Supply Impedance and Voltage Conversion Requirements for CMOS Digital ICs

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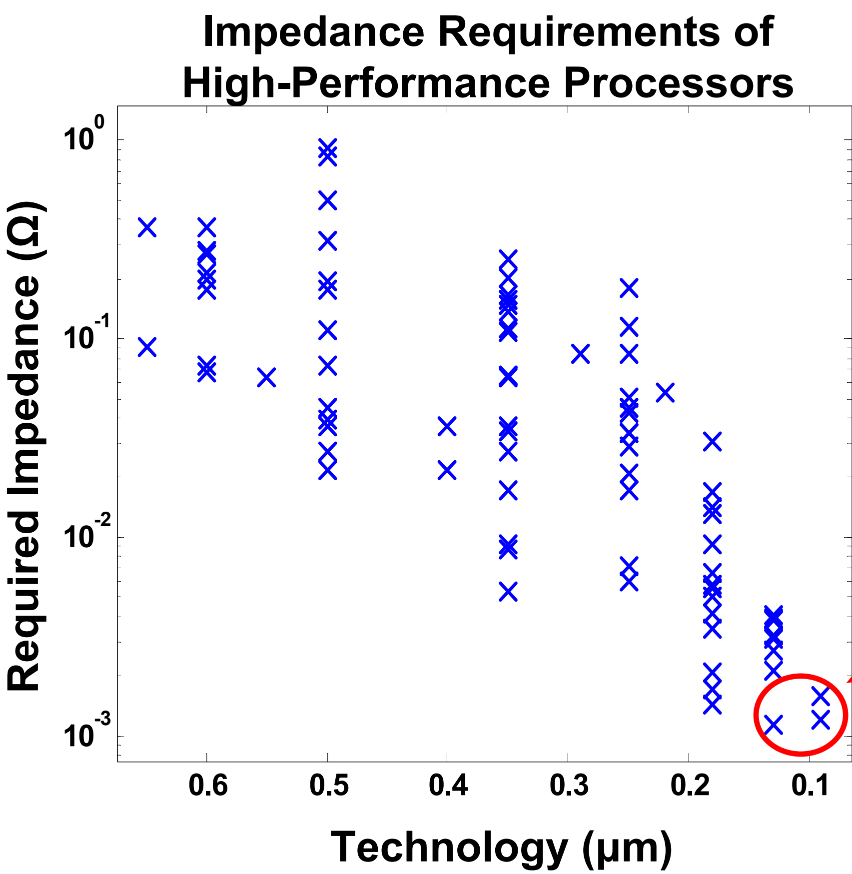
Scaling and Supply Impedance

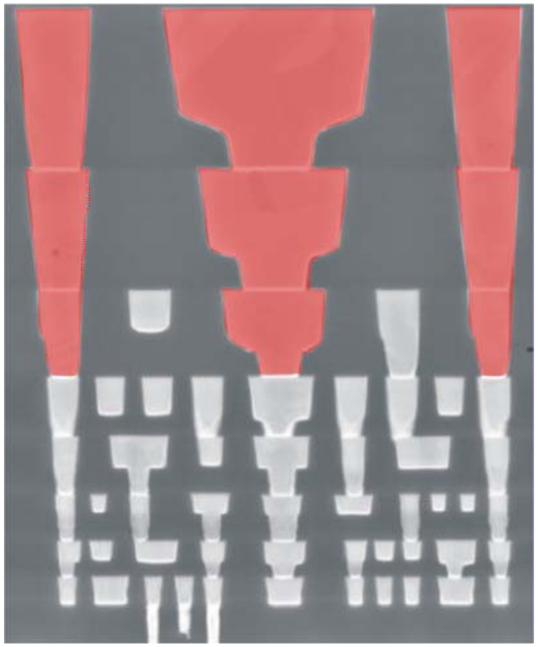
- **CMOS scaling led to lower supply voltages and constant (or increasing) power consumption**



