Literature Number: SNAP001

PLL Fundamentals

Part 1: PLL Building Blocks

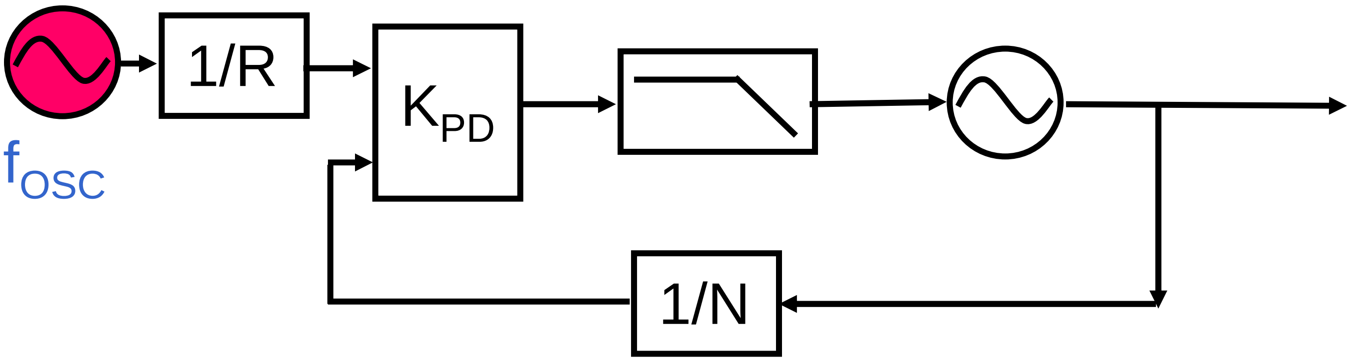
Dean Banerjee

Overview

- Oscillators
  - Crystal Oscillators
  - High Frequency Oscillators
  - Voltage Controlled Oscillators (VCO)
  - Silicon Voltage Controlled Oscillators
  - Oscillator Phase Noise
- Other PLL Building Blocks
  - Counters
  - Phase Detector/Charge Pump
  - Loop Filter

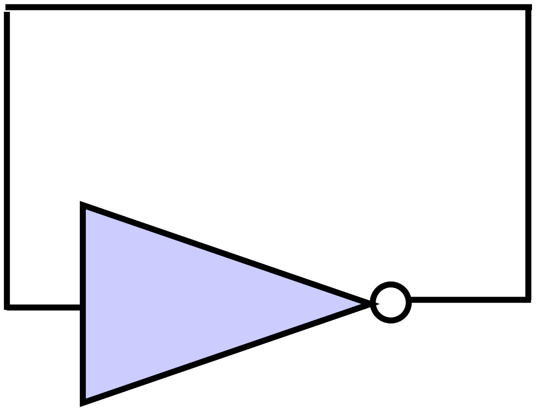
Notes

Reference Oscillator



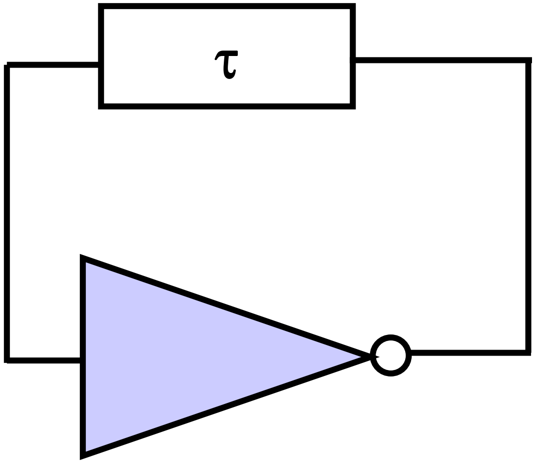
- Typically a fixed frequency of operation = f_{OSC}
- Can come in many forms
  - Crystal
  - Crystal Oscillator (XO)
  - Temperature Compensated Crystal Oscillator (TCXO)
  - Oven Controlled Crystal Oscillator (OCXO)
  - Output from another device
  - Recovered clock
  - DDS Signal

The Traditional Oscillator



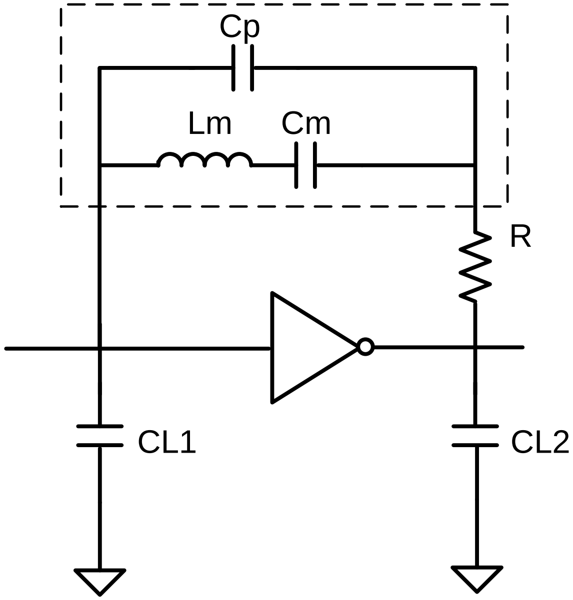
- Output of Inverter is fed back to the input
- Frequency of oscillation is determined by delay of inverter

The Traditional Oscillator



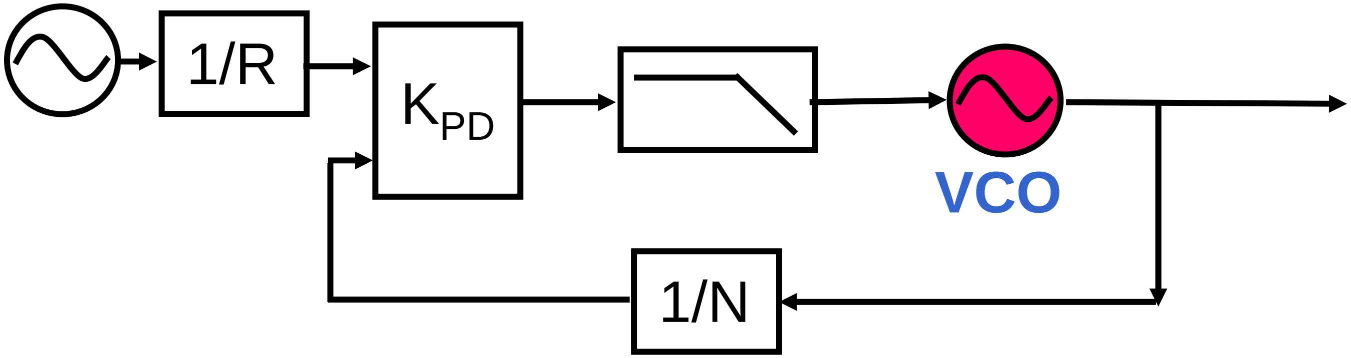
- **Delay of τ can be added in feedback path to set the frequency**
  - **f = 1/ τ**
- **A filter can also be added for a sine wave. Note that it is impossible to filter without delay, so a filter and a delay are related.**

Typical Crystal Oscillator



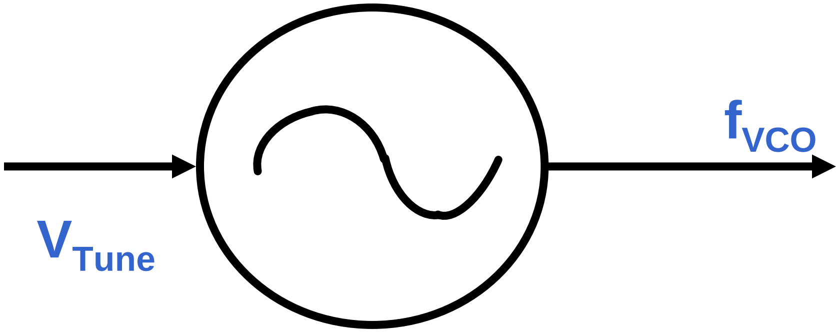
- **Crystal**
  - **Lm (Motional Inductance)**
  - **Cm (Motional Capacitance)**
  - **Cp (Parallel Capacitance)**

