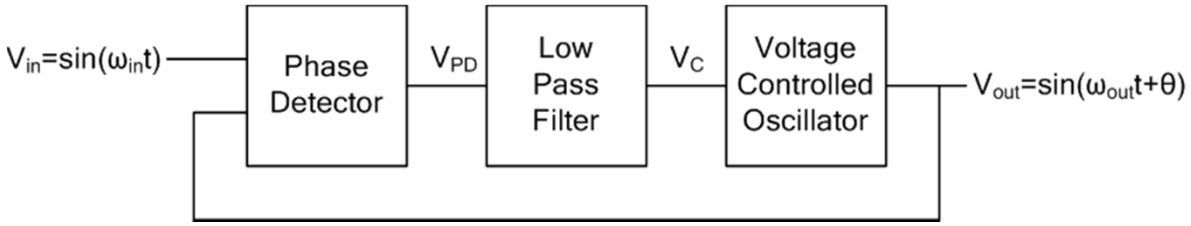
High-Speed Serial Interface Circuits and Systems

Lect. 5 – Phase-Locked Loop (PLL) 2

Limitation of Type I PLL



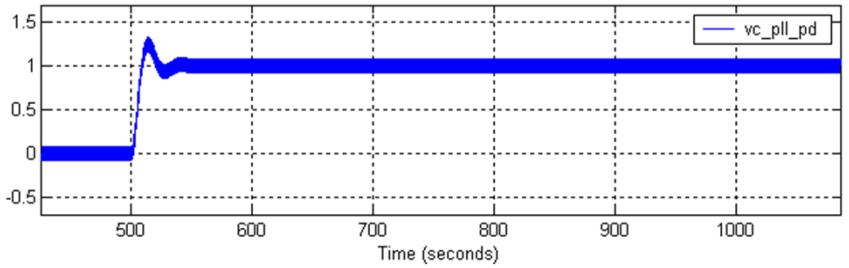
$$H(s)=\frac{K_{PD}K_{VCO}\omega_p}{s^2+\omega_p s+K_{PD}K_{VCO}\omega_p}$$

- Locking range is very narrow

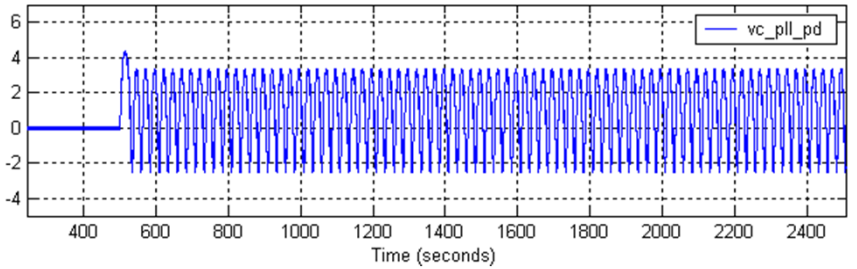
Step response simulations:

$$f_{in}=1Hz,\ K_{PD}=5V/rad,\ K_{VCO}=2\pi\times 0.01rad/s/V,\ and\ \ f_p=0.032Hz$$

$\Delta f_{in}=0.01Hz$

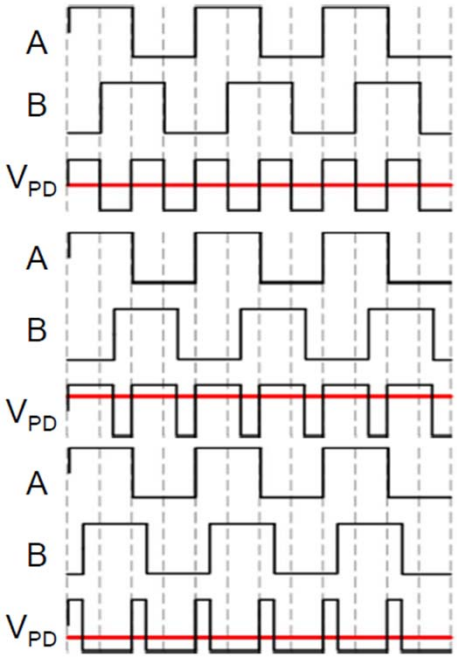


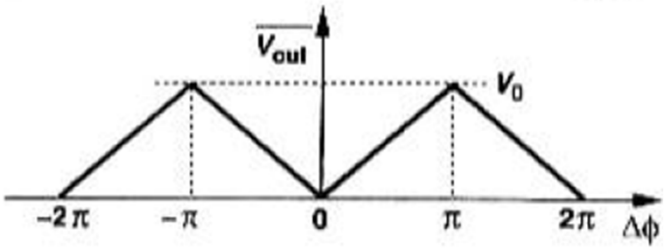
$\Delta f=0.05Hz$



Limitation of Type I PLL

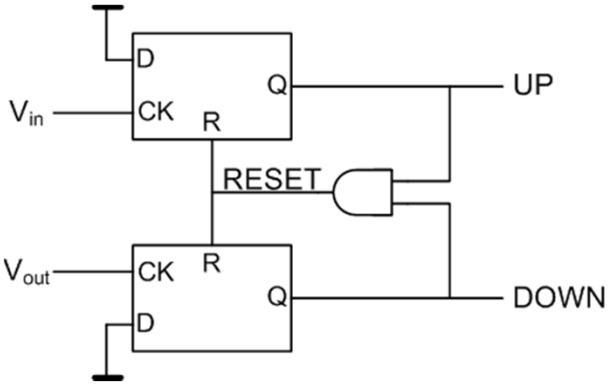
Problem lies in the very narrow linear phase detection range