- **This forces drastic drop in supply impedance**
  - **Even at constant power:**
  - $V_{dd} \downarrow, I_{dd} \uparrow \rightarrow |Z_{required}| \downarrow\downarrow$

- **Today's chips:**
  - $|Z_{required}| \approx$ **1 mΩ!**

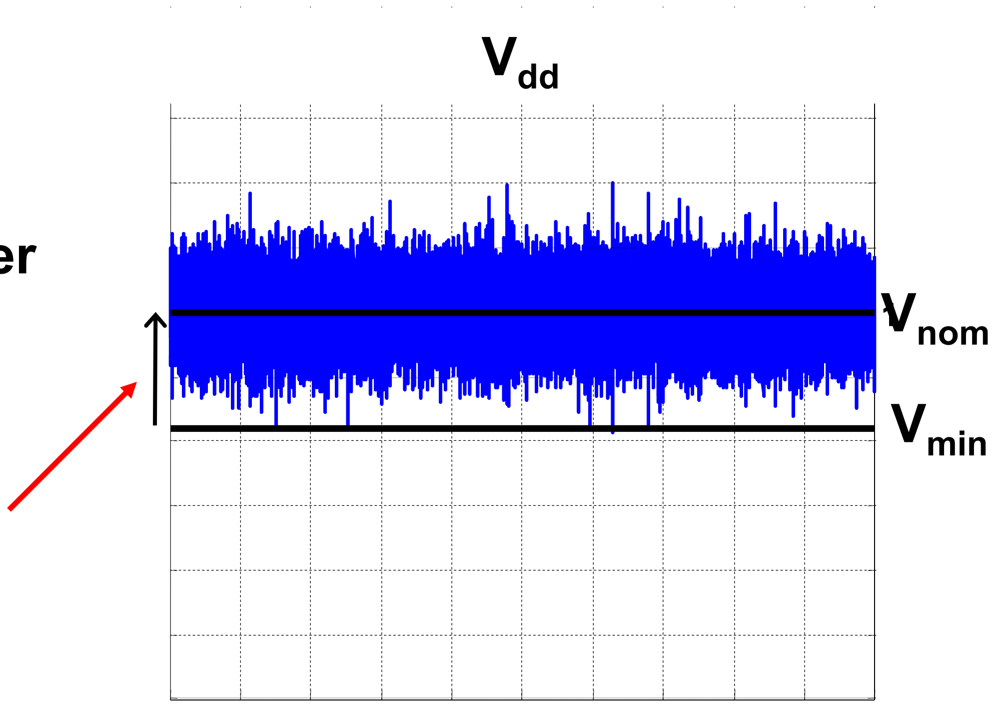
Power Distribution and Regulation



- Significant resources spent to meet impedance requirement
- Initial motivation for integrated DC-DC:
  - Relaxed package/PCB |Z|
  - Active linear regulation can be used to reduce on-chip |Z| too
- But, so far these regulators increased total power
  - Prevents adoption in today's power-limited chips

Power-Neutral Regulation

- Gate delay depends on V_{dd}:
  - So V_{dd} needs to be greater than some V_{min}
- Supply variations force higher nominal voltage
  - Causes extra power dissipation



