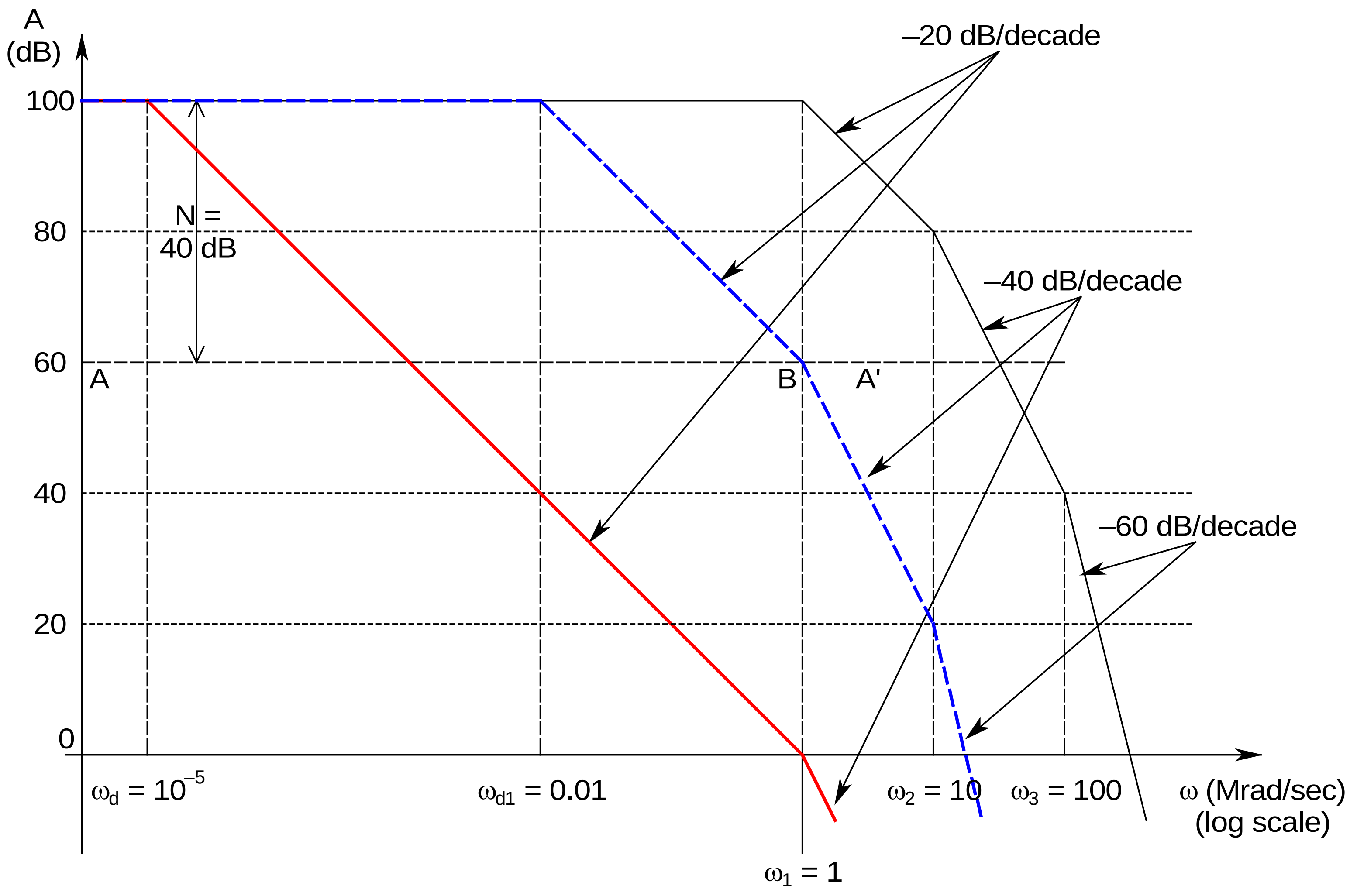
Compensation

- ***Basic Idea***:
  - To ***tailor*** the ***gain characteristic*** of a system, having ***three or more poles***, such that it would be ***stable*** for ***any value*** of the ***feedback factor*** f, all the way ***up to unity*** (referred to as the ***unity feedback system***, where the ***entire output*** is ***fed back*** to the ***input***)
  - ***After compensation***, the system will become ***either conditionally or unconditionally stable***

