# Analog Electronic Circuits

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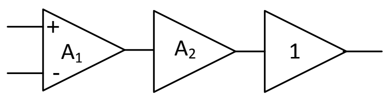
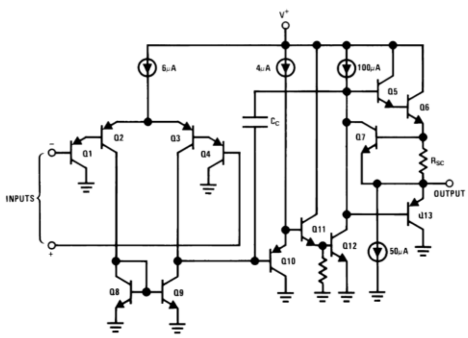
## Lesson #3
## Outline

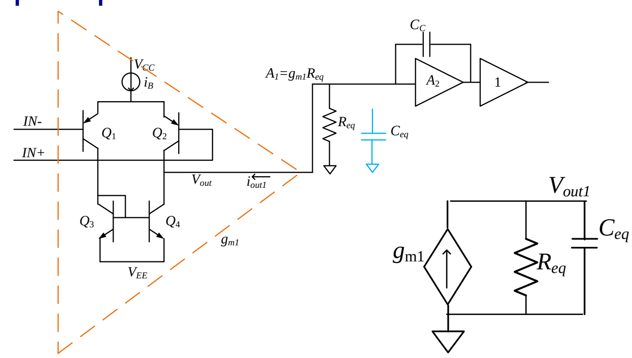
- Dynamic limitations of OpAmps
  - Open-loop response
  - Gain-Bandwidth product
- Drawing $A_{OL}$ , $1/\beta$, $\beta A_{OL}$
- Closed-loop response
  - The GBW trade-off
    - Resistive circuits
    - Frequency-dependent circuits
- Transient response
  - Slew-rate

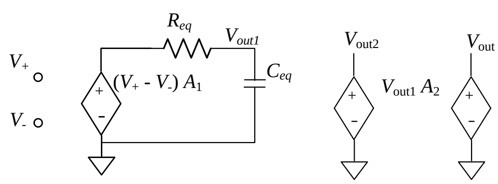
# Open-loop response



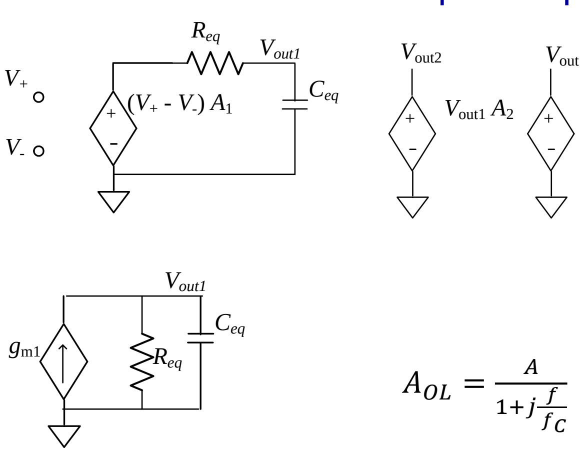

LM324 (Texas Instruments, National)