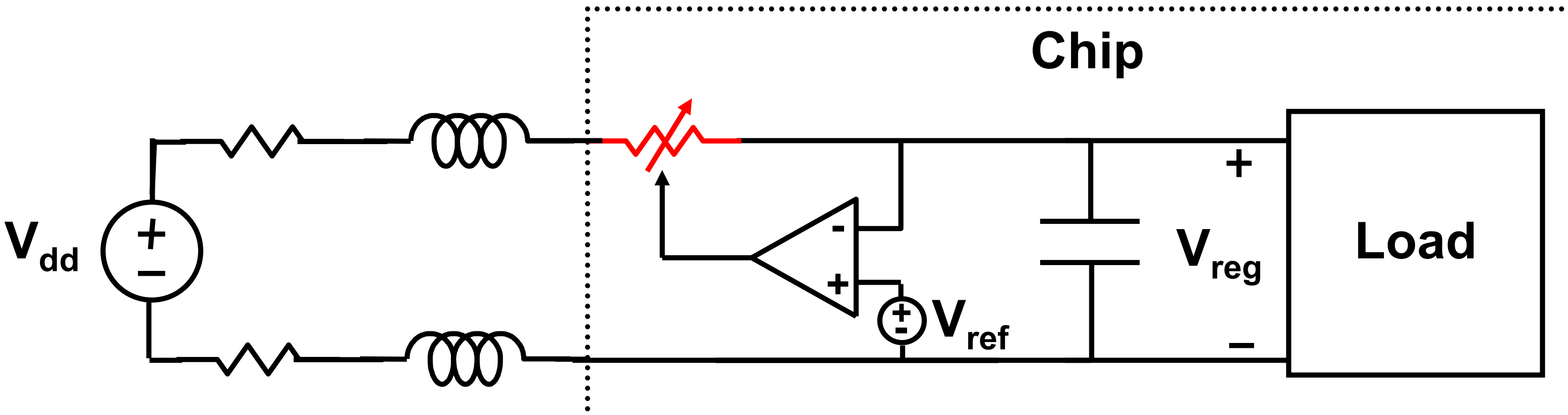
- Goal: Build regulator without negatively impacting chip power
  - Regulator power needs to be less than recovered power

Outline

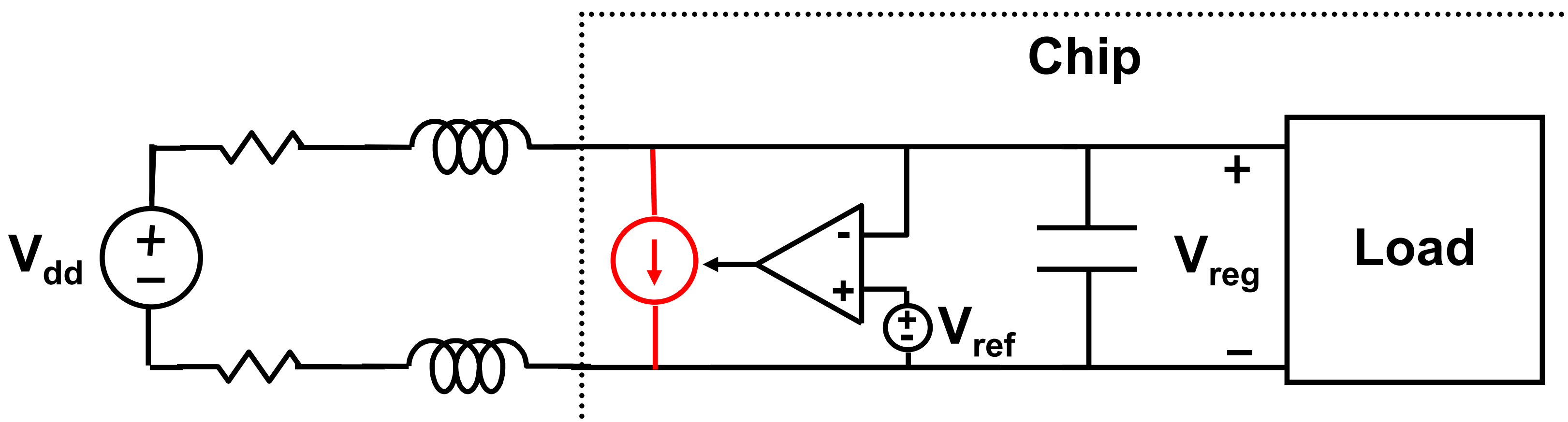
- Motivation
- Linear Regulation and Power Efficiency
- Implications on Integrated Converters
- Conclusions