- ***Two widely used methods***:
  - ***Dominant Pole Compensation*** (***DPC***)
  - ***Pole Zero Compensation*** (***PZC***)
- ***Dominant Pole Compensation (DPC)***:
  - This technique introduces a ***dominant pole*** (***DP***) into the system
  - Also known as ***Miller Compensation Scheme***
  - This ***DP*** is chosen such that the ***compensated gain characteristic*** meets the ***first pole*** of the ***uncompensated system*** at ***0 dB***, with a ***slope*** of ***– 20 dB/decade***

- This will make the system ***unconditionally stable***, i.e., the ***stability*** of the system will be ***independent*** of the ***amount of feedback***
- ***Example***:
  - Assume $A = 10^5$ (100 dB), $\omega_1 = 1$ Mrad/sec, $\omega_2 = 10$ Mrad/sec, $\omega_3 = 100$ Mrad/sec
  - Refer to the slide on the next page
  - For ***unconditional stability***:
    - Refer to the ***red line***
    - The ***compensated transfer function*** should meet the ***first pole*** (ω_1) of the ***uncompensated system*** at ***A = 0 dB*** with a ***slope*** of ***–20 dB/decade***



Normal Line: Open-loop system

Red Line: Compensated system for unconditional stability

Blue Line: Compensated system with conditional stability

(till a feedback of 40 dB)

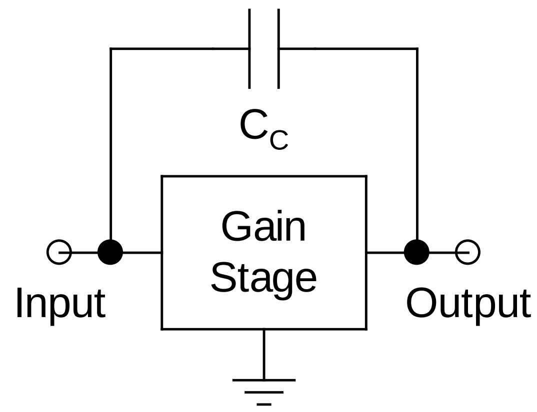
- To construct the ***compensation characteristic***, ***start at ω_1*** and ***go back 5 decades*** (= 100/20)
- ***Ends up at the DP frequency (ω_d) of 10 rad/sec***
- ***Note that in between ω_d and ω_1, the system behaves as if it has a single-pole transfer function***
- The ***total phase*** of the system at ω_1 will be ***–135°*** [***–90° due to the pole at ω_d***, and ***–45° due to the pole at ω_1*** (***since ω_2 is ten times away from ω_1***, the ***phase due to ω_2 is yet to start at this point***)
- Thus, the ***PM of the compensated system will be 45°***
- This implies a ***stable system***, since the ***PM is positive***
- Note that ***if ω_2 and ω_1 were closer than 10 times***, the ***PM would have been less than 45°***, but ***still positive***, and thus, ***would have retained the stable nature of the system***

- ❖ Note that in order to achieve ***unconditional stability*** of the system, the ***bandwidth*** has ***reduced drastically*** from ***1 Mrad/sec*** to only ***10 rad/sec***!
- ❖ ***This is the most severe limitation of the DPC technique***

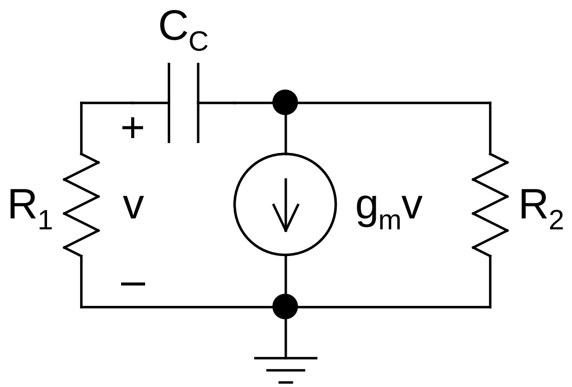
- ***For conditional stability***:
  - ❖ The ***previous compensation scheme*** ensured ***system stability*** for f all the way ***up to unity*** (corresponding to the ***amount of feedback*** of ***100 dB***, i.e., the ***entire output is fed back to the input***)
  - ❖ In some cases, it may be an ***overkill***, if it is known ***a priori*** that the ***entire output*** will ***NOT*** be ***fed back*** to the ***input***, ***rather only a part of it***
  - ❖ This is what is known as ***conditional stability***
  - ❖ Suppose that the ***maximum amount of feedback*** that the system would have is ***40 dB***