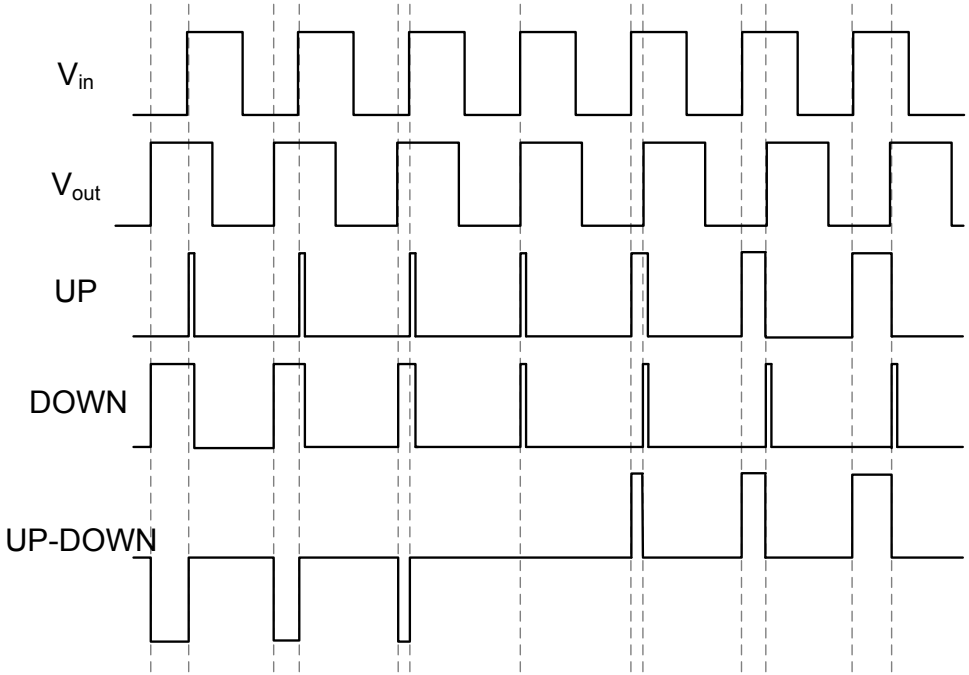




With a large frequency difference, phase difference can become too large to be reliably detected

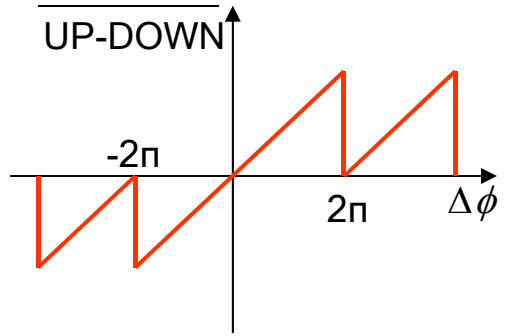
Phase and Frequency Detector (PFD)





D Flip-flop:

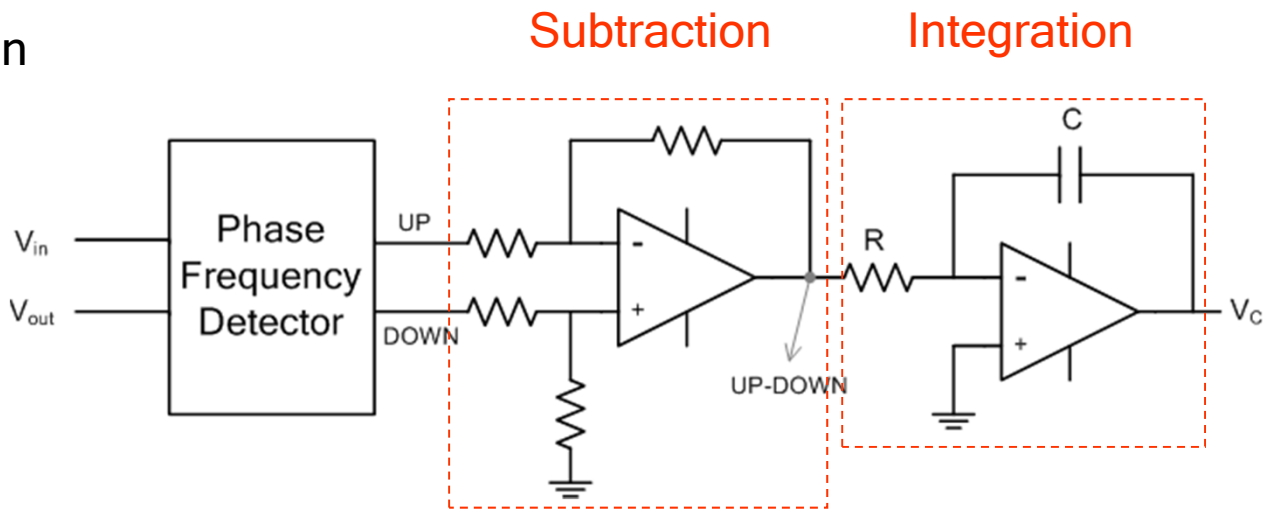
Q becomes D at the rising clock edge
Q resets when R is HIGH