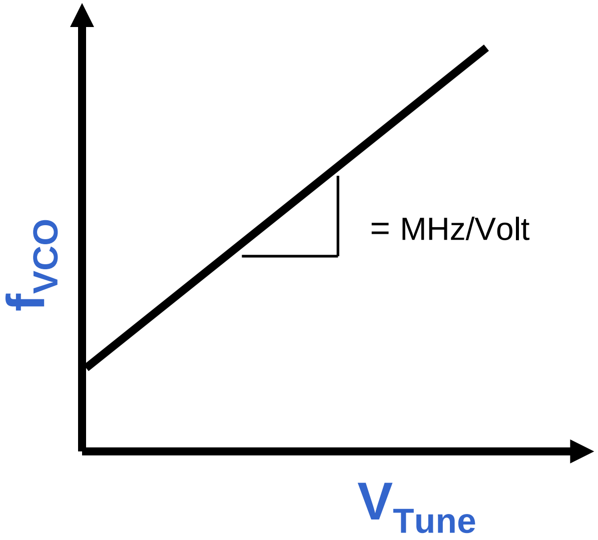
VCO (Voltage Controlled Oscillator)



- **The VCO (Voltage Controlled Oscillator)**
  - Converts voltage to frequency
  - Generates frequencies over restricted frequency range
  - Frequency drifts considerably over temperature, voltage and process
  - Typically Much higher frequency than the reference oscillator

VCO Frequency Tuning



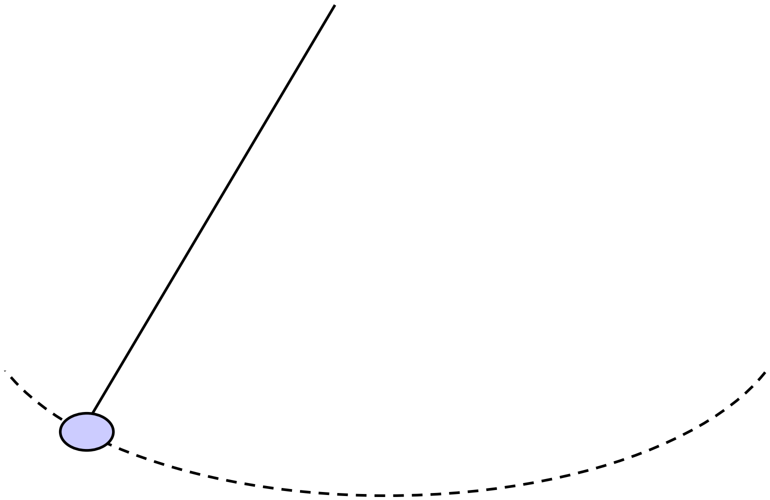


- **VCO Figures of Merit**
  - Tuning Range
  - Output Power
  - Tuning Sensitivity (K_{VCO} in MHz/Volt)
  - Tuning Linearity (Want K_{VCO} constant)
  - Pushing (Frequency shift over supply voltage)
  - Pulling (Frequency shift over load)
  - Harmonics (Undesired Multiples of intended frequency)
  - Power Consumption
  - Size
  - Phase Noise

Understanding How VCOs Work

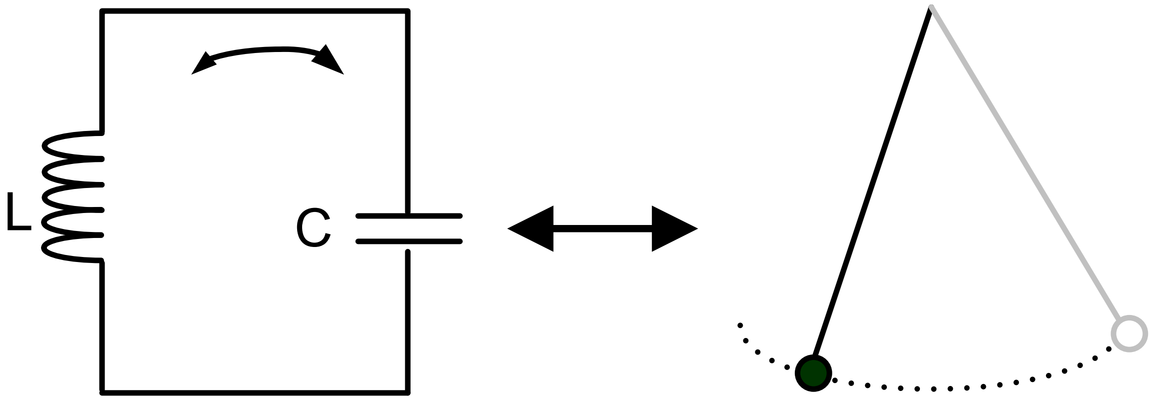
- **Crystals and VCOs are Not the Same**
  - **Crystals are typically limited to lower frequencies (<100 MHz)**
  - **Crystals typically have a frequency range that is too narrow for most applications**
- **Hard to Relate VCO Circuits to Crystal Circuits**
  - **Higher frequency oscillators like VCOs often contain transistors and MOS devices that deal with currents, not voltages**
  - **Trying to relate a VCO schematic to this traditional oscillator model takes a lot of imagination.**

A Better Way to Think of a VCO



- Neglecting the Impacts of Friction, the pendulum conserves energy. It just converts it between potential and kinetic energy
- In the real world, there is friction, so a small stimulus needs to be applied to keep the circuit going.

The Tank Circuit

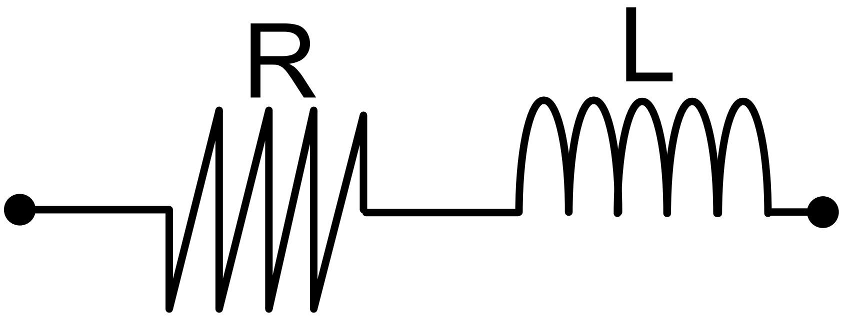


$$f = \frac{1}{2\pi\sqrt{L \cdot C}}$$

$$\tau = 2\pi\sqrt{\frac{L}{g}}$$

- Tank circuit can be viewed as an electronic spring.
  - When voltage across the capacitor is maximum, current in the inductor is minimum, and vise versa
- Assuming no parasitic resistances, circuit would go on forever, but wouldn’t that be nice?