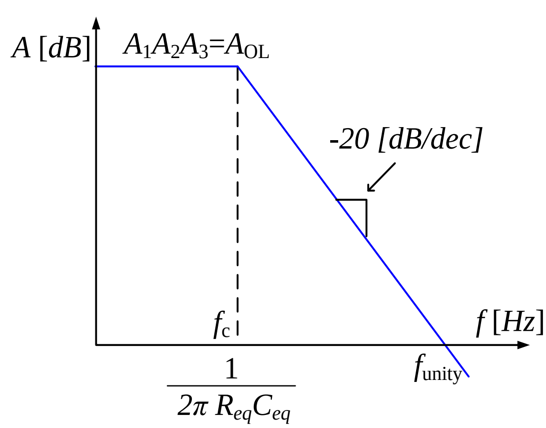





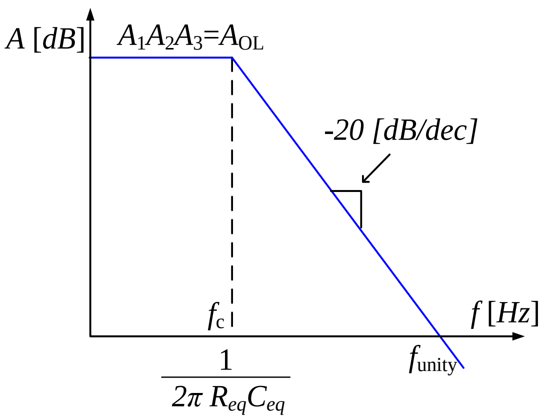

# Open-loop response




$$A_{OL} = \frac{A}{1 + j\frac{f}{f_C}}$$



## Gain-Bandwidth Product - GBW




$$A_{CL} = G\frac{A_{OL}}{1+\beta A_{OL}}$$

$$\beta = 1, G = 1$$

$$A_{CL} = \frac{A_{OL}}{1+A_{OL}}$$

$$GBW = A_{OL}f_c = f_{unity}$$

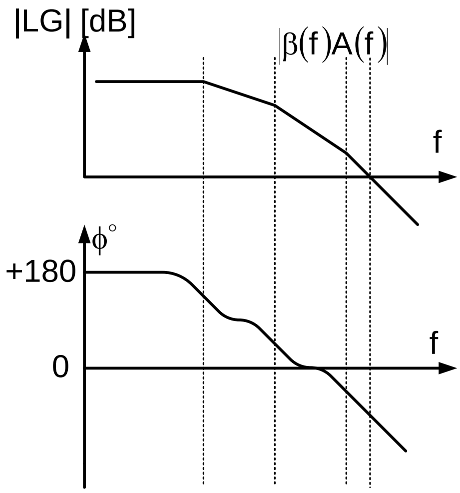


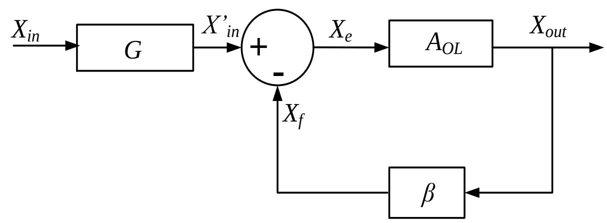
## Loop-Gain
## Nyquist Criterion

$$A_{CL} = G(s)\frac{A_{OL}(s)}{1+\beta A_{OL}(s)}$$

- The system is unstable if the characteristic equation {1+$\beta A_{OL}$(s)} has roots in the right half of the complex plane
- Nyquist criterion is a test for location of {1+$\beta A_{OL}$(s)} roots
- Nyquist criterion can be viewed on the frequency domain (Bode)