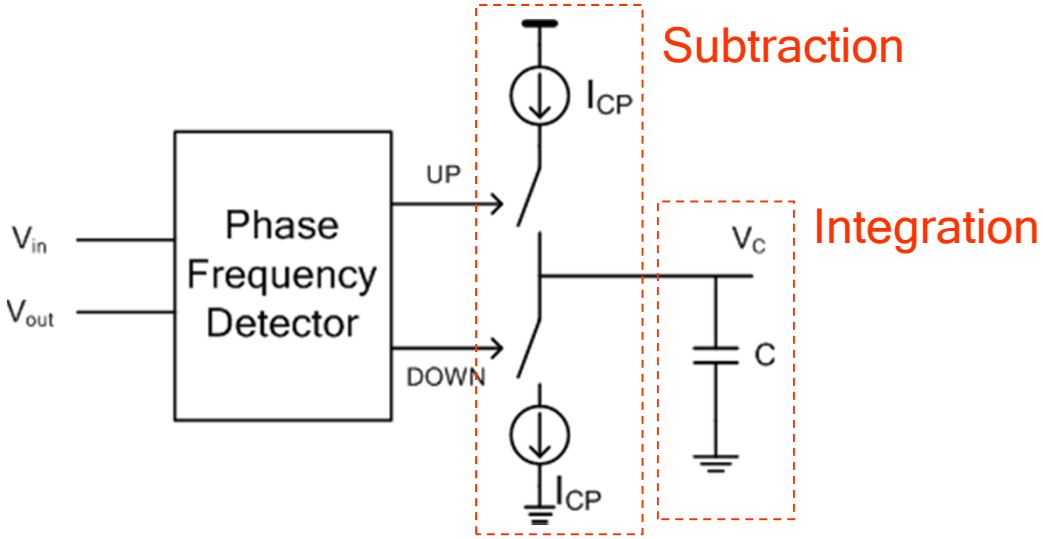
Charge Pump

Subtraction and integration

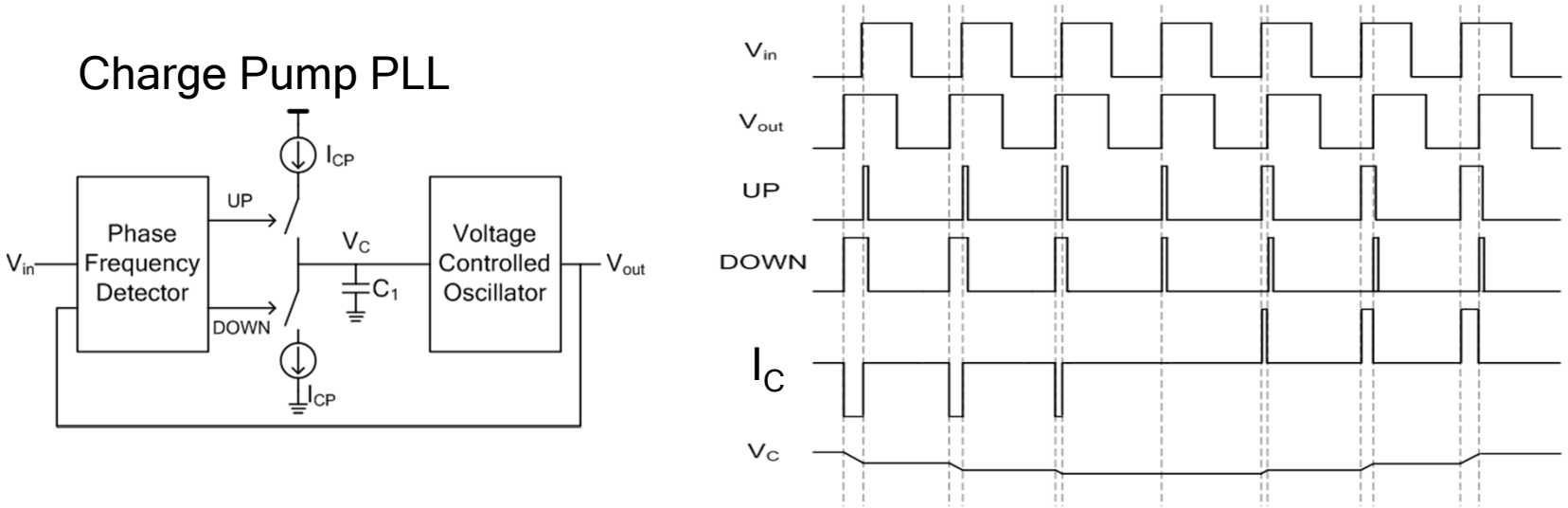
Voltage mode
using OP amplifiers



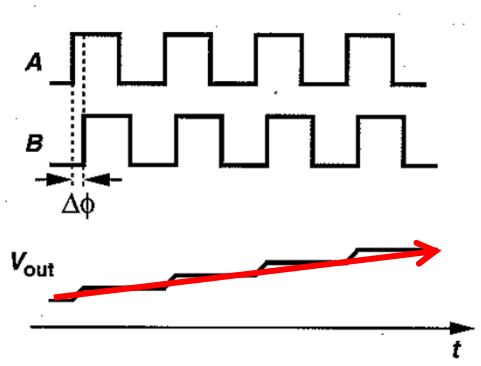
Current mode
using charge pump



Charge Pump PLL



- Linear continuous-time model for charge-pump PLL?
- Charge pump operation is not continuous but discrete
- But make an approximation



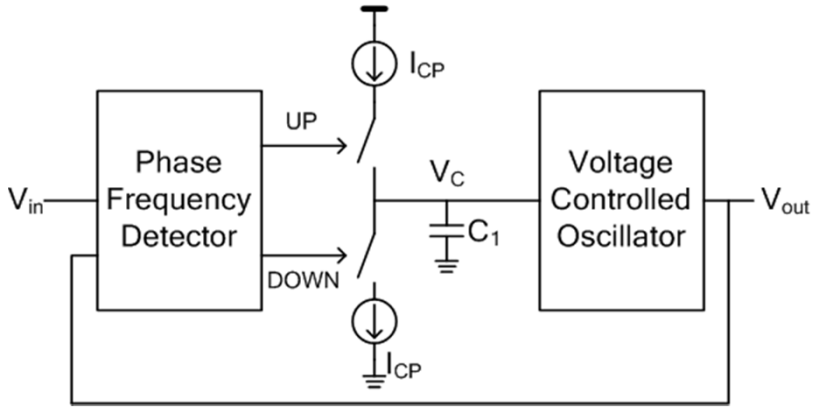
Transfer function for PFD + Charge Pump:

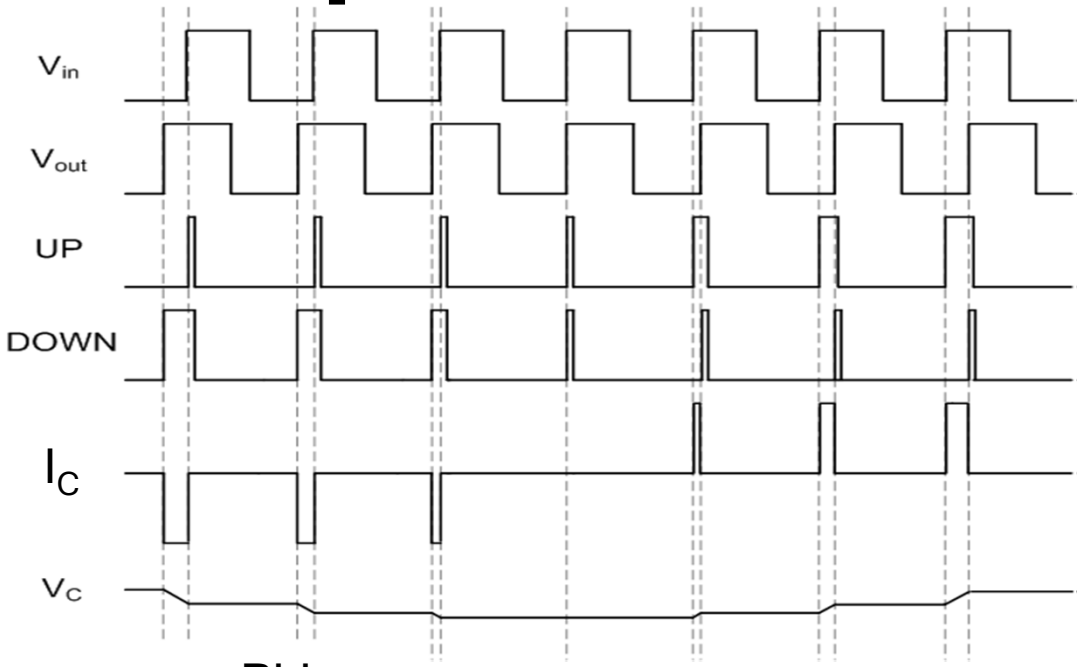
Max $\Delta\phi$: 2π ➔ $V_C(s)$: $I_{CP}\dfrac{1}{sC_1}$