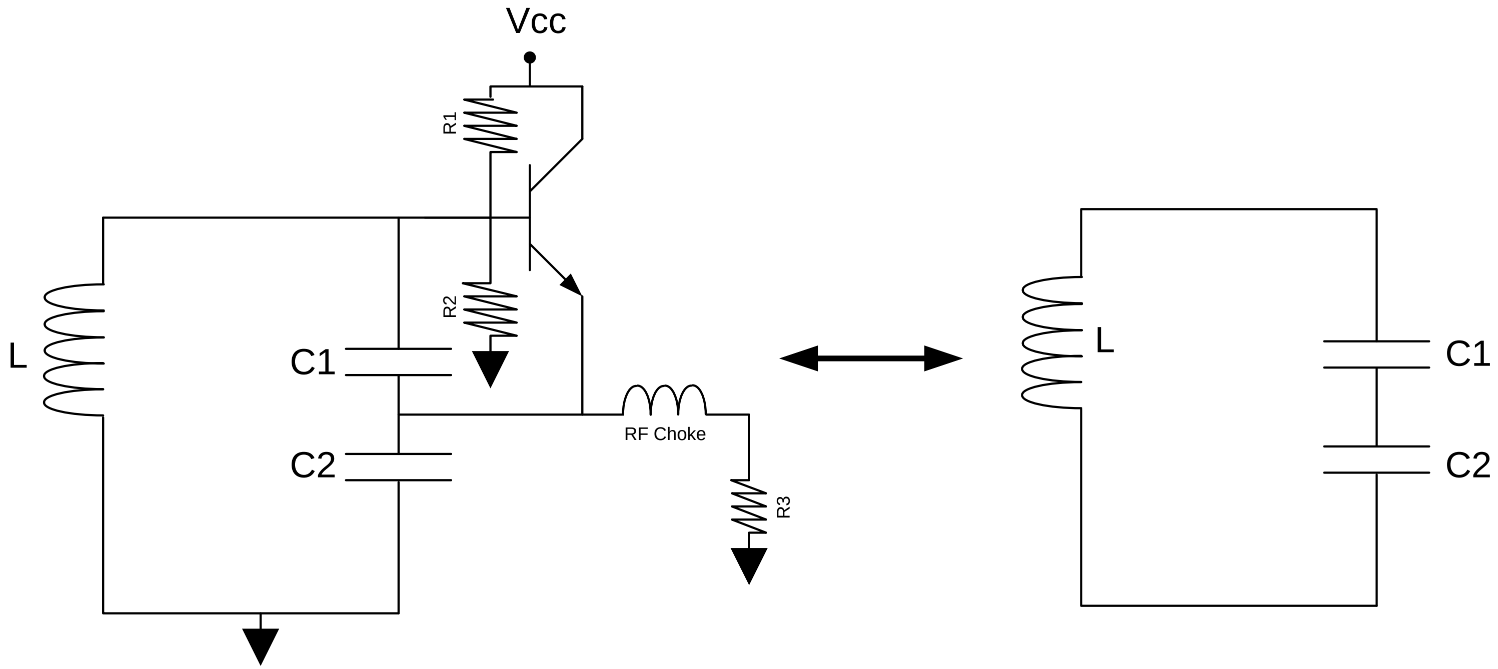
The Real World Inductor



$$Q_L(f) = \frac{X_L}{R_L} = \frac{2\pi \cdot f \cdot L}{R}$$

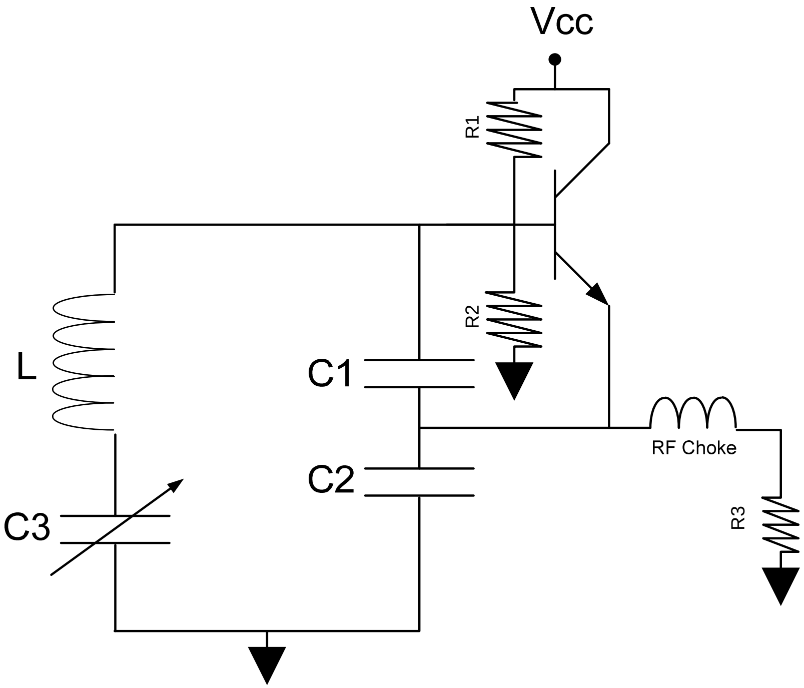
- **Q is the quality factor, measured at the frequency of interest**
- **Parasitic resistances, such as the one in the inductor cause the circuit to eventually stop oscillating.**
- **Just as with the pendulum, it is necessary to provide some stimulus to keep the circuit going.**

Now Add the Stimulus



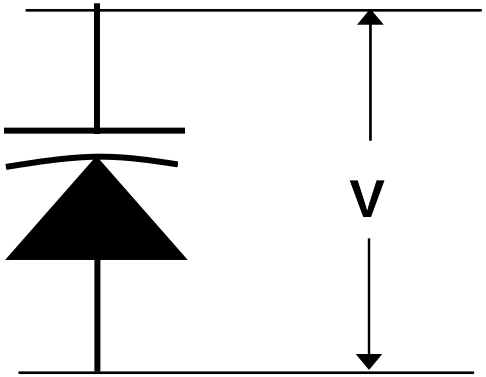
- **Amplified signal from emitter is lightly coupled into the circuit to sustain oscillation**
- **Above Circuit is Colpitts Oscillator**

Typical Clapp (Clapp-Gouriet) Oscillator



- **Very similar to the Colpitts oscillator, except ..**
  - **Series capacitance C3 (Often adjustable), is typically added**
  - **This is better than Colpitts with a variable capacitor because changing the C3 capacitance does not change the feedback at C1 and C2.**

The Varactor Diode

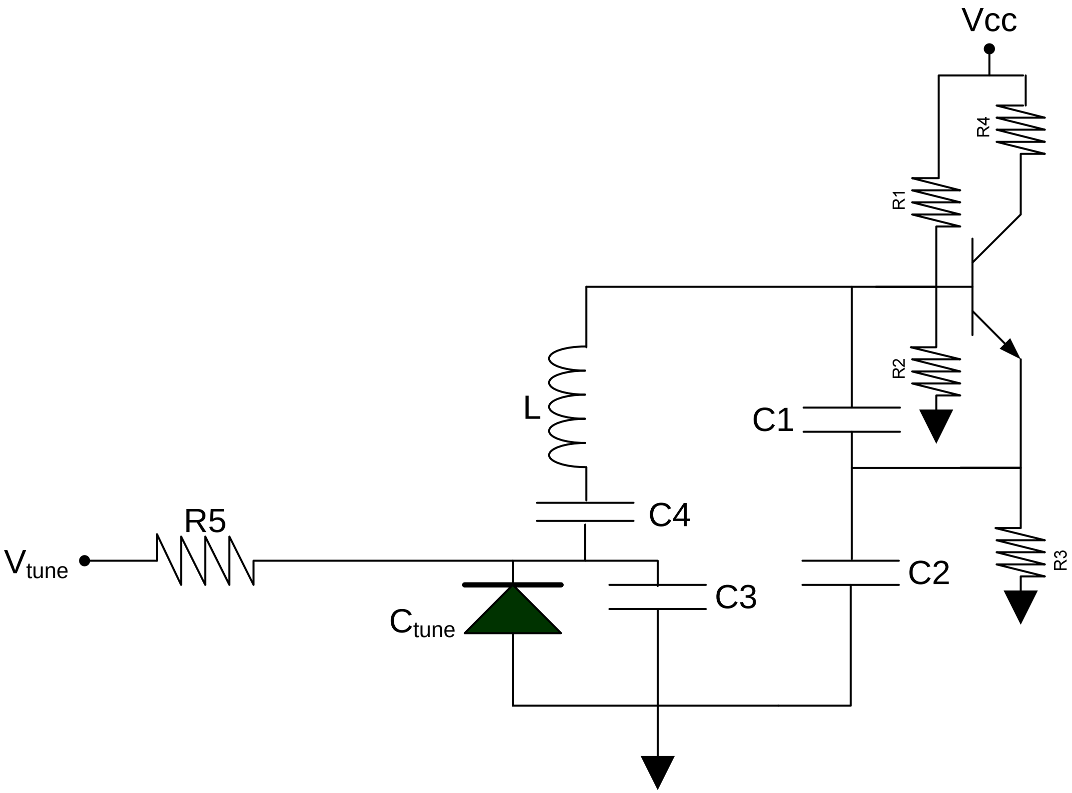


- To implement the variable capacitance for the VCO, a varactor diode is often used. As more voltage is applied to the diode, the capacitance decreases

$$C_{Varactor}(V)=\frac{C_{Varactor}(0\,volts)}{\sqrt{\phi+V}}$$

- 15-20 pF of capacitance is typical

Complete VCO Circuit



- **Varactor Diode Capacitance Adds to C3**
  - **Larger C3 => better Phase Noise, but less tuning range**
- **Resistor R5 isolates Tuning voltage from Loop Filter**