## Loop-gain on the frequency domain




In negative feedback systems $\phi = 180^o \, (-180^o)$

At $f \rightarrow 0$

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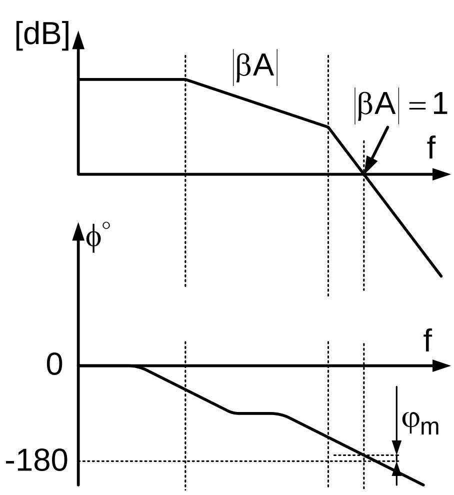
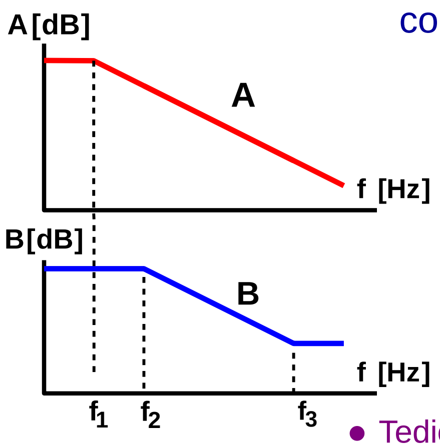
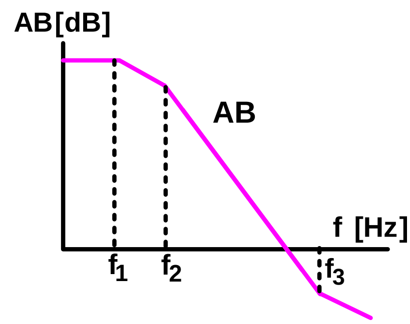
## Bode plot
## Phase margin




$$\varphi_m = \varphi_{|\beta A|=1} - (-180^o) = \varphi_{|\beta A|=1} + 180^o$$

## Graphical representation of $\beta A_{OL}$ conventional method

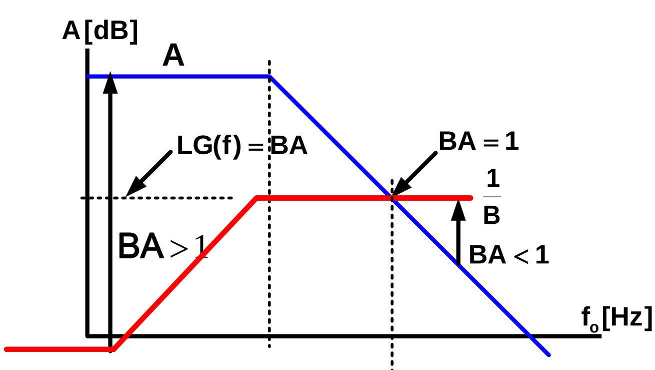



- Tedious – need to re-plot BA
- Analysis (not design) oriented
- Requires iterations



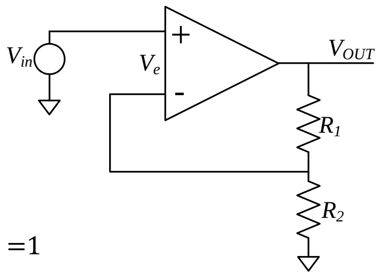
## Graphical Representation of $\beta A_{OL}$




$$20\log A - 20\log\frac{1}{B} = 20\log(BA)$$

$$20\log A = 20\log\frac{1}{B} \Rightarrow B \cdot A = 1$$

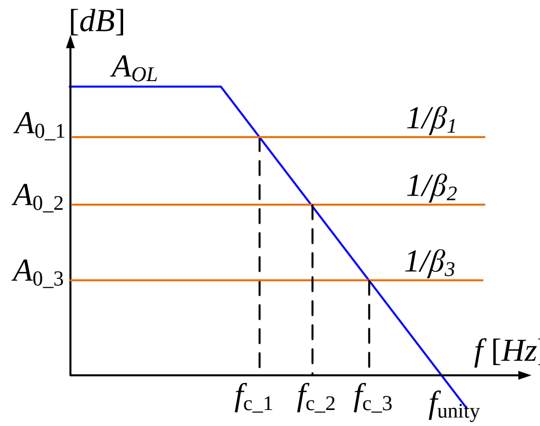
## Closed-loop response
## Non-inverting Amp




