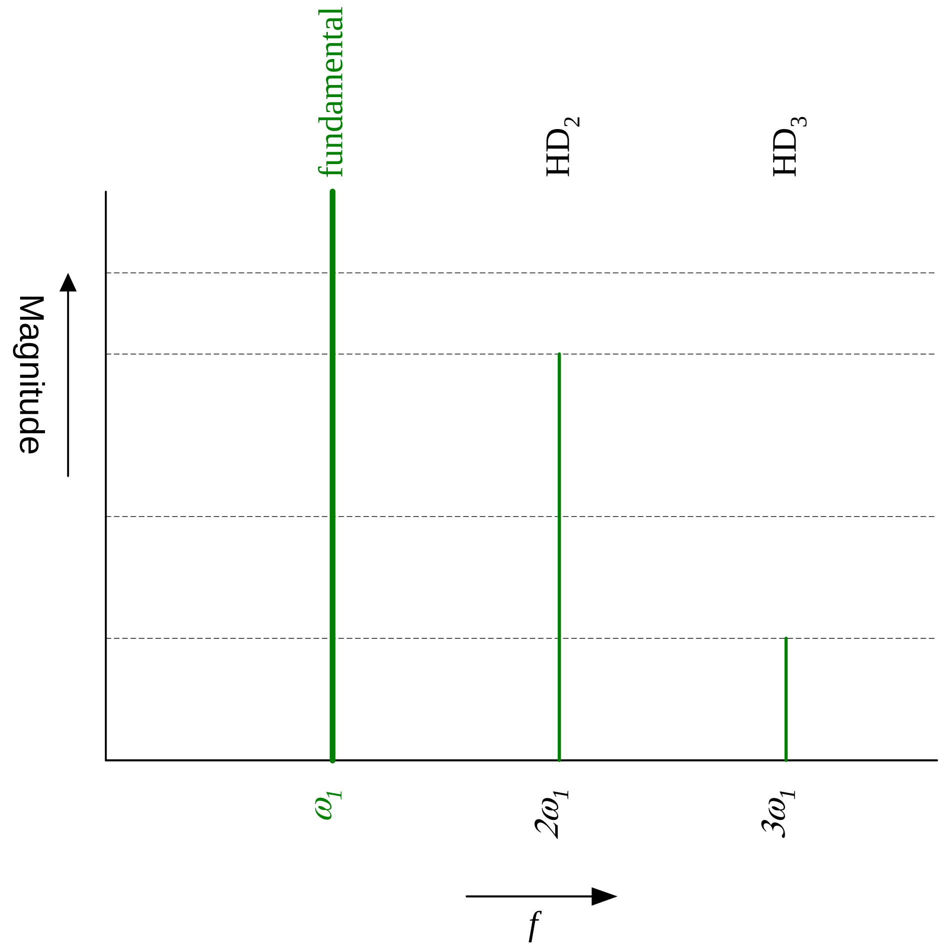
- Harmonic distortion
- Intercept points
- Compression point
- Intermodulation
- Power bandwidth

Harmonic distortion

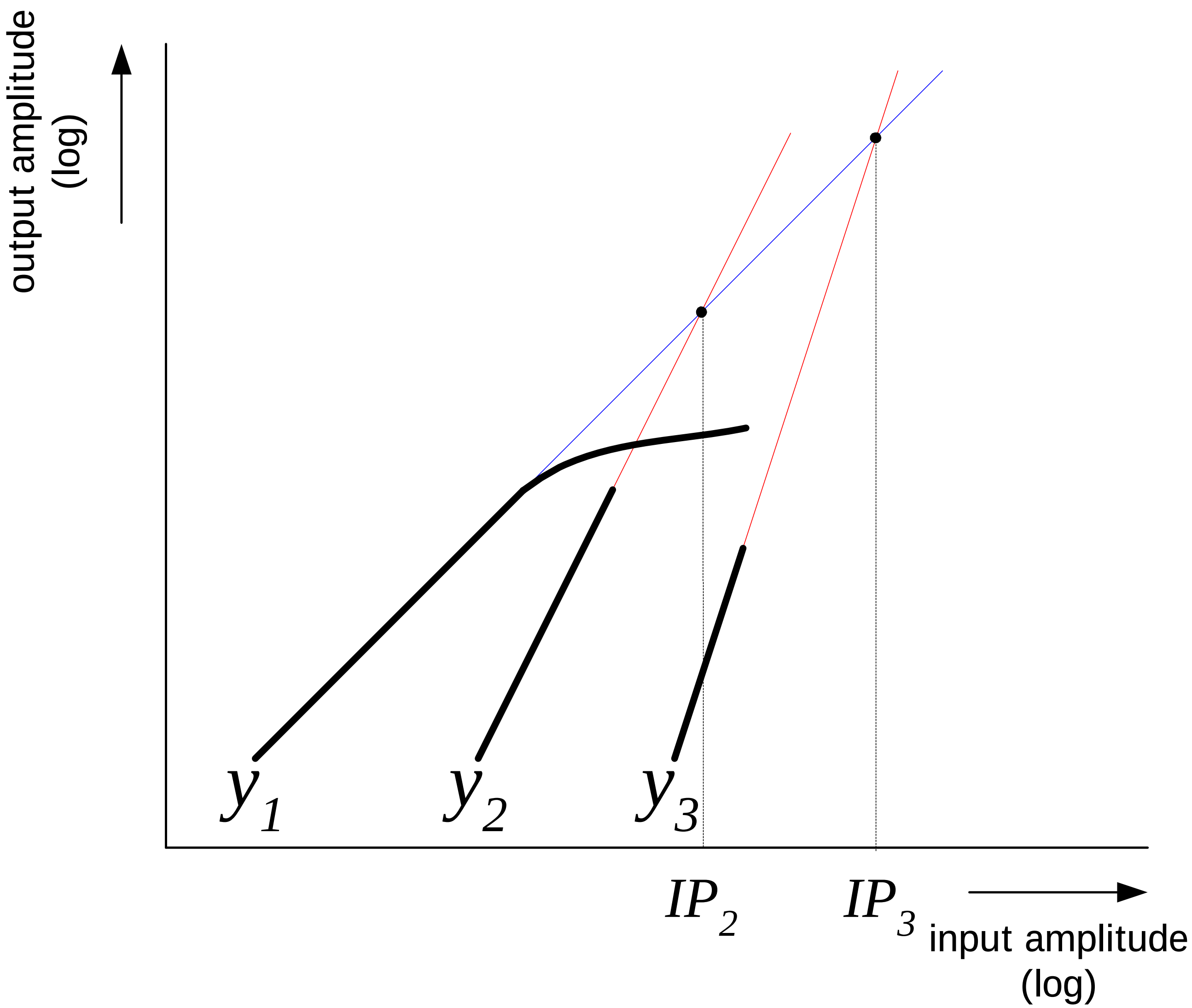
Compare amplitudes fundamental harmonic with n^{th} order harmonic