Linear Regulators

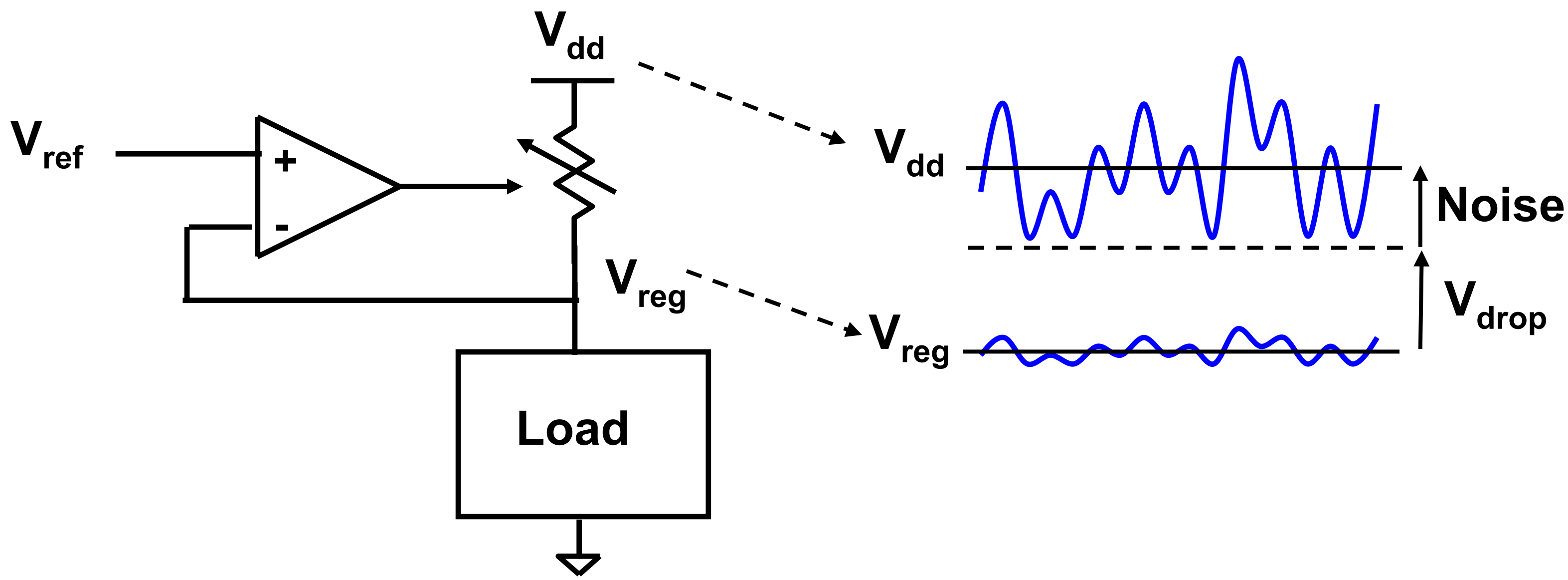
Series Regulator



Shunt (Parallel) Regulator

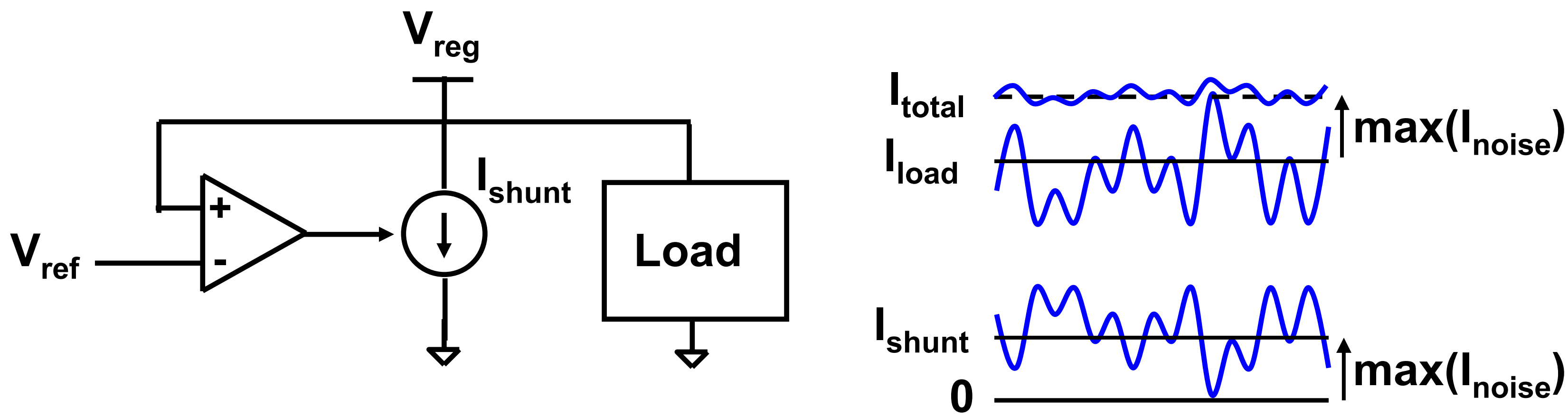


Improved Efficiency with Series Regulator?



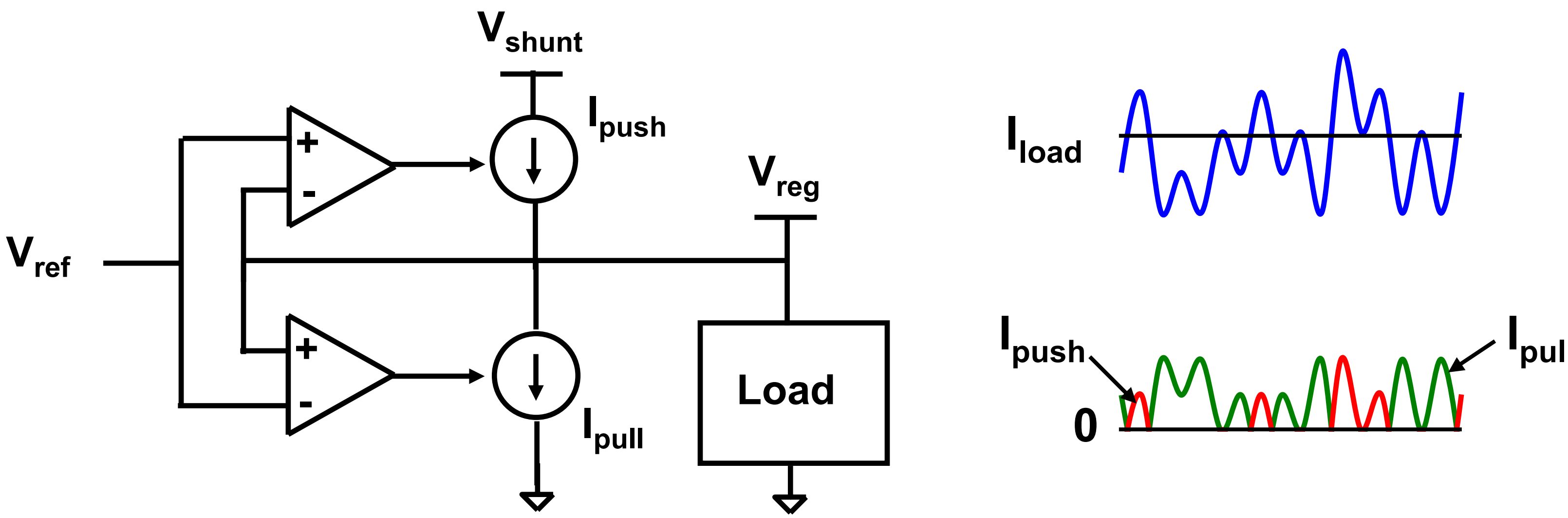
- **Clearly won't meet efficiency goal:**
  - **Regulator doesn't really change noise on V_{dd}**
  - **So still need same margin**
  - **But added an extra V_{drop} from variable resistor…**

Improved Efficiency with Shunt Regulator?