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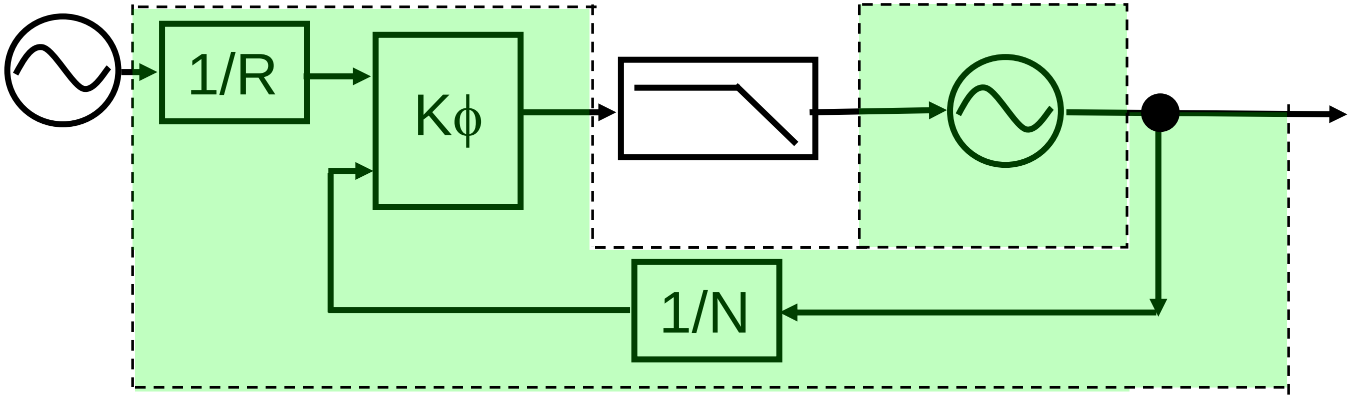
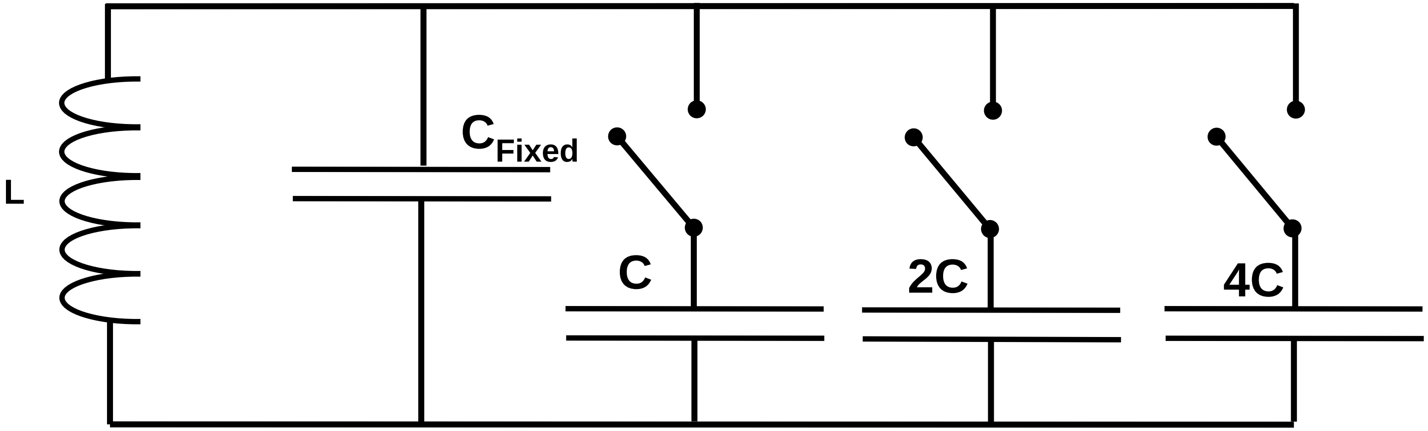
Integrating VCOs on Silicon



- **Inductance is Typically Formed by Bond Wires**
  - VCO frequencies tend to be higher due to low inductances
  - Can also do small inductors on silicon, but they are small
  - Can allow external inductors to be added for lower frequencies
  - Often easier to generate a higher frequency and divide it down
- **Capacitance is Formed by an Internal Bank of Capacitors**
  - Frequency calibration is typically necessary

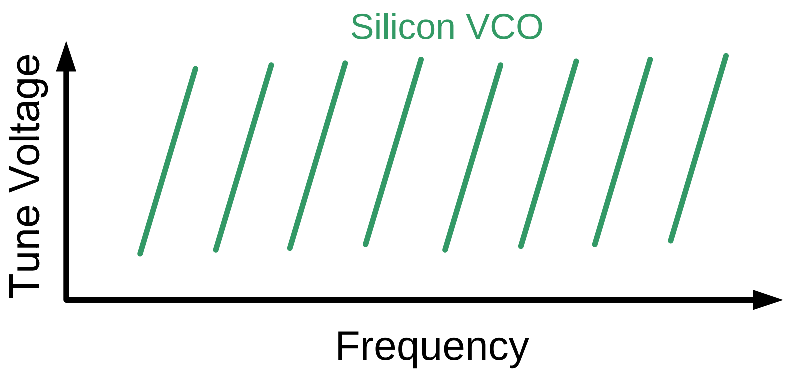
Bank of Switched Capacitors

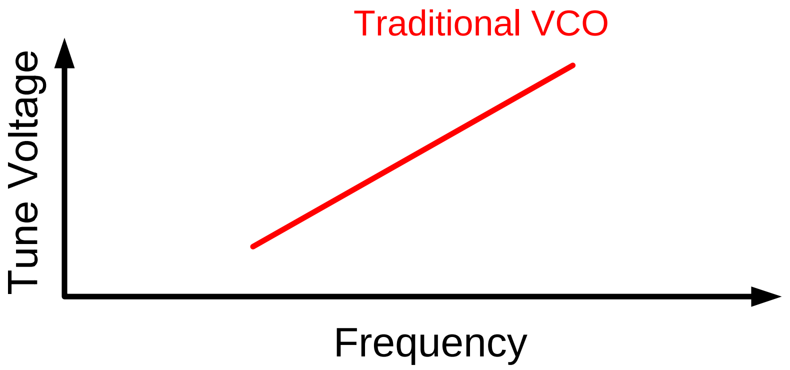


- Capacitors can be switched in and out to create multiple bands
  - The best phase noise and lowest tuning gain is often at the lowest frequency with all the capacitors switched in
- Logic is necessary to switch capacitors in and out to find the correct combination
  - On resistance of the switches is one source of phase noise

Silicon VCO Tuning Range

- **VCO Range Divided into many bands**
- **These bands cover the whole frequency range and need**
- **Bands need to overlap to account for temperature drift**
- **Correct band is selected when frequency is changed**
- **This technique allows wider tuning range without sacrificing phase noise**