For any $\Delta\phi$: $V_C(s) = \dfrac{\Delta\phi}{2\pi} I_{CP}\dfrac{1}{sC_1}$

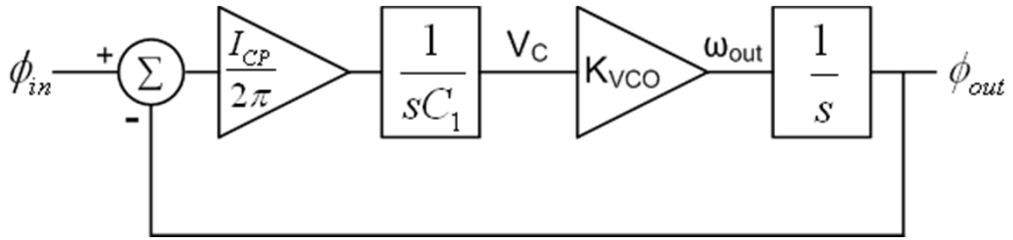
$$T(s) = \frac{V_C}{\Delta\phi}(s) = \frac{I_{CP}}{2\pi}\frac{1}{sC_1}$$

Charge Pump PLL

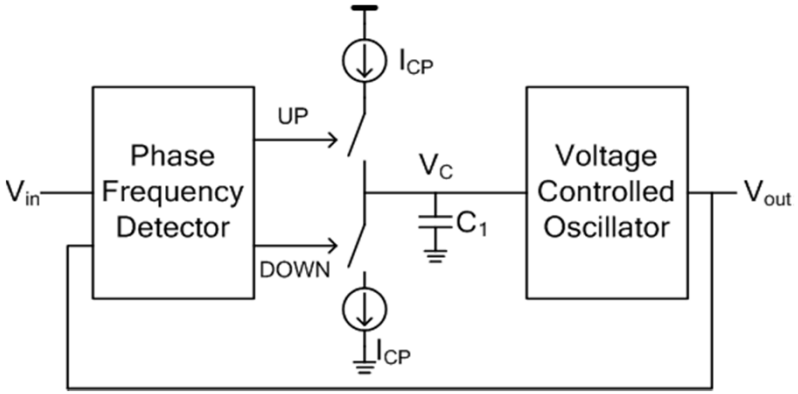


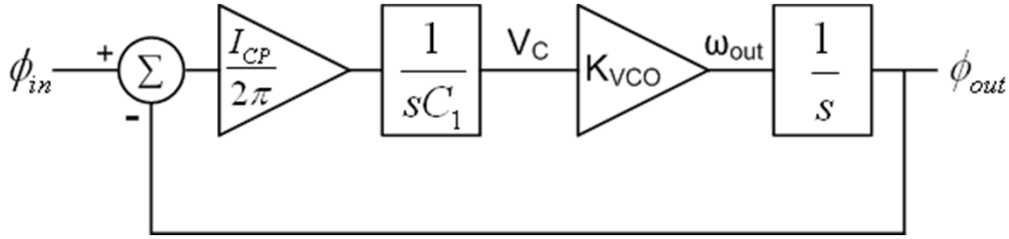


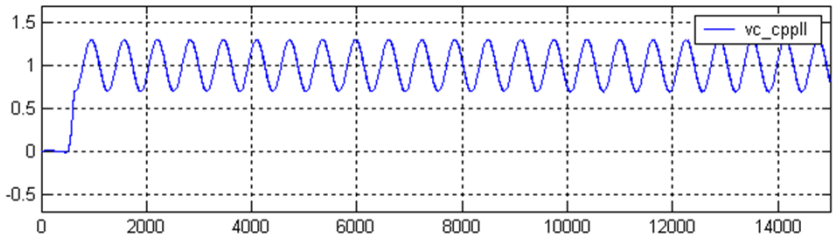
Linear continuous-time model for charge-pump PLL

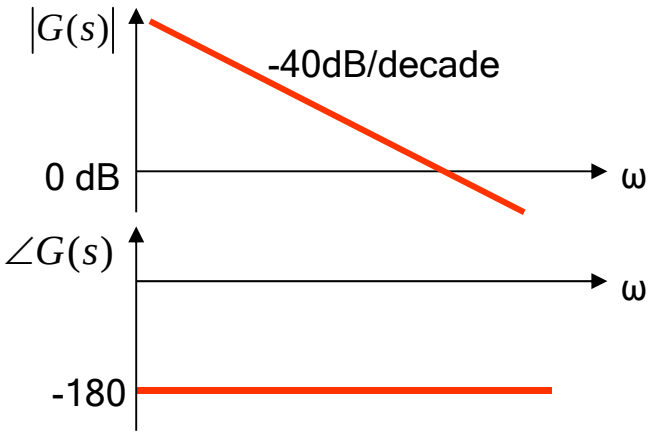


Stability







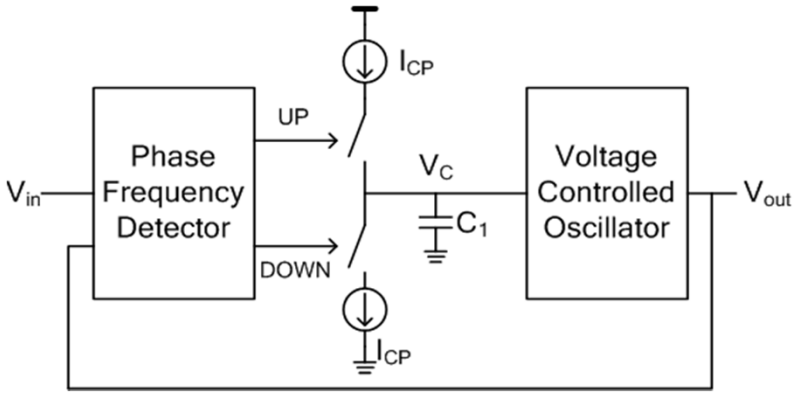


Open loop gain:

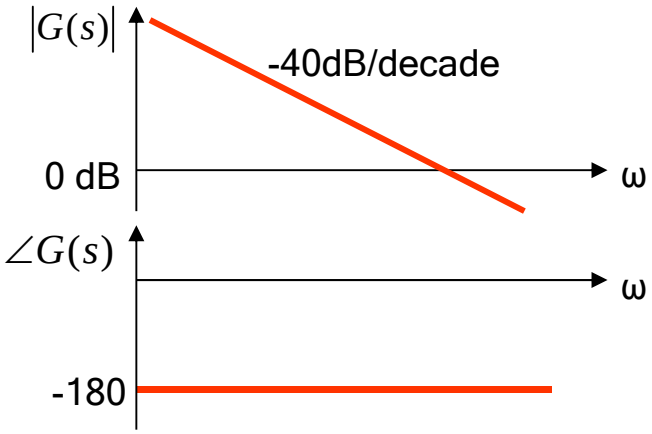
$$G(s) = \frac{1}{2\pi} I_{CP} K_{VCO} \frac{1}{s^2 C_1}$$

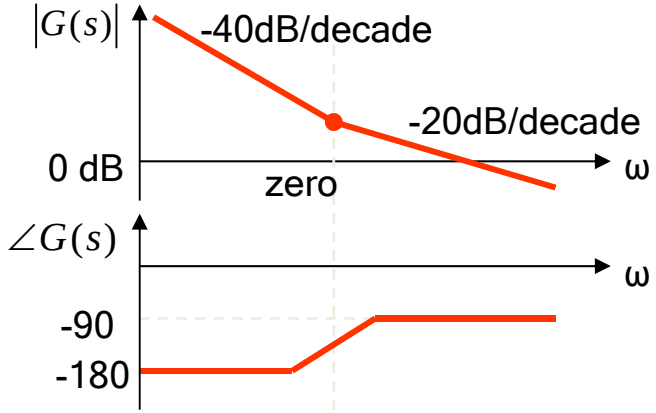
No phase margin → Unstable

Stability



$$G(s) = \frac{1}{2\pi} I_{CP} K_{VCO} \frac{1}{s^2 C_1}$$

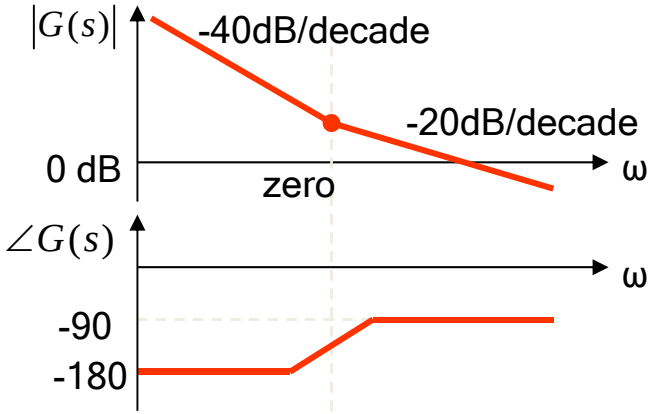


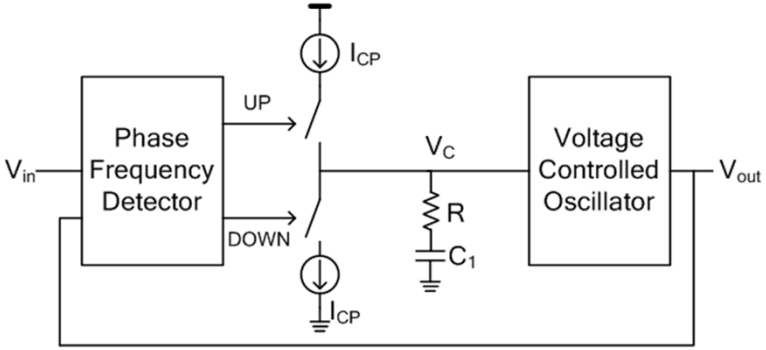


How to improve phase margin?

Introduce a zero

Stability

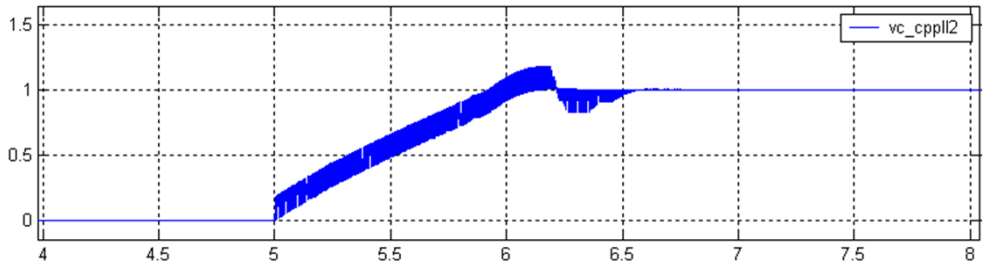




Open loop gain:

$$G(s) = \frac{1}{2\pi} I_{CP} K_{VCO} \frac{sRC_1 + 1}{s^2 C_1}$$

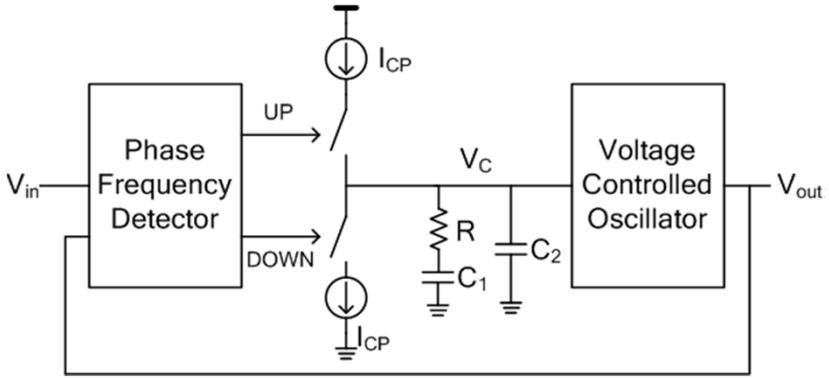
However, there are ripples during transients for the step response