- For this system to be ***stable***, the ***DP frequency need not be at ω_d, but at a higher value***
- To construct the ***compensation characteristic*** of this system, draw a ***horizontal line*** AA′, corresponding to the ***amount of feedback*** (***40 dB in our example*** $\Rightarrow$ ***A_f = 60 dB***)
- From the ***intersection point*** (B) of this ***line*** with the ***first pole*** (ω_1), ***go back 2 decades*** (40/20), to get the ***new dominant pole*** ω_{d1} at ***10 krad/sec*** (shown by the ***blue line***)
- This ***compensation scheme protects the system from any stability issues only till a maximum feedback of 40 dB***, ***by ensuring*** that ***from 0 to 40 dB of feedback***, ***no other pole will be encountered***, ***apart from ω_{d1}***
- Note the ***tremendous bandwidth improvement*** of ***1000 times*** (***from 10 rad/sec*** for ***unconditional stability to 10 krad/sec*** for ***conditional stability till a feedback of 40 dB***)

- ***Technique***:
  - ***Simplest way***: ***Attach a capacitor between the input and output of the gain stage*** (***similar to Miller Capacitor***)
  - ***This capacitor is labeled as the Compensation Capacitor*** (C_C)



Schematic



Equivalent Circuit

- ***By inspection***, the equivalent circuit can be identified as a ***Three-Legged Creature***:

$$\Rightarrow R_C^0 = R_1 + R_2 + g_m R_1 R_2$$

R_1 = ***Thevenin resistance to the left of C_C***

R_2 = ***Thevenin resistance to the right of C_C***

g_m = ***Transconductance of the gain stage***

- Thus:

$$\omega_d = 1\Big/\left(R_C^0 C_C\right)$$

- ***From a knowledge of ω_d, we can find C_C***

- ***Pole Zero Compensation (PZC)***:
  - In the ***DPC technique***, we observed a ***drastic reduction*** in ***bandwidth*** after ***compensation***
  - ***PZC technique alleviates this problem to some extent***
  - ***Novelty of this technique***:
    - ***It adds both a pole and a zero to the open-loop transfer function***, ***with the added zero canceling the first pole of the uncompensated system***

- Consider a ***three-pole uncompensated transfer function***:

$$A(s)\Big|_{\text{uncompensated}} = \frac{A_0}{\left(1+s/\omega_1\right)\left(1+s/\omega_2\right)\left(1+s/\omega_3\right)}$$

A_0: ***Low-Frequency Gain***

ω_1, ω_2, ω_3: ***Pole Frequencies*** ($\omega_3 > \omega_2 > \omega_1$)

- ***After adding the network for PZC***, the ***compensated transfer function*** will be:

$$A(s)\Big|_{\text{compensated}} = \frac{A_0\left(1+s/\omega_z\right)}{\left(1+s/\omega_p\right)\left(1+s/\omega_1\right)\left(1+s/\omega_2\right)\left(1+s/\omega_3\right)}$$