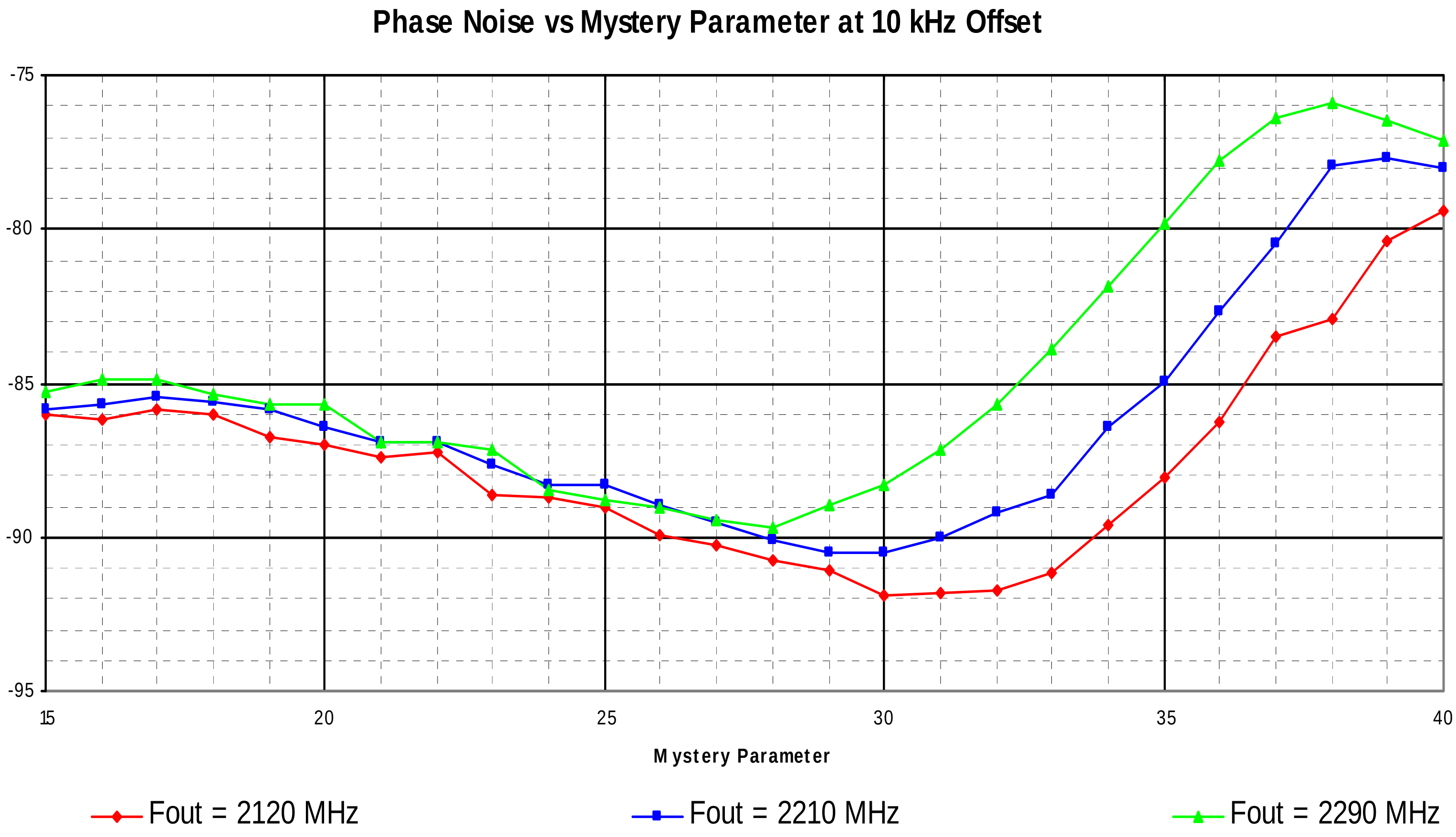




Things to Watch for with Silicon VCOs

- **Temperature Drift**
  - **If temperature changes without the VCO doing it's frequency calibration, tuning voltage drifts towards a rail**
  - **Typically bands overlap to accommodate for this**
  - **National has a proprietary method to deal with this issue**
- **Calibration Time**
  - **Faster for higher OSCin frequencies**
  - **Improves lock time if bandwidth is narrow or if there are large cycle slipping issues**
  - **Hurts lock time if loop filter is fast (i.e. <400 us)**

LMX2531 VCO Phase Noise Optimization



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Traditional vs. Silicon VCOs

- **Traditional VCO Advantages**
  - **Potentially better performance (tuning range and/or phase noise) if there is a large tuning voltage supplied**
  - **Can be customized to frequency**
- **Silicon VCO Advantages**
  - **Lower Cost**
  - **Smaller Size**
  - **Higher Reliability**
  - **VCO to PLL mismatch issues eliminated**
  - **Wider tuning range for a given supply voltage**
  - **Extra bells and whistles**
    - **Programmable Output Power**
    - **Switchable Dividers**

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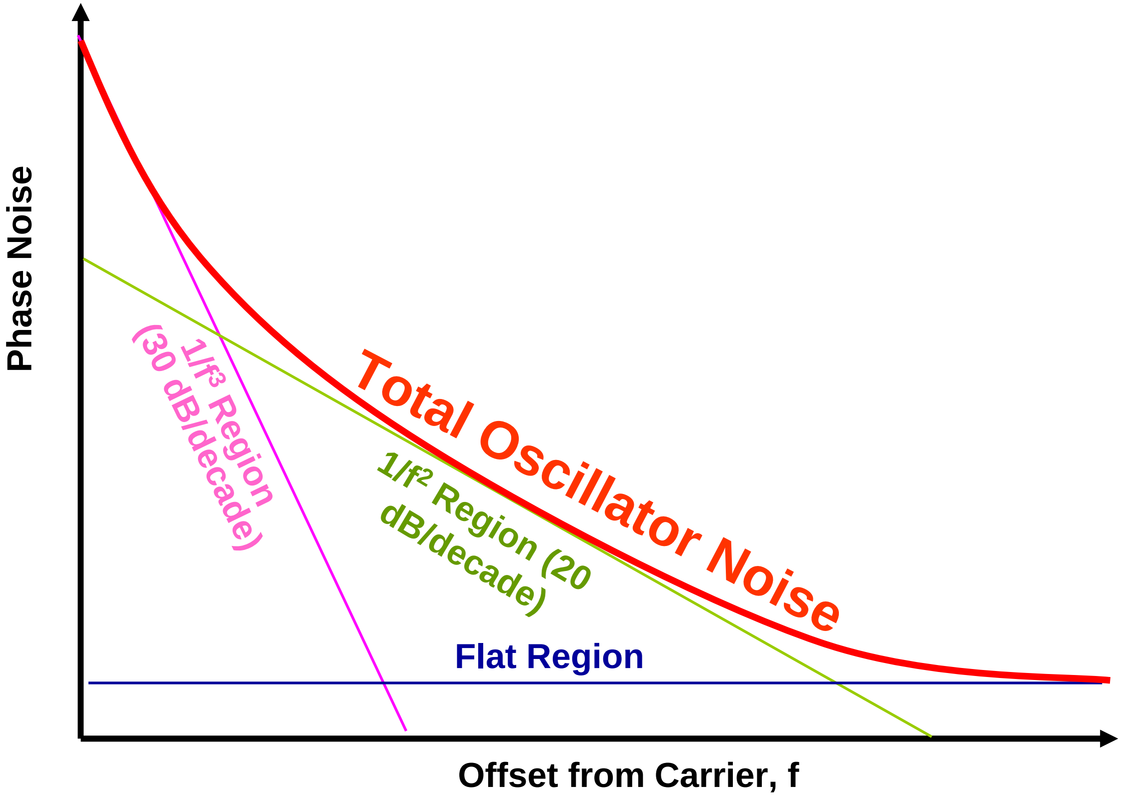
Classical Oscillator Phase Noise Model



Lesson’s Equation

- **Lesson’s Equation**

$$L(f)=10\bullet\log\left(N3\bullet\overset{\substack{\textbf{1/f}^{3}\\\textbf{Region}\\\downarrow}}{\left(\frac{f_{default}}{f}\right)^{3}}+N2\bullet\overset{\substack{\textbf{1/f}^{2}\\\textbf{Region}\\\downarrow}}{\left(\frac{f_{default}}{f}\right)^{2}}+\overset{\substack{\textbf{Flat}\\\textbf{Region}\\\downarrow}}{N0}\right)$$

- **Parameters**
  - **N3, N2, N0 are constants to be discussed later**
  - **$f_{default}$ is the a default frequency where these constants are defined, and is constant**
  - **f is the offset frequency**

1/f^3 Region

- **Noise Coefficient**

$$N3 = \frac{1}{f^3}\ Noise\,Coefficient = \frac{F \bullet k \bullet T}{P} \bullet \frac{f_{1/f^3} \bullet f_{vco}^2}{8 \bullet Q_L^2 \bullet f_{default}^3}$$

- **Phase noise goes down by 30 dB/decade in this region**
- **Phase Noise is caused by the flicker noise of the transistor**
- **Q_L is the loaded Q of the inductor, and is the most important term and the one with the greatest influence**

$1/f^2$ Region

- **N2 Noise Coefficient**

$$N2 = \frac{1}{f^2}\ Noise\ Coefficient \ = \frac{F \bullet k \bullet T}{P} \bullet \frac{f_{vco}^{2}}{8 \bullet Q_L^2 \bullet f_{default}^{2}} + \frac{2 \bullet k \bullet T \bullet R_{var} \bullet Kvco^2}{f_{default}^{2}}$$

- **Phase Noise goes down by 20 db/decade in this region**
- **R_{var} is the noise resistance of the varactor diode. Note that for a larger VCO gain, Kvco, this noise is multiplied.**
  - **Putting multiple varactor diodes in parallel helps reduce this noise.**
- **Loaded Q_L is also important**

Flat Region

- **Noise Coefficient**

$$N0 = VCO\ Noise\ Floor = \frac{F \bullet k \bullet T}{P}$$

- **Terms here**
  - **F is the noise figure**
  - **T is the temperature in Kelvin**
  - **k is Boltzmann’s constant**
  - **P is the output power**
- **Output buffer dominates here. High output power is good for phase noise because of the thermal noise floor**
- **Theoretically, the best VCO phase noise is at cold temperature and worse at hot temperature in all three regions**