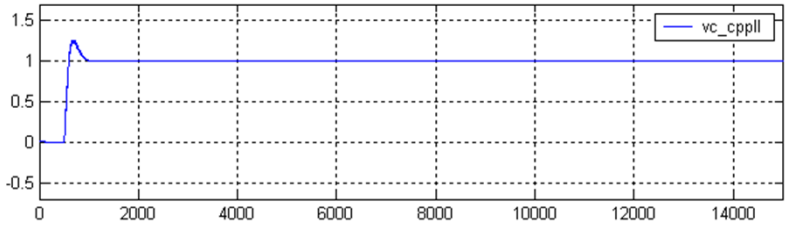
Qualitatively,
changes in charge pump currents directly affect V_C

Charge Pump PLL

Solution



➔Ripple reduction with small C_2 (< C_1/10)

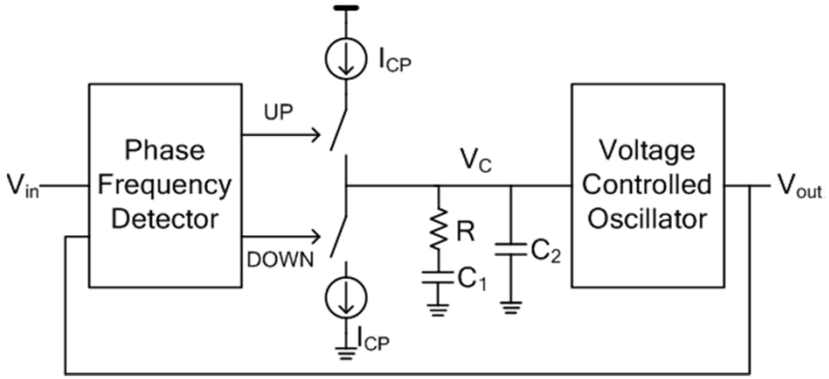


➔ 3rd order system

For dynamics analysis, 2nd-order PLL without C_2 is often used

Charge Pump PLL

Solution



$$G(s) = \frac{1}{2\pi} I_{CP} K_{VCO} \frac{sRC_1 + 1}{s^2 C_1}$$

$$H(s) = \frac{\frac{I_{CP} K_{VCO}}{2\pi C_1}(RC_1 s + 1)}{s^2 + \frac{I_{CP}}{2\pi} K_{VCO} R s + \frac{I_{CP}}{2\pi C_1} K_{VCO}}$$

$$H(s) = \frac{2\varsigma\omega_n s + \omega_n{}^2}{s^2 + 2\varsigma\omega_n s + \omega_n{}^2} \qquad \omega_n = \sqrt{\frac{I_{CP} K_{VCO}}{2\pi C_1}} \qquad \varsigma = \frac{R}{2}\sqrt{\frac{I_{CP} C_1 K_{VCO}}{2\pi}}$$

C_2 does affect PLL dynamics:
It introduces an additional pole, which reduces the phase margin

Careful simulation is required for real PLL design

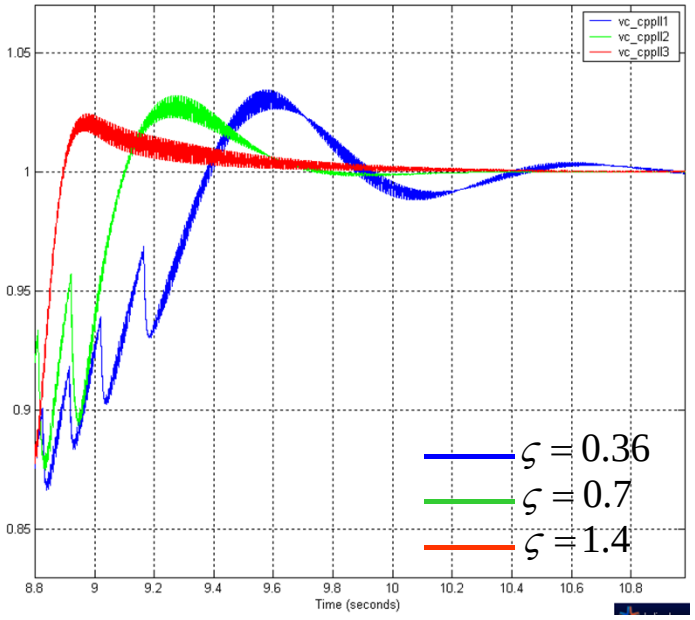
CP PLL Step Responses

$f_{in} = f_{out} = 200Hz$

$I_{CP} = 100\mu A$

$K_{VCO} = 2\pi \times 100 rad/s/V$

$f_n = 1Hz$



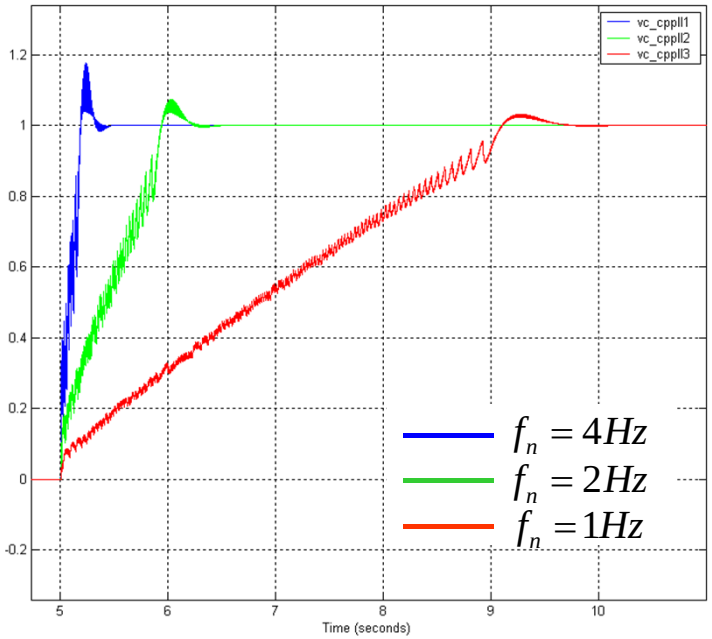
(ζ dependence)

$f_{in} = f_{out} = 200Hz$

$I_{CP} = 100\mu A$

$K_{VCO} = 2\pi \times 100 rad/s/V$

$\varsigma = 0.7$



(ω_n dependence)

➔ Optimization for desired performance!

