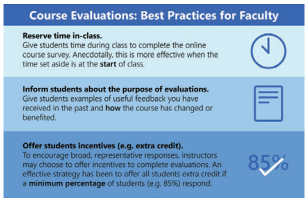
inst.eecs.berkeley.edu/~ee241b

# EE241B : Advanced Digital Circuits

## Lecture 25 – Power Supply

**Borivoje Nikolić**

Time for course surveys!






## Announcements

- Quiz today!
- Final on Thursday, April 30, 9:30-11am
- Project presentations on Monday, May 4
- Course surveys:
  - https://drive.google.com/file/d/1saRVPwUtLIRBApUzZ0Y9XAAG9vAhFkdV/view



## Outline

- Module 6
  - Supply distribution

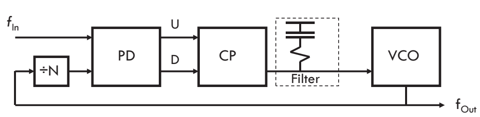


## 6.C Clock Generation: PLLs



## Phase-Locked Loop

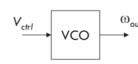
- PLL is locked when the phase difference is zero
- Second/third order loop
- ÷N for frequency synthesis (and x M)
- Filters input jitter
- Accumulates phase error





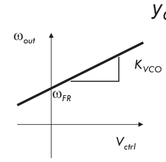

## Voltage-Controlled Oscillator

- Oscillation frequency controlled by voltage




$$\omega_{out} = \omega_{FR} + K_{VCO}V_{ctrl}$$

$$y_{out}(t) = A\cos\left(\omega_{FR}t + K_{VCO}\int_{-\infty}^{t} V_{ctrl}dt\right)$$

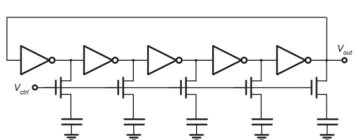



$\omega_{FR}$ – free-running frequency

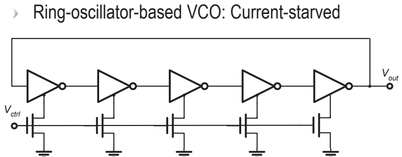


## Example VCO

- Ring-oscillator-based VCO: RC loaded




- Ring-oscillator-based VCO: Current-starved





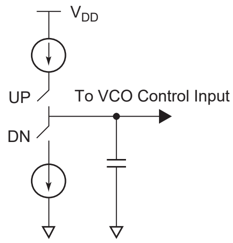

## PLL vs. DLL Dynamics

- The key difference is in the VCDL vs. VCO transfer characteristics
- VCO integrates (accumulates) phase

  $H_{VCO}(s) = K_{VCO}/s$

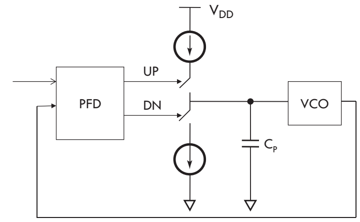
## Charge Pump

- Push/pull current source operation






## Charge-Pump PLL



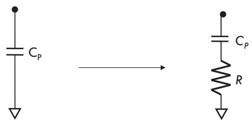

- Phase transfer function

$$H(s)=\frac{\frac{K_{PFD}}{s}\cdot\frac{K_{VCO}}{s}}{1+\frac{K_{PFD}}{s}\cdot\frac{K_{VCO}}{s}}=\frac{K_{PFD}K_{VCO}}{s^2+K_{PFD}K_{VCO}}$$



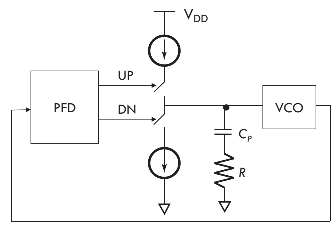
## Charge Pump PLL with a Zero

- Charge pump PLL has a stability problem
- Compensation by adding a zero






## Charge Pump PLL with a Zero




$$\omega_n=\sqrt{\frac{I}{2\pi C_P}K_{VCO}}$$

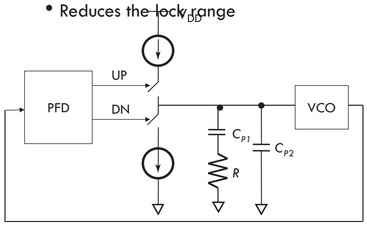
$$\zeta=\frac{R}{2}\sqrt{\frac{IC_P}{2\pi}K_{VCO}}$$

$$H(s)=\frac{\frac{K_{VCO}\cdot I}{2\pi C_P}\cdot(RC_Ps+1)}{s^2+\frac{I}{2\pi}K_{VCO}R_S+\frac{I}{2\pi C_P}K_{VCO}}$$