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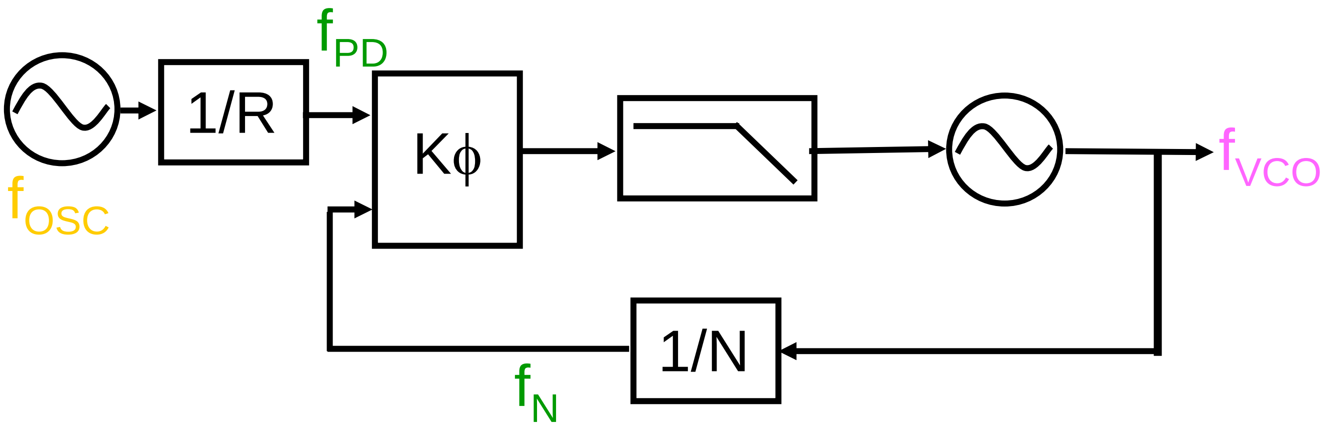
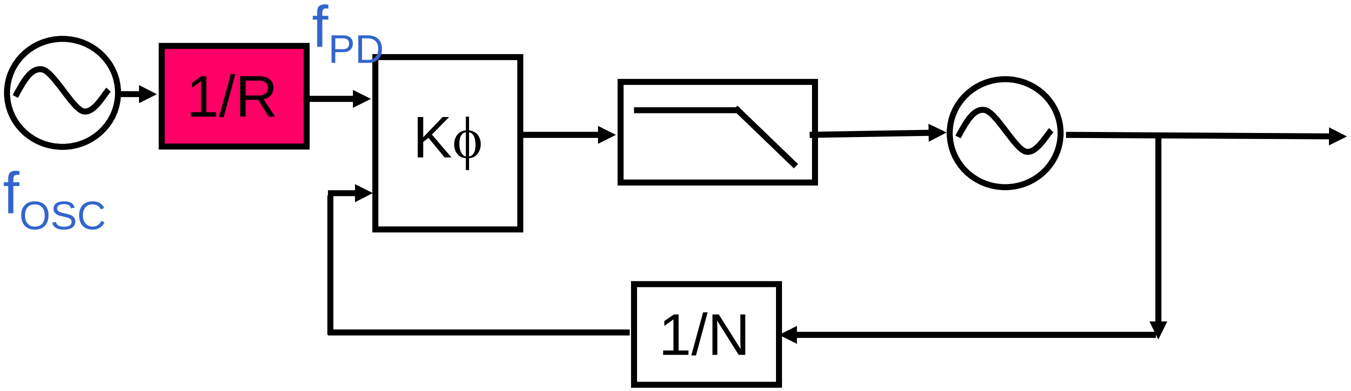
Basic PLL Operation



$$f_{OSC} / R = f_{PD} = f_N = f_{VCO} / N$$

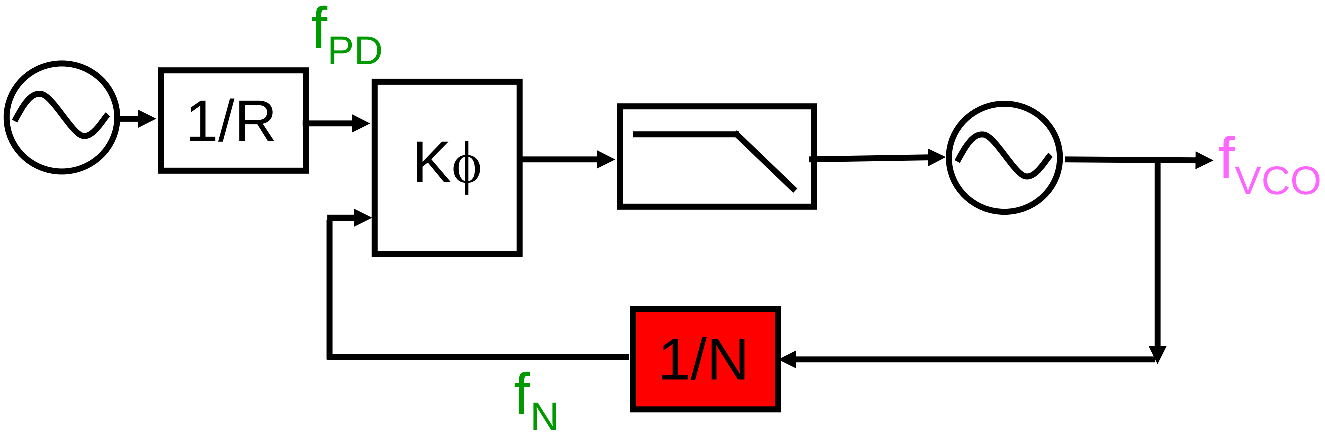
$$f_{VCO} = f_{OSC} \bullet (N/R)$$

Reference Oscillator and R Counter



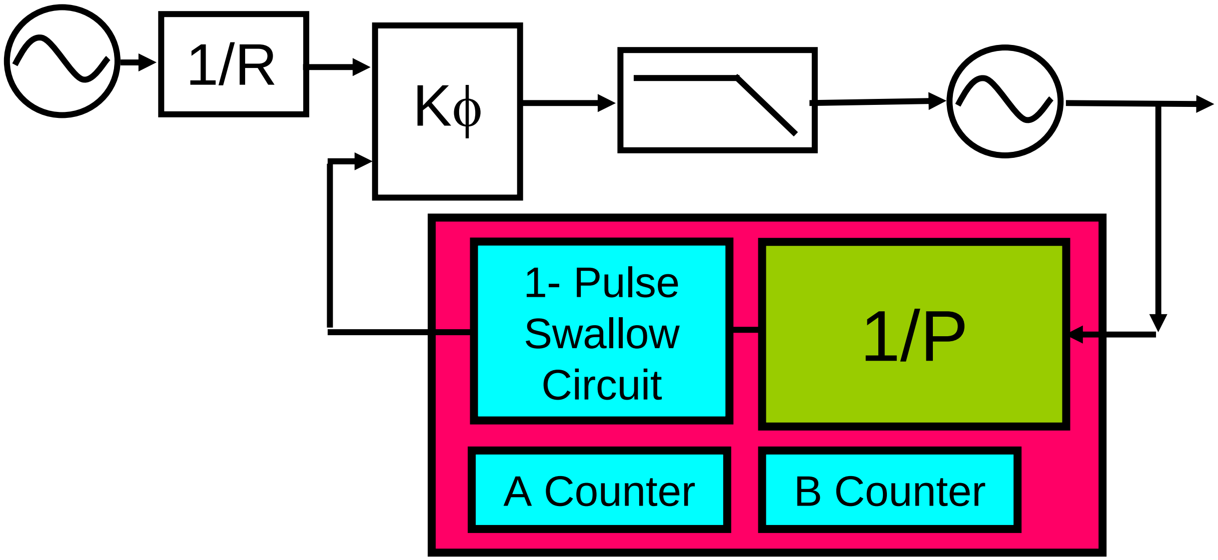
- **Phase Detector Frequency**
  - Fixed frequency of operation = f_{PD}
  - Equal to the channel spacing for an integer PLL
- **R Counter Value**
  - $R = f_{OSC} / f_{PD}$

N Counter



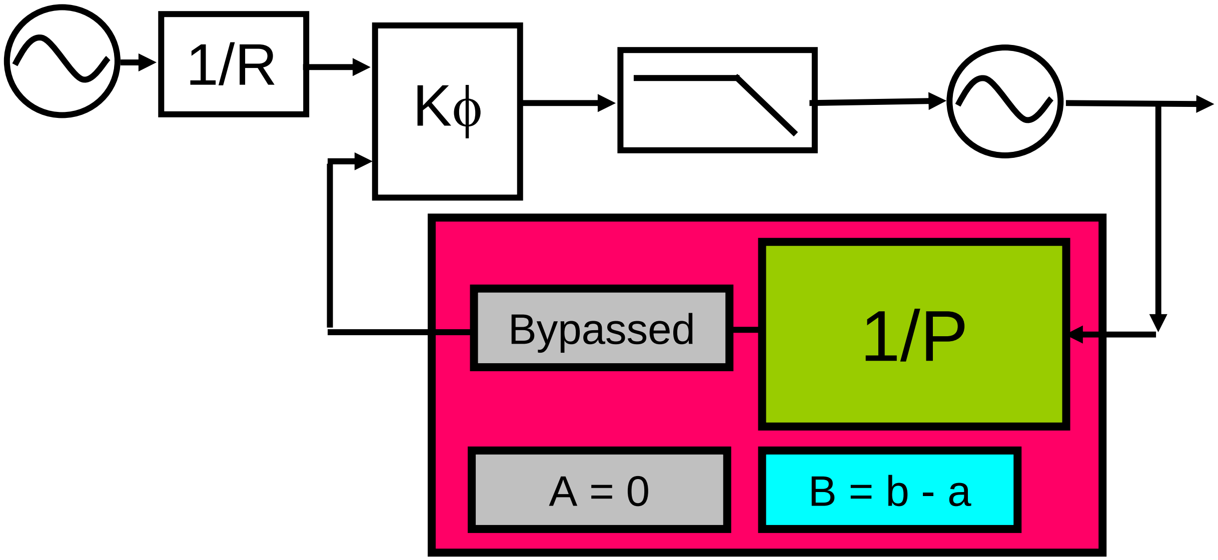
- **N Counter Value**
  - **N = f_{VCO}/f_N = f_{VCO}/f_{PD}**
- **Because the input to this counter can be high frequency, prescalers are typically inside this counter**