Charge Pump PLL with a Divider

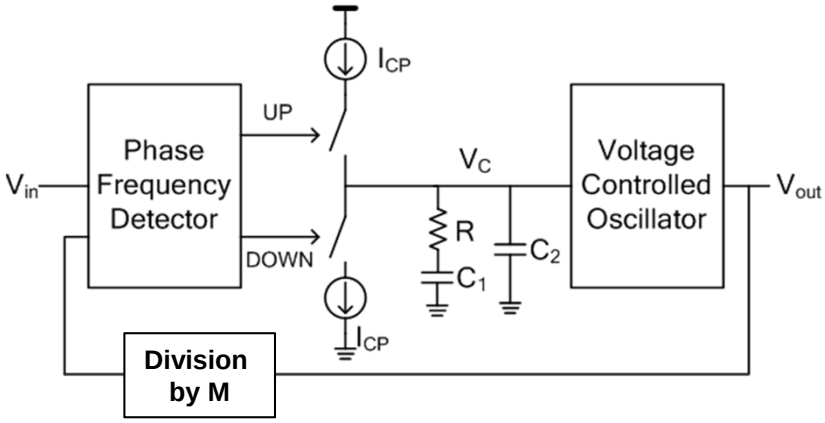
$$H(s) = \frac{\frac{I_{CP}K_{VCO}}{2\pi C_1}(RC_1 s + 1)}{s^2 + \frac{I_{CP}}{2\pi}K_{VCO}Rs + \frac{I_{CP}}{2\pi C_1}K_{VCO}} = \frac{2\zeta\omega_n s + \omega_n{}^2}{s^2 + 2\zeta\omega_n s + \omega_n{}^2}$$

$$\omega_n = \sqrt{\frac{I_{CP}K_{VCO}}{2\pi C_1}} \qquad \zeta = \frac{R}{2}\sqrt{\frac{I_{CP}C_1K_{VCO}}{2\pi}}$$

What if the feedback loop has a divider?

Forward loop gain? $G(s) = \frac{1}{2\pi} I_{CP}K_{VCO}\frac{sRC_1 + 1}{s^2 C_1}$

Feedback loop gain? $\frac{1}{M}$



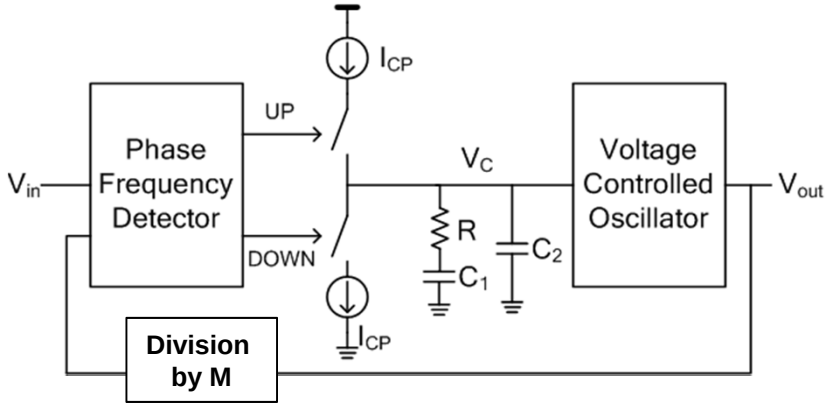
$$H(s) = \frac{G(s)}{1 + \frac{G(s)}{M}} = \frac{\frac{I_{CP}K_{VCO}}{2\pi C_1}(RC_1 s + 1)}{s^2 + \frac{1}{M}\frac{I_{CP}}{2\pi}K_{VCO}Rs + \frac{1}{M}\frac{I_{CP}}{2\pi C_1}K_{VCO}}$$

$$= \frac{(2\zeta\omega_n s + \omega_n{}^2)M}{s^2 + 2\zeta\omega_n s + \omega_n{}^2}$$

$$\omega_n = \sqrt{\frac{I_{CP}K_{VCO}}{2\pi C_1 M}} \qquad \zeta = \frac{R}{2}\sqrt{\frac{I_{CP}C_1K_{VCO}}{2\pi M}}$$

PLL Phase Errors

$$H(s) = \frac{(2\varsigma\omega_n s + \omega_n{}^2)M}{s^2 + 2\varsigma\omega_n s + \omega_n{}^2} \qquad \omega_n = \sqrt{\frac{I_{CP}K_{VCO}}{2\pi C_1 M}} \qquad \varsigma = \frac{R}{2}\sqrt{\frac{I_{CP}C_1 K_{VCO}}{2\pi M}}$$



$$H_e(s) = \left(\phi_{in} - \frac{\phi_{out}}{M}\right)/\phi_{in} = 1 - \frac{H(s)}{M}$$

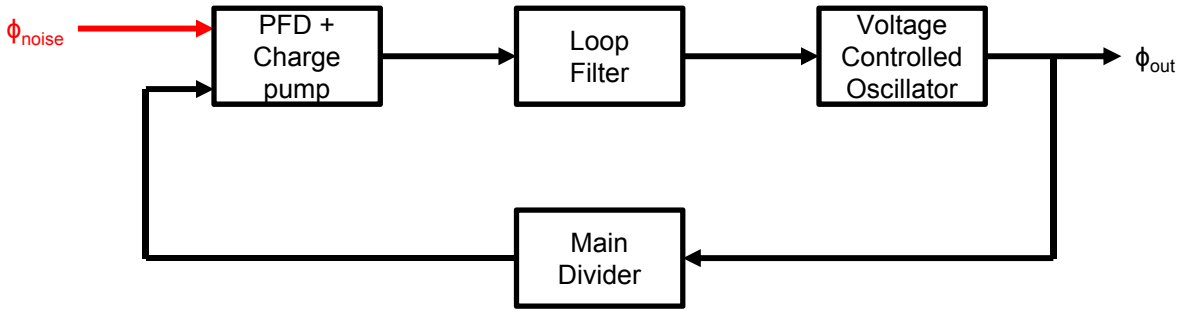
$$= \frac{s^2}{s^2 + 2\varsigma\omega_n s + \omega_n^2}$$