ω_z: ***added zero***, and ω_p: ***added pole***

- ***By design***, ***ω_z is made equal to ω_1***

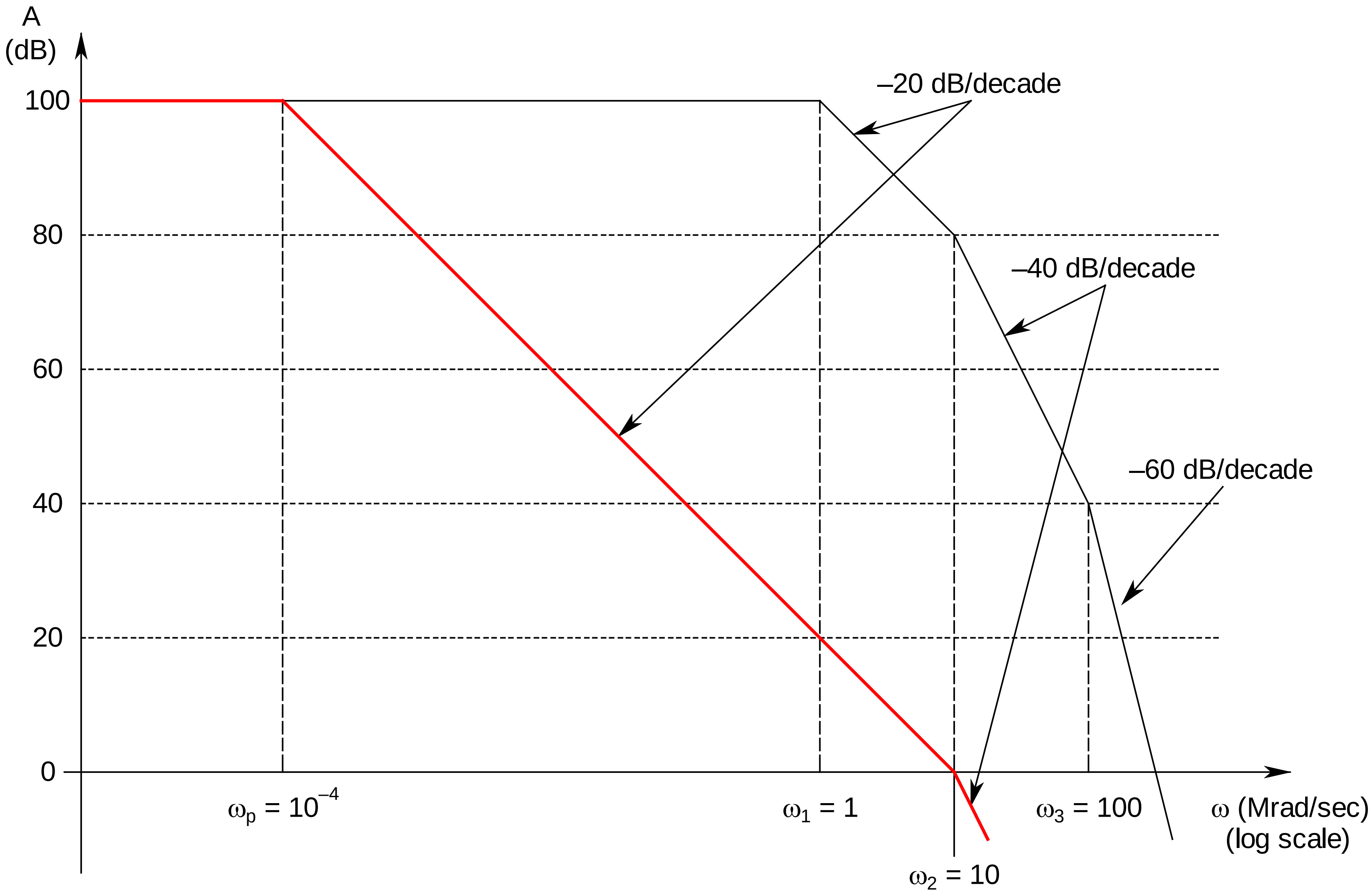
  $\Rightarrow$ ***They cancel each other***

- Thus, the ***compensated transfer function*** still has ***three poles***, but the ***first pole gets shifted from ω_1 to ω_p***

- ***The procedure for finding ω_p is the same as that for the DPC technique***

- We take the ***same example*** as that considered for the ***DPC technique***

- Refer to the next slide



Normal Line: Open-loop system

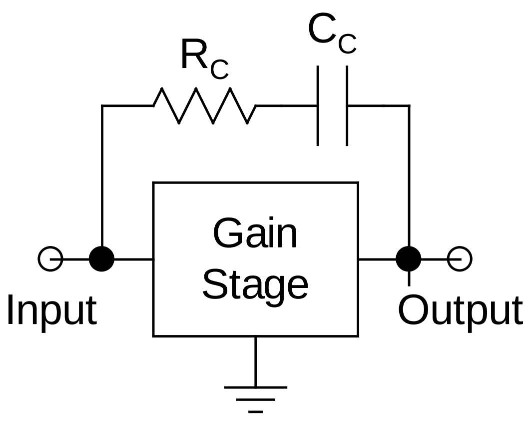
Red Line: Compensated system for unconditional stability