- Regulator can only pull current out of supply
  - To counter noise in both directions, need to burn significant static current
  - Again, clearly inefficient
- Need to allow shunt to deliver energy to the load
  - Not just dissipate it

Push-Pull Shunt Regulator



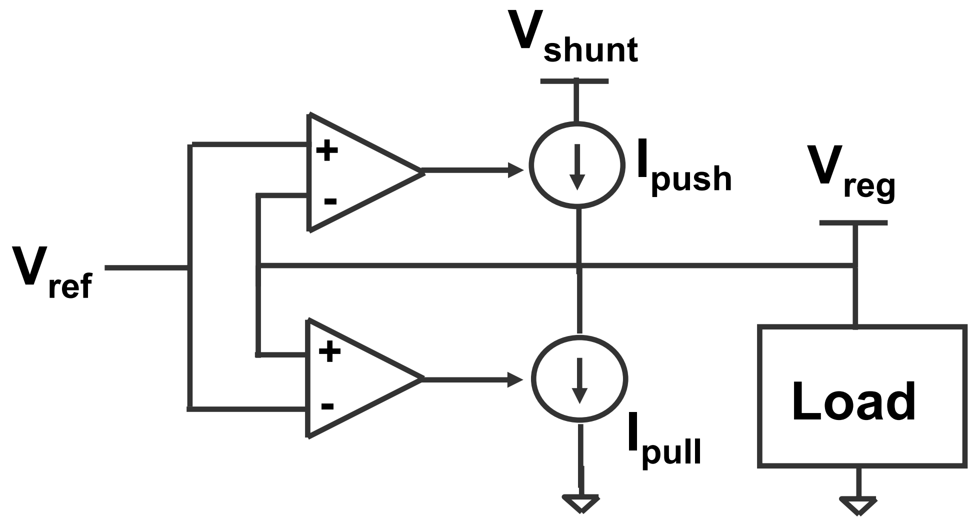
- Use extra "shunt" supply to push current into V_{reg}
  - Regulator capable of countering large variations
  - But regulator loss set mostly by (significantly smaller) <u>average</u> variation

- Similar to Active Clamp* for board VRMs
  - Build on previous work to improve on-die impedance

*A.M. Wu and S.R. Sanders, "An Active Clamp Circuit for Voltage Regulation Module (VRM) Applications," *Transactions on Power Electronics*. Sept. 2001.

Regulator Design Challenges

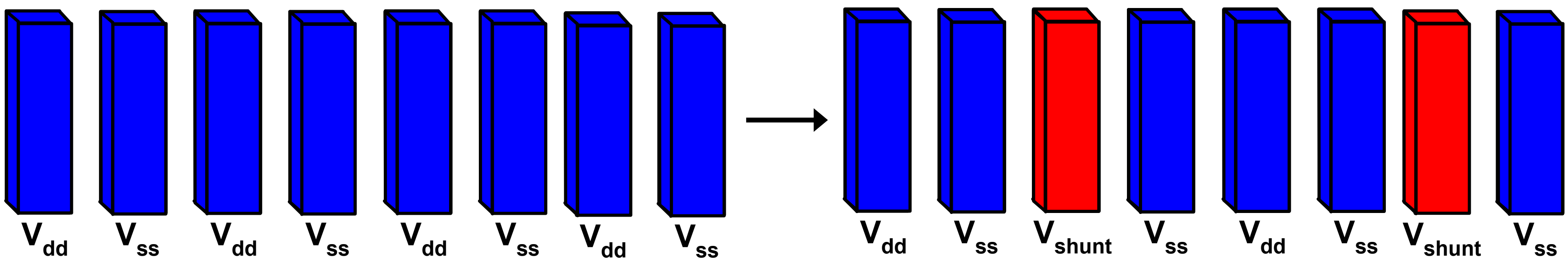
- V_{shunt} isn't free
  - Takes resources away from main supply
  - Increases loss



