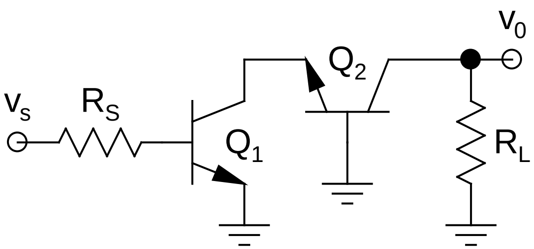
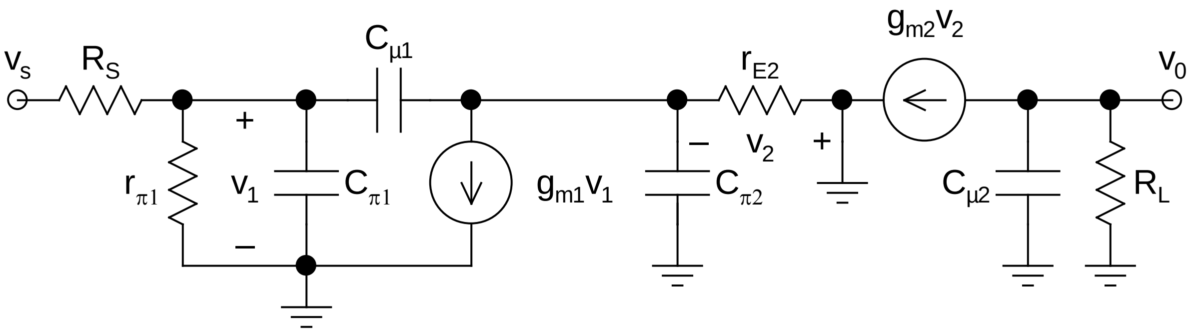
- ***npn Cascode***:



ac Schematic



High-Frequency Equivalent

- ***Looks intimidating***, but ***extremely easy to solve*** (***just by inspection***)
- Also known as ***Wideband*** (or ***Broadband***) ***Amplifier*** due to its ***superb frequency response***

- ***Reason***:
  - ***The circuit does have an input-output coupling capacitor*** ($C_{\mu 1}$)
  - ***Miller Effect Multiplication Factor*** (MEMF) of $C_{\mu 1} = (1 - A_{v1})$

    A_{v1} = ***voltage gain of Q_1*** $= - r_{E2}/r_{E1} = -1$

    (***since Q_1 and Q_2 are biased with the same I_C***)

    $\Rightarrow$ Thus, the ***MEMF of $C_{\mu 1}$ is only 2***
  - For ***NMOS Cascode*** stage, the ***MEMF of C_{gd1}*** of M_1 (***CS stage***) will be $[1 + 1/(1 + \chi_2)]$ (***verify this expression***), which is ***even less than 2***

- ***$C_{\pi 1}$***:
  - ***By inspection***:

$$R^0_{\pi 1} = R_S \,||\, r_{\pi 1} \quad \Rightarrow \tau_1 = R^0_{\pi 1} C_{\pi 1}$$

- ***$C_{\mu 1}$***:
  - Can be easily identified as the ***Three-Legged Creature***

$$\Rightarrow R^0_{\mu 1} = R^0_{\pi 1} + r_{E2} + g_{m1} R^0_{\pi 1} r_{E2}$$

$$\Rightarrow \tau_2 = R^0_{\mu 1} C_{\mu 1}$$

- ***$C_{\pi 2}$***:
  - ***By inspection***:

$$R^0_{\pi 2} = r_{E2} \quad \Rightarrow \tau_3 = R^0_{\pi 2} C_{\pi 2}$$

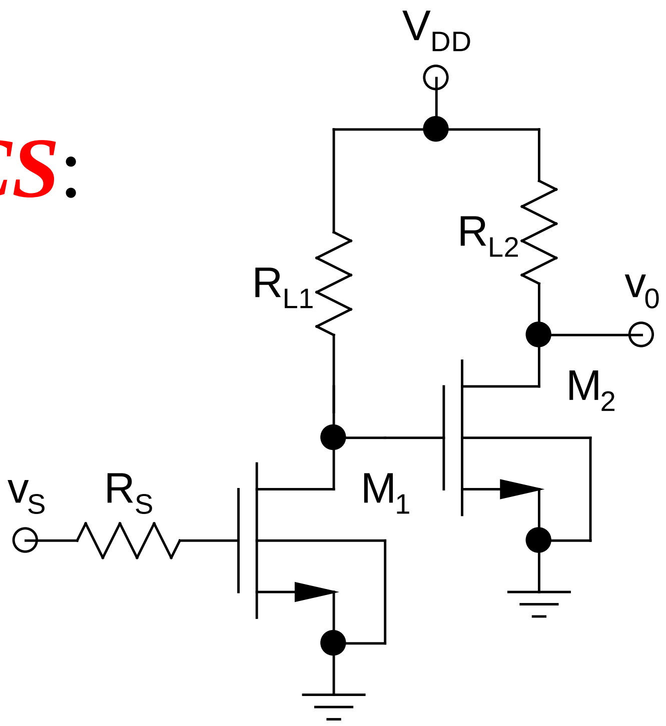
- ***$C_{\mu 2}$***:
  - ***By inspection***:

$$R^0_{\mu 2} = R_L \quad \Rightarrow \tau_4 = R^0_{\mu 2} C_{\mu 2}$$

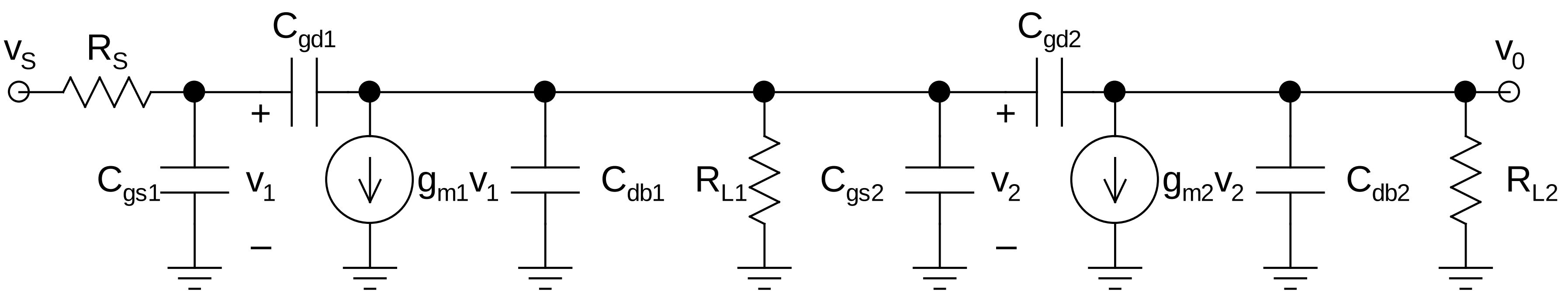
- Generally, for this circuit, $C_{\pi 1}$ is the ***dominant capacitor*** that determines f_H, since it sees the ***largest resistance***
- The ***resistance seen by $C_{\mu 1}$***, which is the ***largest for CE stage***, ***becomes quite small here***, ***due to the low gain of Q_1***
- Note how ***simple*** it is to use this ***technique*** even for ***multi-stage amplifiers***!

- ***NMOS 2-Stage Cascaded CS***:
  - *Except C_{sb}, all other capacitors will be present for both devices*
  - *6 capacitors*

    $\Rightarrow$ *6 time constants*



ac Schematic



High-Frequency Equivalent

- ***Note***: An ***exact analysis*** would have required ***solving*** a ***6th-order equation in ω***!
- Let's perform a ***quantitative analysis*** of this circuit
- ***Data***: g_{m1} = 3 mA/V, g_{m2} = 6 mA/V, C_{gs1} = 5 pF, C_{gs2} = 10 pF, C_{gd1} = C_{gd2} = 1 pF, C_{db1} = C_{db2} = 2 pF, R_S = 10 kΩ, R_{L1} = 10 kΩ, and R_{L2} = 5 kΩ.
  - ***C_{gs1}***:

$$R_{gs1}^0 = R_S = 10\ \text{k}\Omega \quad \Rightarrow \tau_1 = R_{gs1}^0 C_{gs1} = 50\ \text{ns}$$

- ***C_{gd1}***:

$$R_{gd1}^{0} = R_S + R_{L1} + g_{m1}R_SR_{L1} = 320\ k\Omega$$

$$\Rightarrow \tau_2 = R_{gd1}^{0}C_{gd1} = 320\ ns$$

- ***C_{db1} and C_{gs2} in parallel***

$\Rightarrow$ ***Club them to a single capacitor*** $C_3 = C_{db1} + C_{gs2} = 12$ pF

$$R_3^0 = R_{L1} = 10\ k\Omega$$

$$\Rightarrow \tau_3 = R_3^0C_3 = 120\ ns$$

- ***C_{gd2}***:

$$R^0_{gd2} = R_{L1} + R_{L2} + g_{m2}R_{L1}R_{L2} = 315\ k\Omega$$

$$\Rightarrow \tau_4 = R^0_{gd2}C_{gd2} = 315\ ns$$

- ***C_{db2}***:

$$R^0_{db2} = R_{L2} = 5\ k\Omega$$

$$\Rightarrow \tau_5 = R^0_3C_3 = 10\ ns$$

- Thus:

  τ_{net} = 815 ns and f_H = 195.3 kHz

- Such a ***low value*** of f_H is the ***result*** of the ***presence*** of a ***large number of capacitors*** in the circuit

- ***Limitations of the ZVTC Technique***:
  - ***One obvious limitation is the suppression of information of all other poles and zeros of the system except the DP***
    - ***This limitation is not that acute since we are actually interested in only the DP, which gives the information about f_H***
  - ***The other limitation is the error, which can reach as high as 22%***
  - However, ***this error is negative***, i.e., ***underestimation*** (far better than ***overestimation***)

- The ***maximum error*** of 22% occurs if the ***actual circuit*** has ***two overlapping poles***
- In ***real situations***, this is ***highly unlikely***, due to the effect of ***pole splitting*** caused by ***compensation*** (***to be discussed in the next chapter***)
- ***The resulting circuit after compensation would have a single DP***

- ***Proof that the maximum error is 22%***
  - Consider a circuit having ***2 negative real poles*** at the ***same angular frequency*** ω_x
  - The ***Transfer Function***:

    $A(j\omega) = A_0/(1 + j\omega/\omega_x)^2$

    A_0: ***Midband gain***

    $\Rightarrow |A(j\omega)| = A_0/[1 + (\omega/\omega_x)^2]$
  - At the ***upper cutoff frequency*** ω_H, the ***gain would drop to 1/√2 of its maximum value***

    $\Rightarrow 1 + (\omega_H/\omega_x)^2 = \sqrt{2}$

    $\Rightarrow \omega_H = [\sqrt{(\sqrt{2} - 1)}]\omega_x = 0.64\omega_x$

- Now, using the ***ZVTC technique***, the ***net time constant***

$$\tau = \sum_{i=1}^{n} \left(-1/p_i\right)$$

i = ***number of poles***

p_i = ***individual poles***

- For the ***given problem***, $i = 2$ and $p_i = -\omega_x$ (***for both***)
- Thus:

$\tau_{net} = 2/\omega_x$ and $\omega_H = 1/\tau_{net} = 0.5\omega_x$

- Therefore, the ***maximum error is about –22%***
- This being an ***underestimation***, is ***not that dangerous*** :)

- ***Rise/Fall Time***:
  - ***Recall***: ***f_L caused tilt/sag in the output for square-wave input***
  - ***On the other side of the frequency spectrum***, ***f_H causes rise/fall time of the output for square-wave input***
  - ***These two phenomena can be thought of as an interlinking between the analog and digital domains***
  - Assume that a circuit has some ω_H, with the ***corresponding pole*** at p_1 ($= -\omega_H$)

- The ***Transfer Function*** is ***single-pole***:

  $v_0(s)/v_i(s) = A_0/(1 - s/p_1)$

  A_0: ***Midband gain***

- Now, consider v_i to be ***step input*** of ***amplitude*** V_A ($\Rightarrow v_i = V_A/s$)