- Here, the ***added zero*** (ω_z) ***cancels*** the ***first pole*** (ω_1)
- Thus, we now ***start from*** $\boldsymbol{\omega_2}$ and ***go back 5 decades*** to find $\boldsymbol{\omega_p}$, which comes out to be ***100 rad/sec*** (refer to the ***red line***)
- The ***compensated system*** will be ***unconditionally stable*** with ***PM of 45°*** (***since*** $\boldsymbol{\omega_3}$ ***is ten times away from*** $\boldsymbol{\omega_2}$)
- The ***increase in bandwidth***, ***as compared to DPC***, is ***10 times*** (***from 10 rad/sec to 100 rad/sec***: ***equal to the ratio of*** $\boldsymbol{\omega_2}$ ***and*** $\boldsymbol{\omega_1}$)

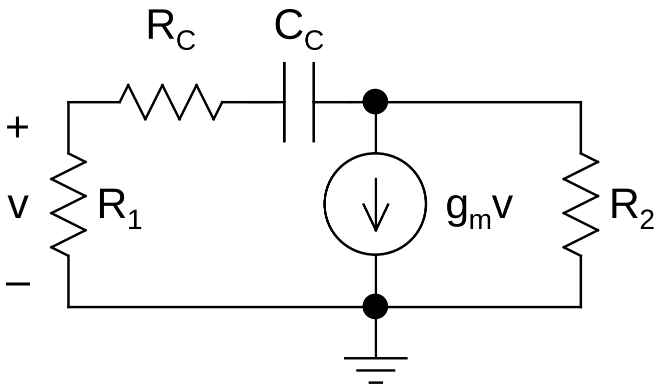
➢ *Technique*:

- ***Just attach a resistor R_C with the compensation capacitor C_C***
- ***Put this R_C-C_C network between the input and output of the gain stage***
- Show that the ***transfer function*** of the ***compensated system*** is of the form:

$$A(s)\Big|_{\text{compensated}} \propto \frac{1+s\left(R_C - 1/g_m\right)C_C}{1+s\left(R_C + R_2\right)C_C}$$



Schematic



Equivalent Circuit

- Here

  $\omega_z = 1/[(R_C - 1/g_m)C_C]$

  $\omega_p = 1/[(R_C + R_2)C_C]$

- ***Choose R_C and C_C such that***
  - ***ω_z is equal to ω_1*** (***the first pole of the uncompensated system***)
  - ***ω_p is as found from the example given***

THE OPERATIONAL AMPLIFIER (OP-AMP)

- ***The Ultimate***: A ***phenomenal application*** of everything that we have learnt so far in this course
- ***Op-Amp***: ***Operational Amplifier***
- ***Hugely powerful block***
- ***Capable of performing various circuit functions***
- ***Original inventor***: ***George Philbrick*** of ***Bell Labs*** in ***1952*** using ***vacuum tube technology***

- ***Remarkable innovations*** in ***design*** in the form of an ***IC*** by ***Bob Widlar*** of ***Fairchild Semiconductors*** in ***1963***
- After that, ***several improvements*** took place, and the ***most versatile design***, widely came to be known as the ***741 op-amp***, originated
- Basically a ***three-stage architecture***:
  - ***The Input Stage***
  - ***The Gain Stage***
  - ***The Output Stage***

- ***The Input Stage***:
  - ***Should be capable of double-ended to single-ended conversion***
  - ***Should have moderate to high gain***
  - ***Must definitely have extremely large CMRR*** (***this is the main requirement***)
  - ***Almost invariably a Differential Amplifier*** (***DA***)

- ***The Gain Stage***:
  - ***Can be any one of the many that we have studied in the chapter on Amplifiers***
  - ***CC-CE Darlington configuration preferred***
  - ***Should have moderate to large gain***
- ***The Output Stage***:
  - ***Needed when the op-amp is expected to either source or sink large amount of current to or from the load***