- Need to minimize quiescent output current
  - Otherwise regulator too inefficient

- Need GHz bandwidth feedback path
  - With minimum feedback circuit power

Allocating Resources for Shunt Supply



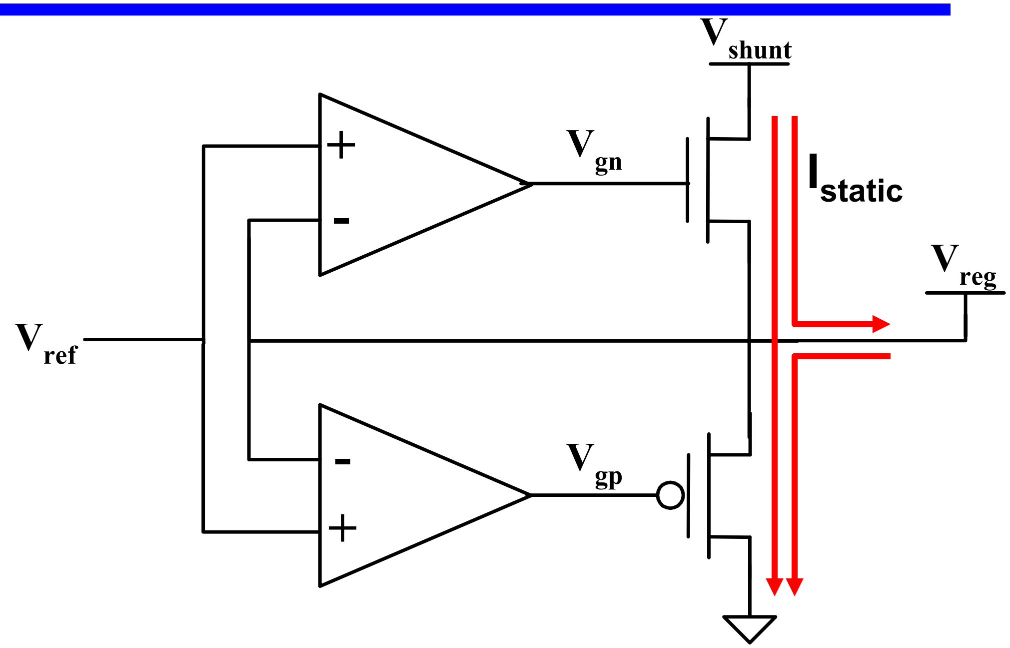
- Limited number of pins, metal lines for power
  - Need to allocate resources between main and shunt supplies
- For resistive losses:

$$p_{shunt} = \frac{\overline{I_{shunt}}}{\overline{I_{load}} + \overline{I_{shunt}}}, \quad p_{main} = \frac{\overline{I_{load}}}{\overline{I_{load}} + \overline{I_{shunt}}}$$

- If guarantee that V_{shunt} only handles transients
  - Resistive losses of main supply not really affected