## Higher Order Loops

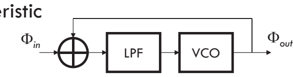
- Another pole naturally exists
  - Filters the control voltage $V_{CTRL}$
  - Lowers phase margin
  - Reduces the lock range



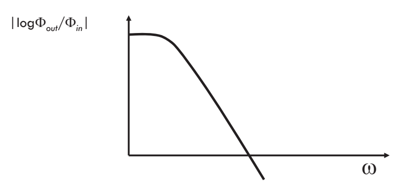



## Phase Noise at the PLL Input

- Low-pass characteristic



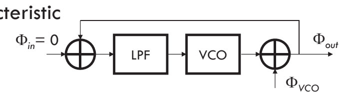

$$H(s)=\frac{\omega_n^{\ 2}}{s^2+2\zeta\omega_n s+\omega_n^{\ 2}}$$



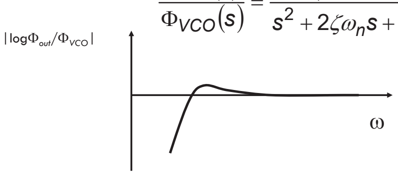



## VCO Phase Noise

- High-pass characteristic




$$\frac{\Phi_{out}(s)}{\Phi_{VCO}(s)}=\frac{s(s+\omega_{LPF})}{s^2+2\zeta\omega_n s+\omega_n^{\ 2}}$$