  $\Rightarrow v_0(s) = (A_0V_A/s)/(1 - s/p_1)$

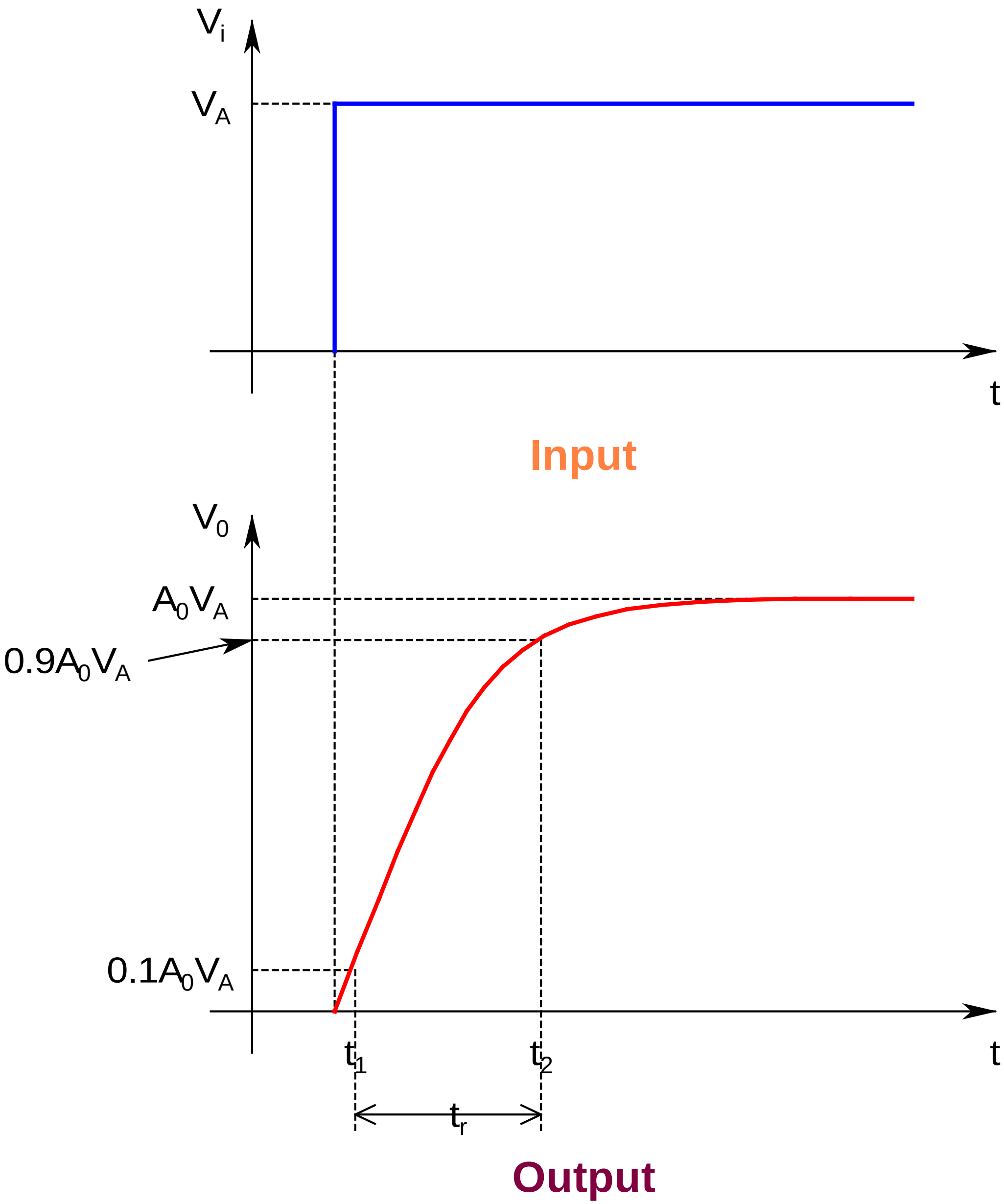
  $= A_0V_A[1/s - 1/(s - p_1)]$

- Taking ***inverse Laplace Transform***:

  $v_0(t) = A_0V_A[1 - \exp(|p_1|t)]$

  $\Rightarrow$ ***Output approaches its maximum value of A_0V_A with a time constant $1/|p_1|$*** (***p_1 negative***)

- ***Calculation of Rise/Fall Time*:**
  - ***Time taken for the output to rise (fall) from 10% (90%) to 90% (10%)***
  - ***Can be calculated from the figure***



- ***At t = t_1***:

  $0.1A_0V_A = A_0V_A[1 - \exp(p_1t_1)]$

  $\Rightarrow t_1 = \ln(0.9)/p_1$

- ***At t = t_2***:

  $0.9A_0V_A = A_0V_A[1 - \exp(p_1t_2)]$

  $\Rightarrow t_2 = \ln(0.1)/p_1$

- Thus, the ***rise time***:

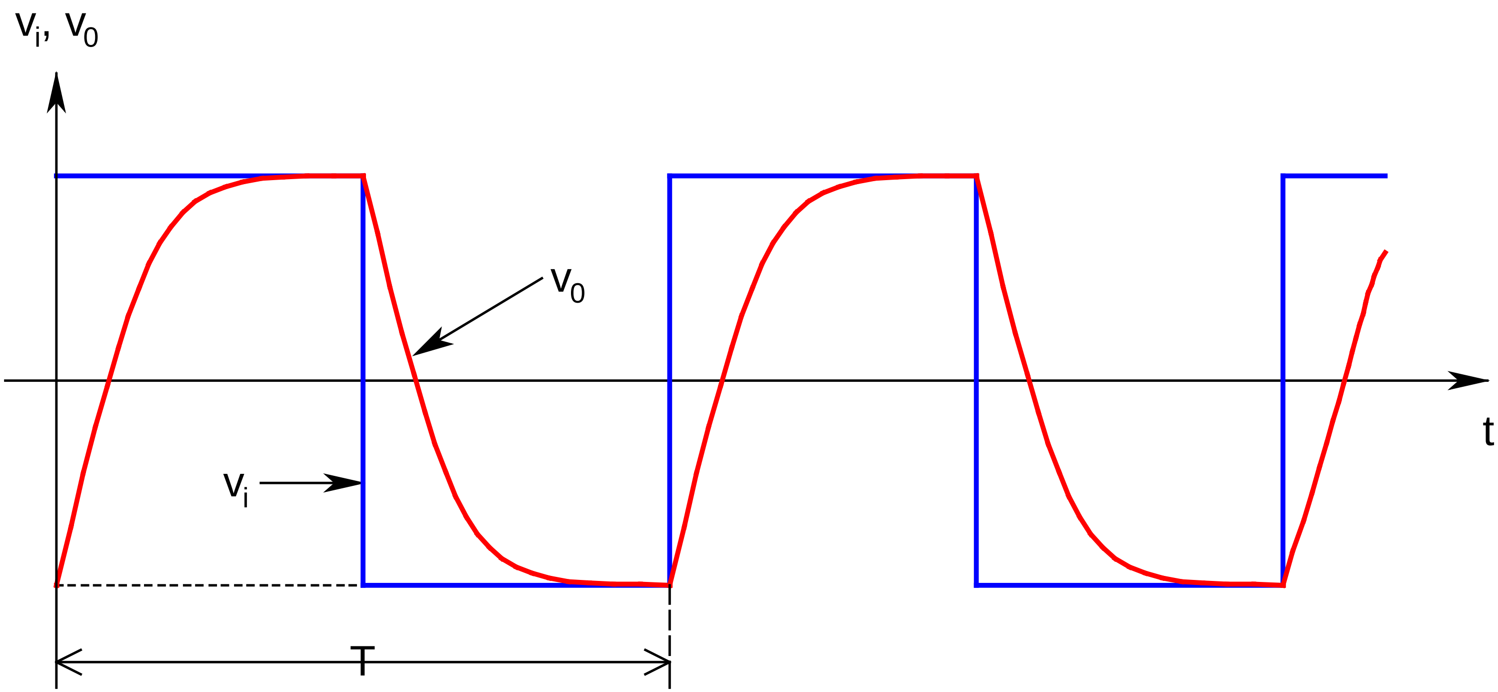
  $t_r = t_2 - t_1 = -2.2/p_1 = 2.2/\omega_H = 0.35/f_H$

- Hence, ***higher the f_H***, ***smaller the t_r***

- ***The same expression holds for the fall time (t_f) as well***

- Thus, circuits having ***high bandwidth*** under ***sinusoidal excitation*** (***analog domain***), will also have ***superb switching characteristics*** under ***square-wave excitation*** (***digital domain***)
- Under ***square-wave excitation***, ***due to t_r/t_f***, ***enough time should be provided for the transient in the output to get completed***
- ***Rule of Thumb***:
  - ***At least 5 time constants should be allowed for each rising and falling transient***
  - This determines the ***maximum allowable frequency*** of the ***input pulse train***:

    $f_{max} = 1/T_{min} \approx 1/(10\tau) = \omega_H/10 = |p_1|/10$



Effect of t_r/t_f on the Output for Square-Wave Excitation

- ***As f↑, T↓, V_0 first starts to become trianglular*** (***incomplete transient***), ***then the amplitude starts to drop***, ***and eventually drops to zero*** (***no output at all***!)

FEEDBACK, STABILITY, & COMPENSATION

Feedback

- ***Connection between input and output* - *either directly through a wire*, *or through some circuit elements***
  - $\Rightarrow$ ***Input and output gets coupled***
  - $\Rightarrow$ ***Any change in either of them*, *affects the overall behavior***
- ***2 Types*:**
  - ➢ ***Negative***
  - ➢ ***Positive***

- ***Negative Feedback***:
  - ***Output fed back to input in such a way that it reduces net input***

    $\Rightarrow$ ***Causes a reduction in the output***
  - Known as ***Degenerative Feedback***
- ***Positive Feedback***:
  - ***Output fed back to input in such a way that it increases net input***

    $\Rightarrow$ ***Causes an increase in the output***
  - Known as ***Regenerative Feedback***