Dual Modulus Prescalers



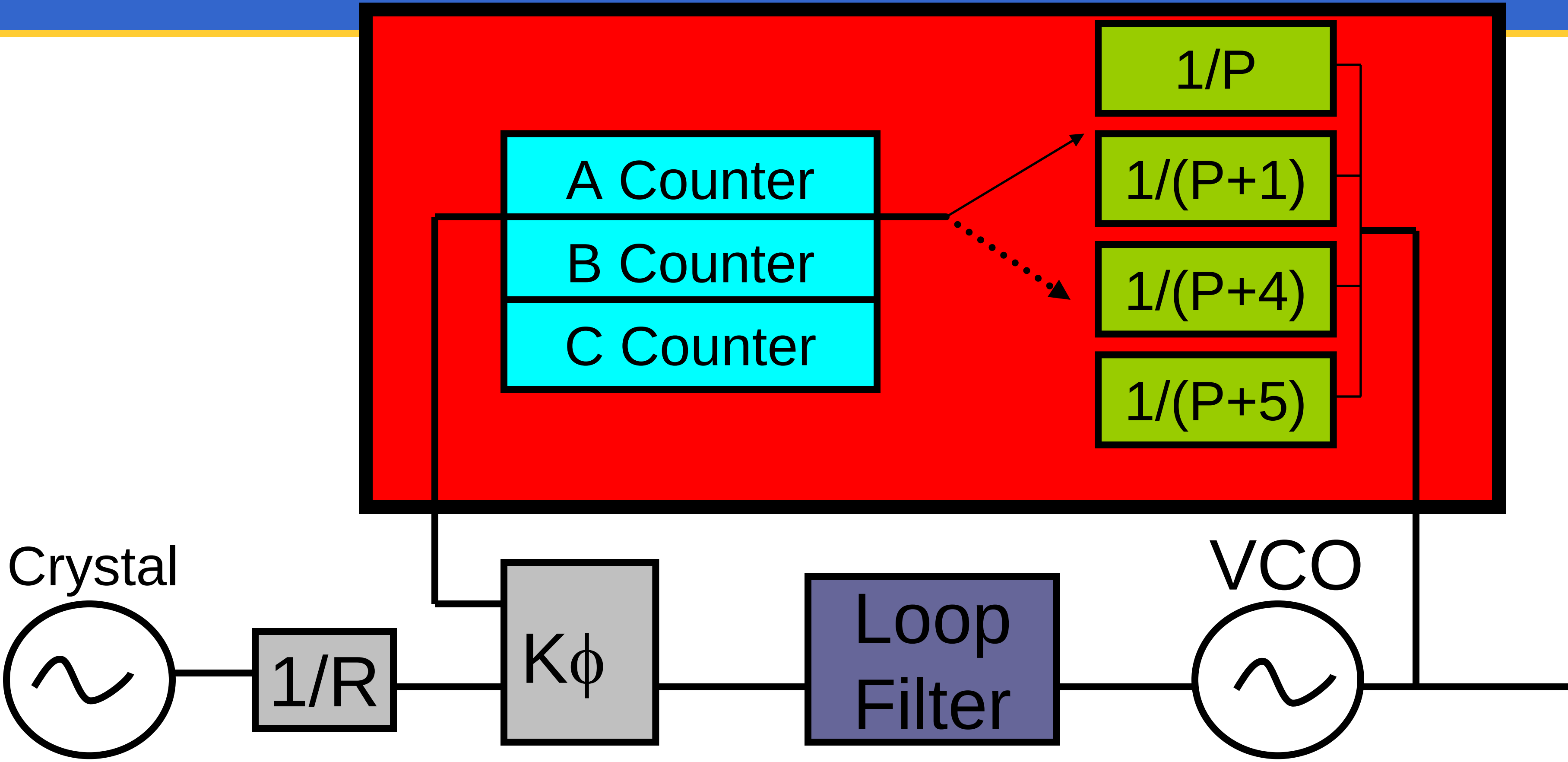
- **VCO Frequency is divided by prescaler**
  - Only the Prescaler has high frequency requirements
- **After the prescaler and the 1-pulse swallow circuit, each cycle decreases the A counter by 1 cycle**
  - This takes a•(P+1) cycles
  - B Counter is also decreased with the A counter

Dual Modulus Prescalers



- **After the A counter reaches zero ..**
  - Pulse Swallow circuitry is disabled
  - B counter counts down to zero
  - This takes (b-a)lP cycles
- **Total N Count**
  - $N = a\bullet(P+1) + (b-a)\bullet P = P\bullet B+A$
  - b>=a is a consequence of this architecture

Quadruple Modulus Prescaler



- **Advantage** Allows lower divide ratios.
- N = P•C + 4•B + A

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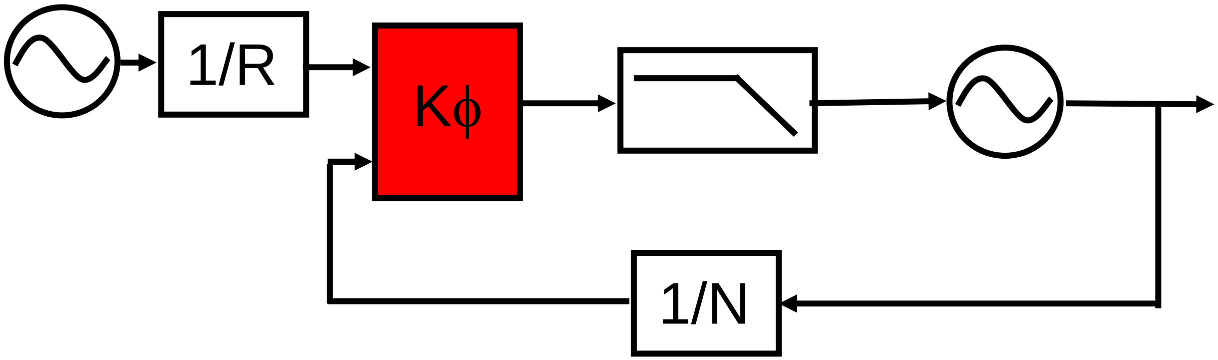
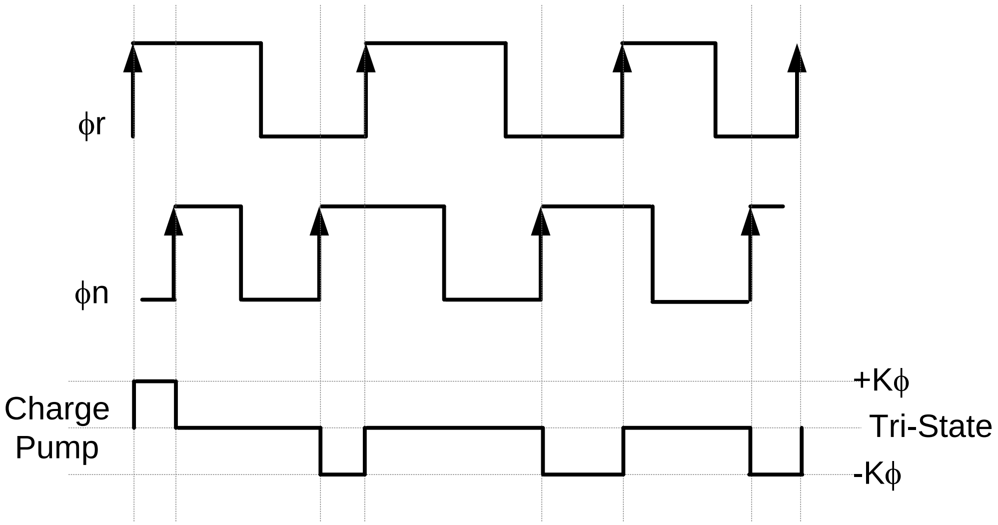
Phase Frequency Detector/Charge Pump