$G = 1$

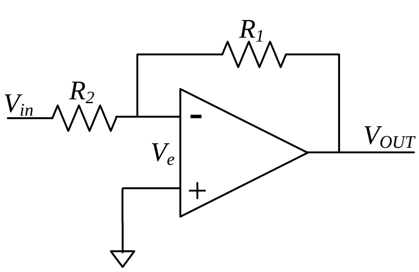
$\frac{1}{\beta} = \frac{R_1 + R_2}{R_2}$

$GBW = A_0 f_c = f_{unity}$





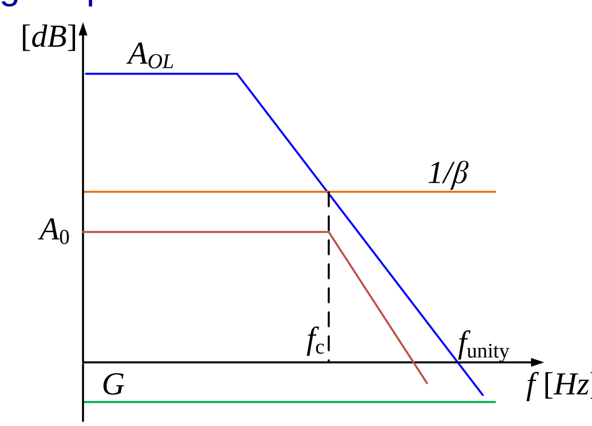

## Closed-loop response
## Inverting Amp




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

$\frac{1}{\beta} = \frac{R_1 + R_2}{R_2}$

$GBW = A_0 f_c = f_{unity}$



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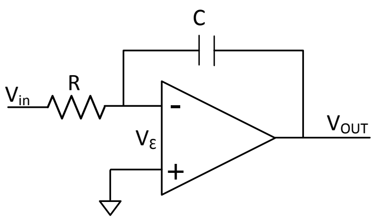
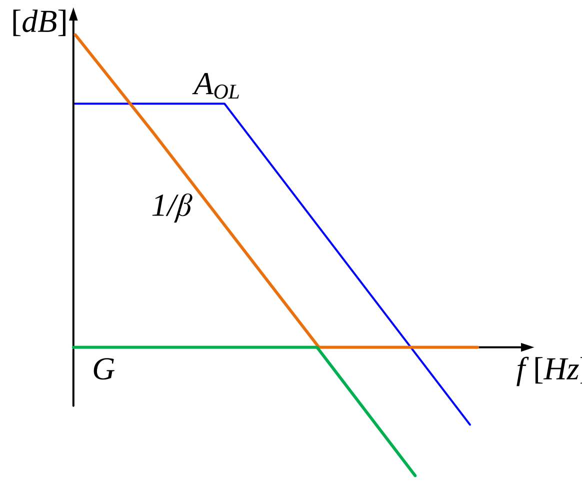
## Closed-loop response
## Integrator




$$G = \frac{1}{sCR + 1}$$

$$\frac{1}{\beta} = \frac{sCR + 1}{sCR}$$

$$GBW = A_0 f_c = f_{unity}$$

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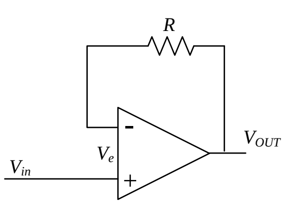
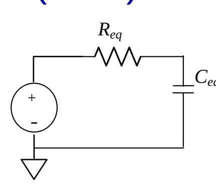
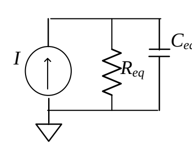
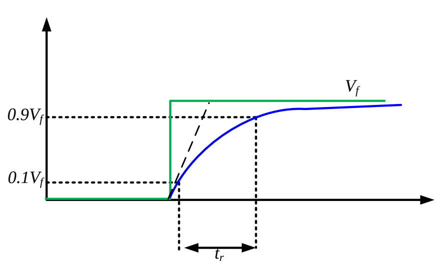
## Transient response
## Rise-time (ideal)



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