$$HD_n \hat{=} \frac{y_n}{y_1}$$

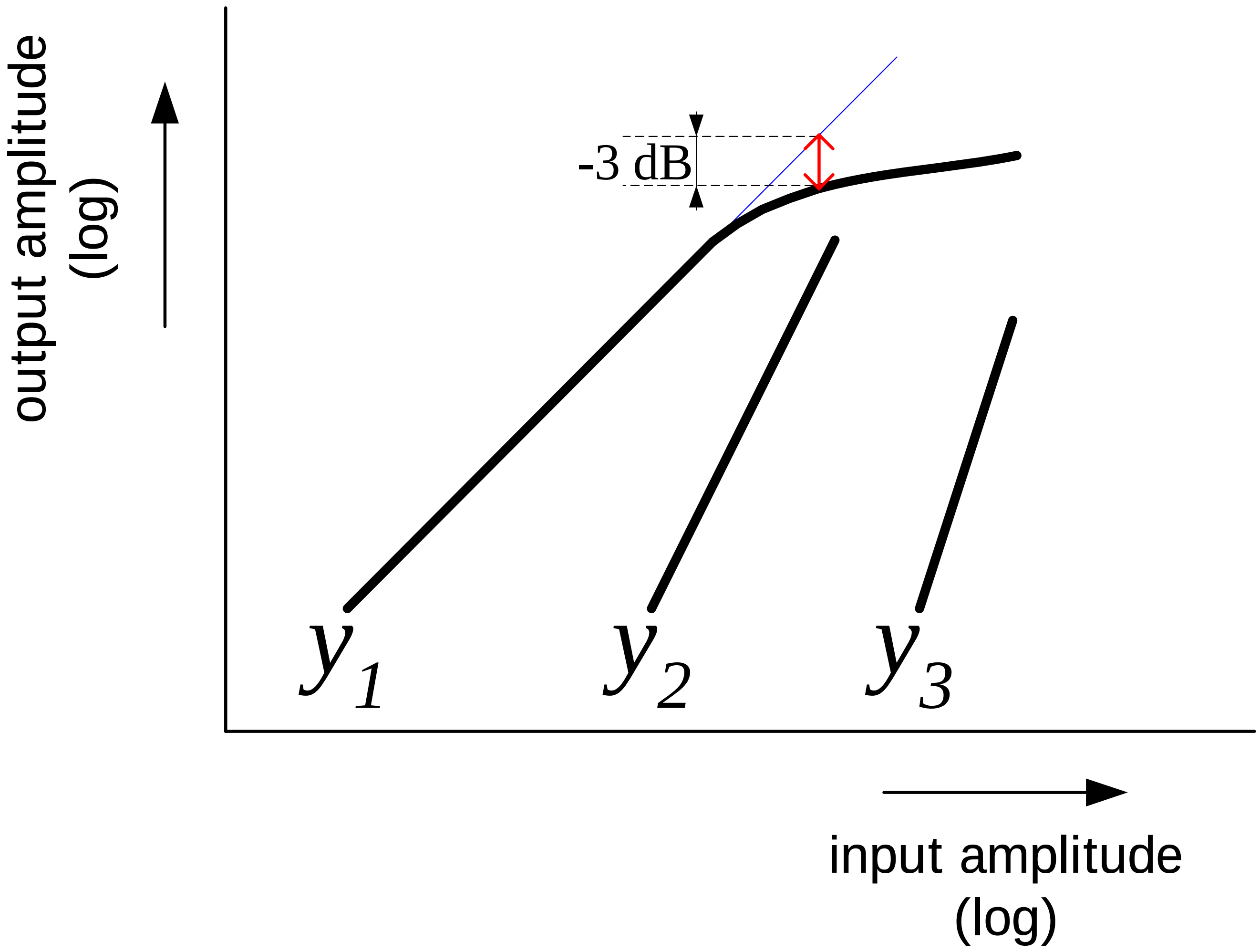
$$THD = \sqrt{\sum_{n=2}^{m} \left| HD_n \right|^2}$$



Intercept points



Compression point



Intermodulation