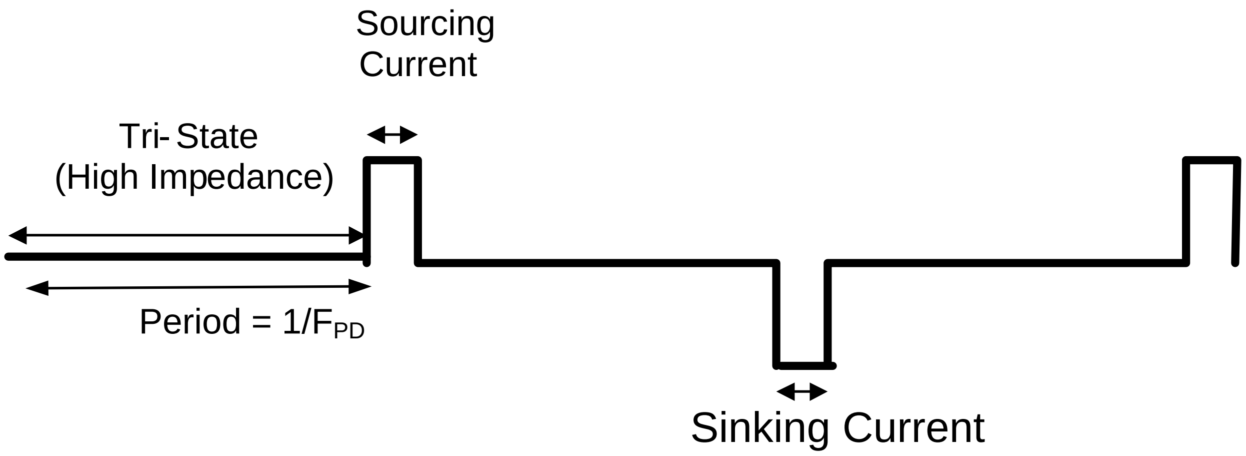
- **Phase Frequency Detector (PFD)**
  - Detects Frequency Error Between N and R Counter
- **Charge Pump**
  - Converts this frequency Error to a Correction Current
- **Usually, the PFD and Charge Pump are Integrated Together**

Phase Frequency Detector/Charge Pump



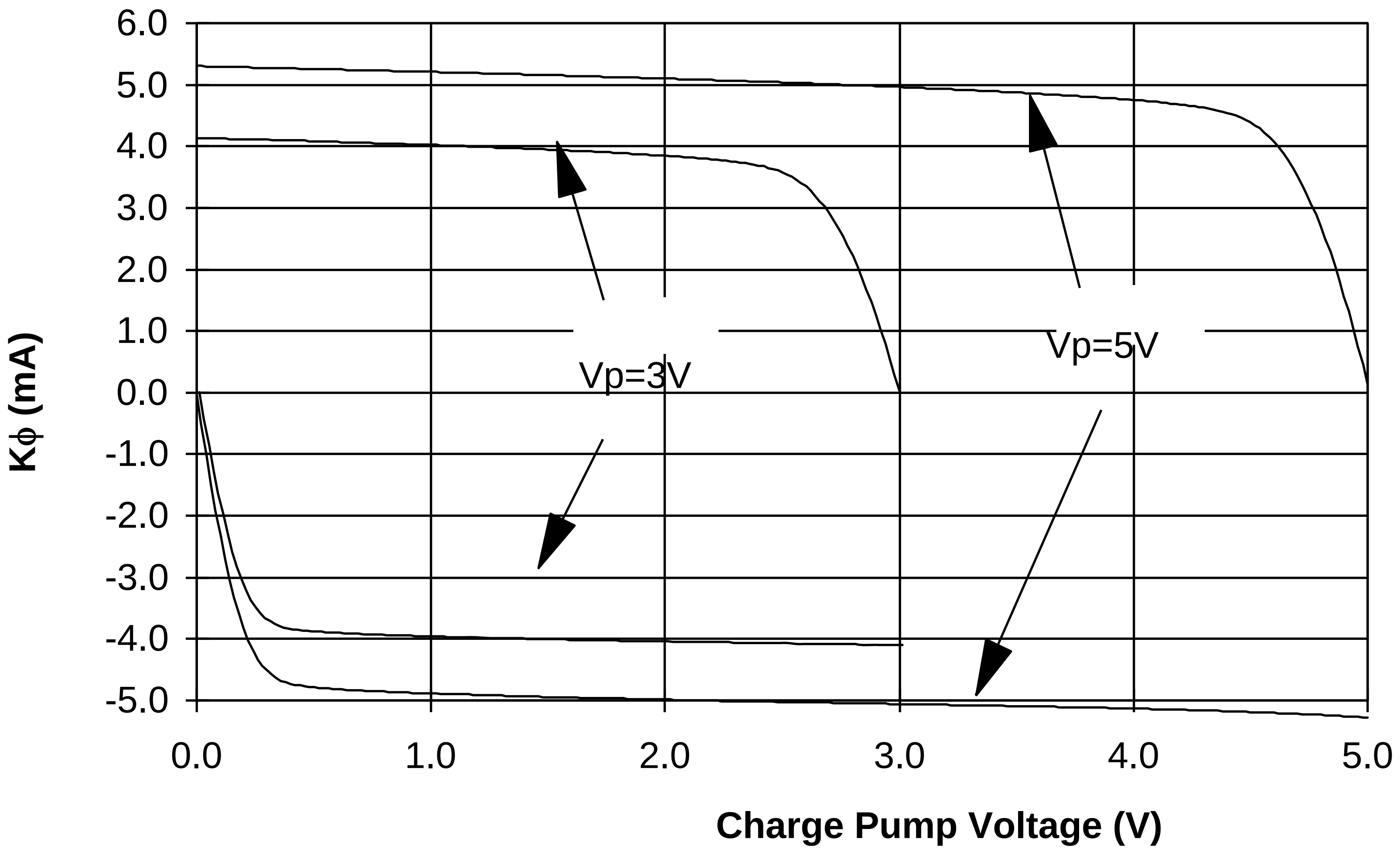
- **Detects differences in input signals**
  - Detects phase error between 2 input signals
  - Detects frequency error between 2 input signals
- **Outputs a voltage to the charge pump**
  - The average value of this voltage is proportional to the phase/frequency error.
  - Along with the rest of the system, ensures the 2 input signals are the same frequency and phase

Phase Frequency Detector/**Charge Pump**

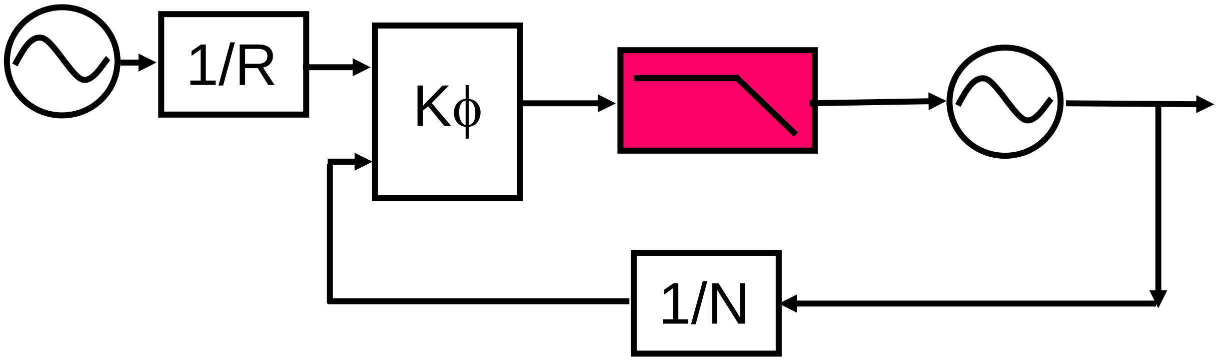


- **Charge Pump/Phase-Frequency Detector**
  - Sources Current if output frequency/phase is too low
  - Sinks Current if output frequency/phase is too high
  - High Impedance (tri-state)if output frequency/phase is correct (within tolerances)
- **Spurs Can Originate from the Charge Pump**
  - Want source and sink currents closely equal
  - Want tri-state to be very low leakage current

Charge Pump Current



Loop Filter



- **The loop filter is a low pass filter**
  - Accumulates correction currents from the Charge pump into a voltage
- **The loop filter has a dramatic effect on performance**
  - Determines the loop bandwidth
  - Impacts switching speed
  - Impacts spurs
  - Can impact phase noise
  - Many Design trade-offs involved
  - National has tools for this

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