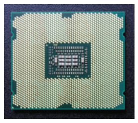




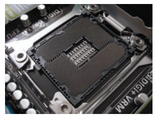

## 6.D Interaction with Supply

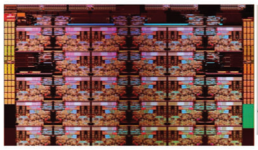
## Power Delivery

- Decoupling in Core i7

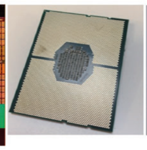


Andreas Hopf/Flickr





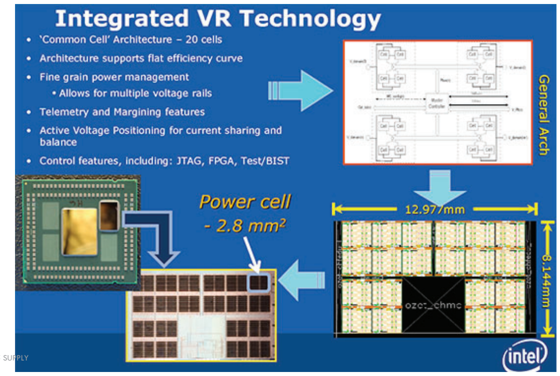
Skylake-SP, ISSCC'18



- Decoupling in Skylake-SP

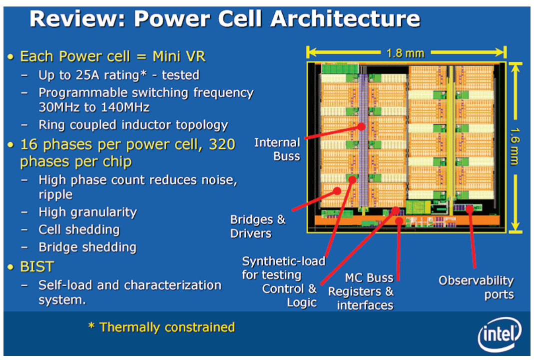


## Inside Haswell





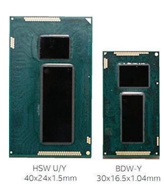

## Inside Haswell

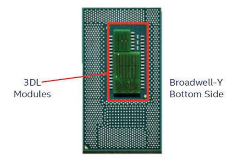


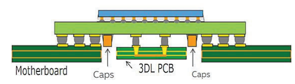


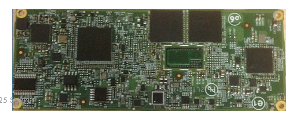

## Intel Broadwell

- Inductors moved to a small PCB



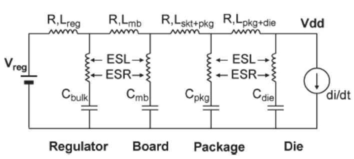



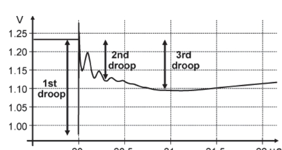





## Power Delivery

- Typical model




Wong, JSSC'06



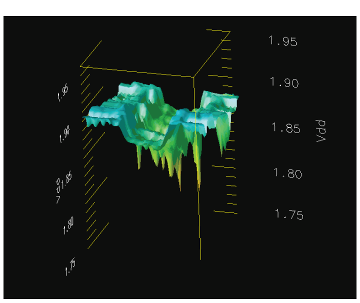
## Supply Resonances

- First droop
  - Package L + on-die C
- Second droop
  - Motherboard + package decoupling
- Third droop
  - Board capacitors



## What happens with supply?

http://www.research.ibm.com/people/r/restle/Animations/DAC01top.html

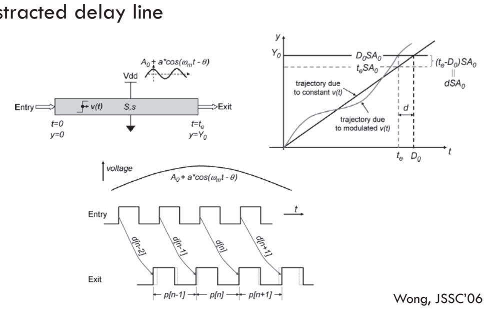





Phillip Restle, IBM

## How to model

- Abstracted delay line

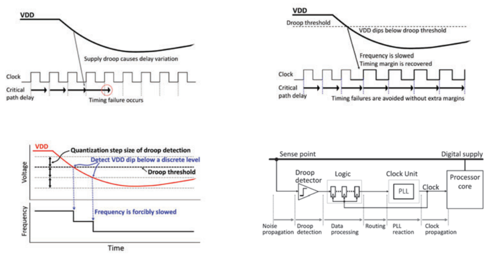



Wong, JSSC'06

Period modulation from successive modulated delays

## Droop Detection

- Hashimoto, JSSC 4/18






## This Class

- Put design choices in technology perspective
- The design constraints have changed and will be changing
  - Cost, energy, (power, leakage, …), performance
- Focused on variability, power-performance tradeoffs, power management
- Did not cover arithmetic, domino, I/O, supply generation, packaging, …



## This Field

- Moore's law will end sometime during your (my?) career
  - 5nm in 2020 scales to 0.1nm by 2050 with 2-yr cycles (or to 1nm with 4-yr cycles)
- Physics will stop CMOS somewhere ~3nm (?)
  - Will we see a different CMOS device in the meantime
- Economics will likely stop it somewhere while still in single digits
  - And the nodes will be stretched out
- We will see multi-chip/packaging solutions
- Don't worry: Creativity is unlimited!
  - What can you build with 10B/100B/1 trillion transistors?
  - Even filling 10B-transistor chips with SRAM is not trivial!

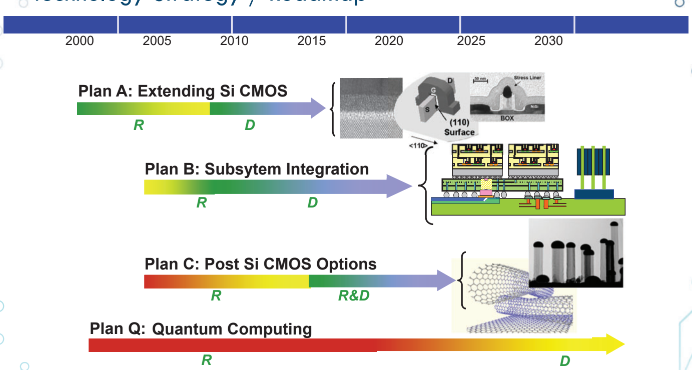


## This Field

- Focus on principles
- Watch out for opportunities
- Stay current!



## Technology Strategy / Roadmap




T.C. Chen, Where Si-CMOS is going: Trendy Hype vs. Real Technology, ISSCC'06