- Phase error due to phase step? $\phi_e(t=\infty) = \lim_{s\to 0}\left[sH_e(s)\frac{\Delta\phi}{s}\right]$

- Phase error due to frequency step? $\phi_e(t=\infty) = \lim_{s\to 0}\left[sH_e(s)\frac{\Delta\omega}{s^2}\right]$

Input-Noise Transfer Function

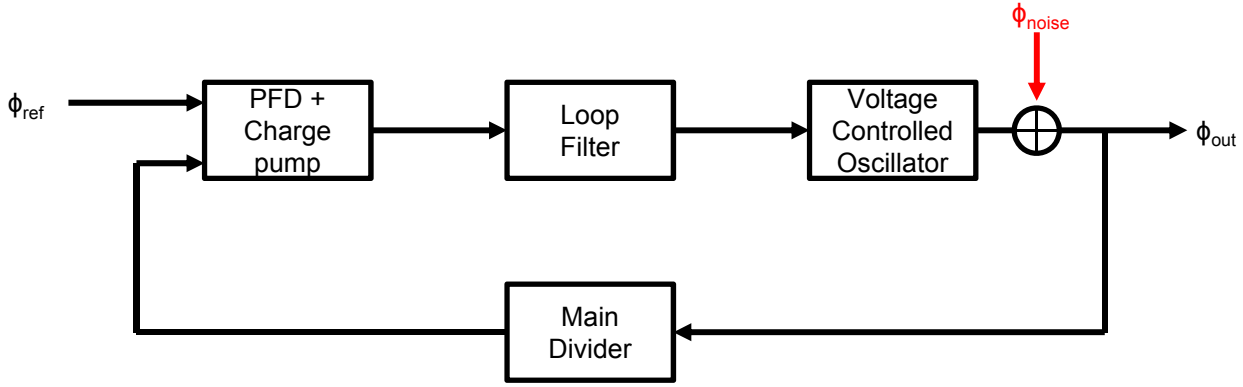
- Input noise



$$H(s) = \frac{\phi_{out}}{\phi_{noise}} = \frac{(2\varsigma\omega_n s + \omega_n{}^2)M}{s^2 + 2\varsigma\omega_n s + \omega_n{}^2}$$

VCO-Noise Transfer Function

- VCO phase noise



$$\phi_{out} = -\frac{\phi_{out}}{M} G(s) + \phi_{noise}$$

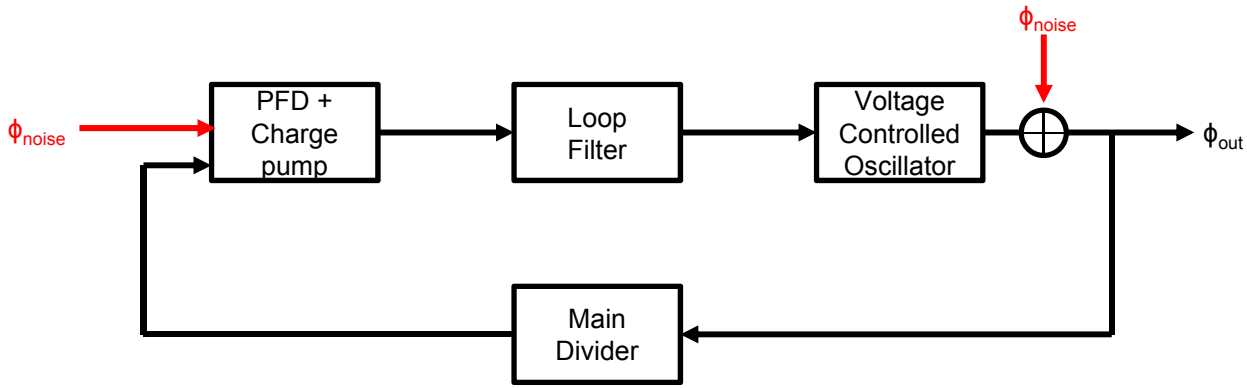
$$H(s) = \frac{\phi_{out}}{\phi_{noise}} = \frac{1}{1 + G(s)/M} = \frac{1}{1 + G(s)/M} = \frac{s^2}{s^2 + 2\varsigma\omega_n s + \omega_n^{\ 2}}$$

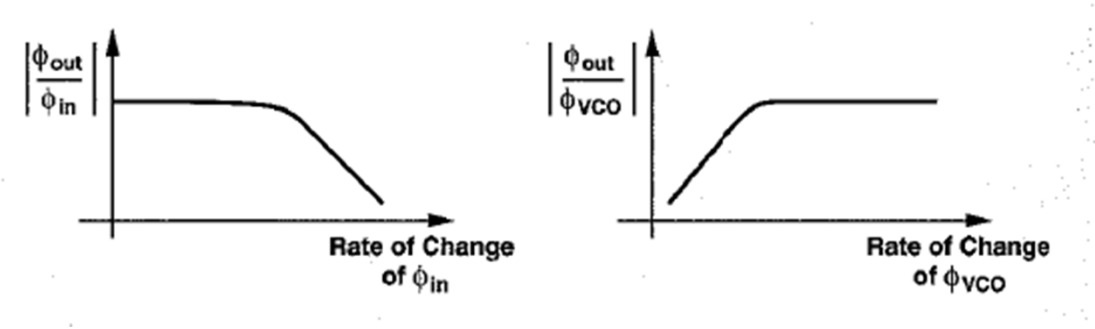
$$\omega_n = \sqrt{\frac{I_{CP} K_{VCO}}{2\pi C_1 M}}$$

$$\varsigma = \frac{R}{2}\sqrt{\frac{I_{CP} C_1 K_{VCO}}{2\pi M}}$$

➔ High pass filter

Optimal PLL Bandwidth





- Optimal PLL bandwidth depends on characteristics of each noise source

➔ Design Project 1