Quiescent Output Current

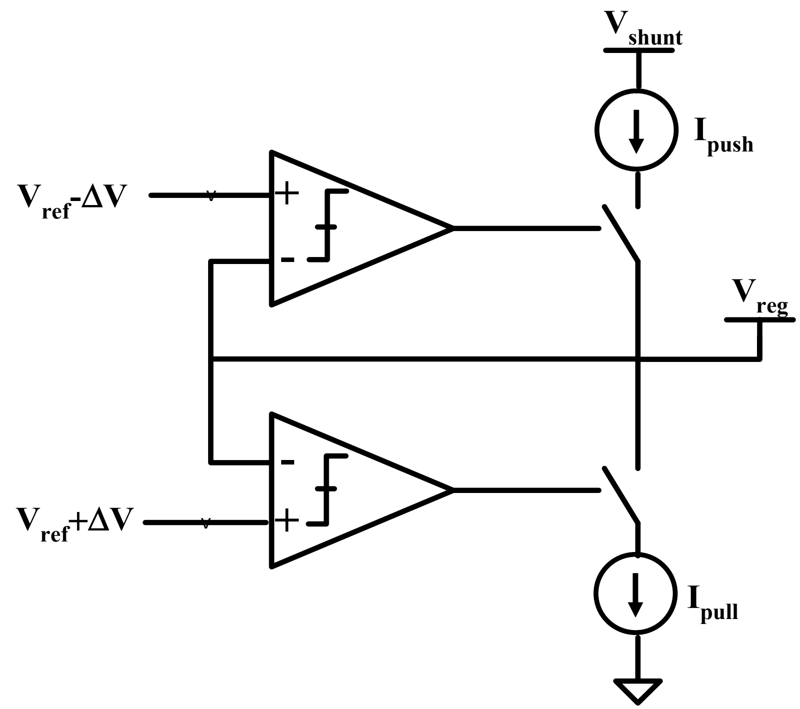
- Went to push-pull to minimize regulator power overhead
- But many designs have significant I_{static}



- Similar issues in RF and audio power amplifiers
  - In all cases, need to efficiently deliver energy based on a (small) input signal
- Build on PA knowledge to achieve high efficiency:
  - Non-linearly switch the output power devices

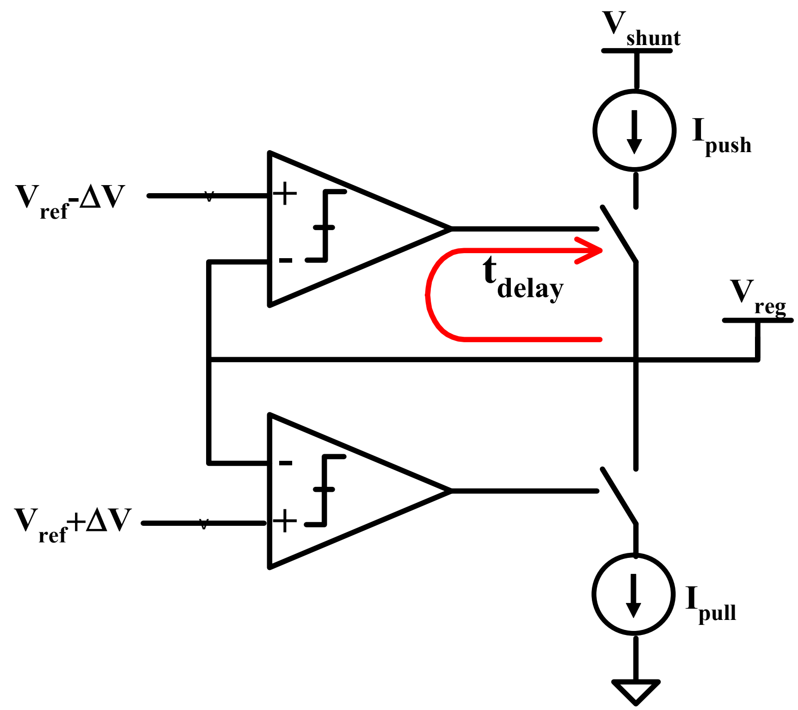
Switched-Output Regulator: Comparator Feedback with Dead-Band

- Convert small signal on V_{reg} into full-swing to drive switch
  - Use comparators in feedback path
- To avoid limit cycle:
  - Offset thresholds to create dead-band



Feedback Delay

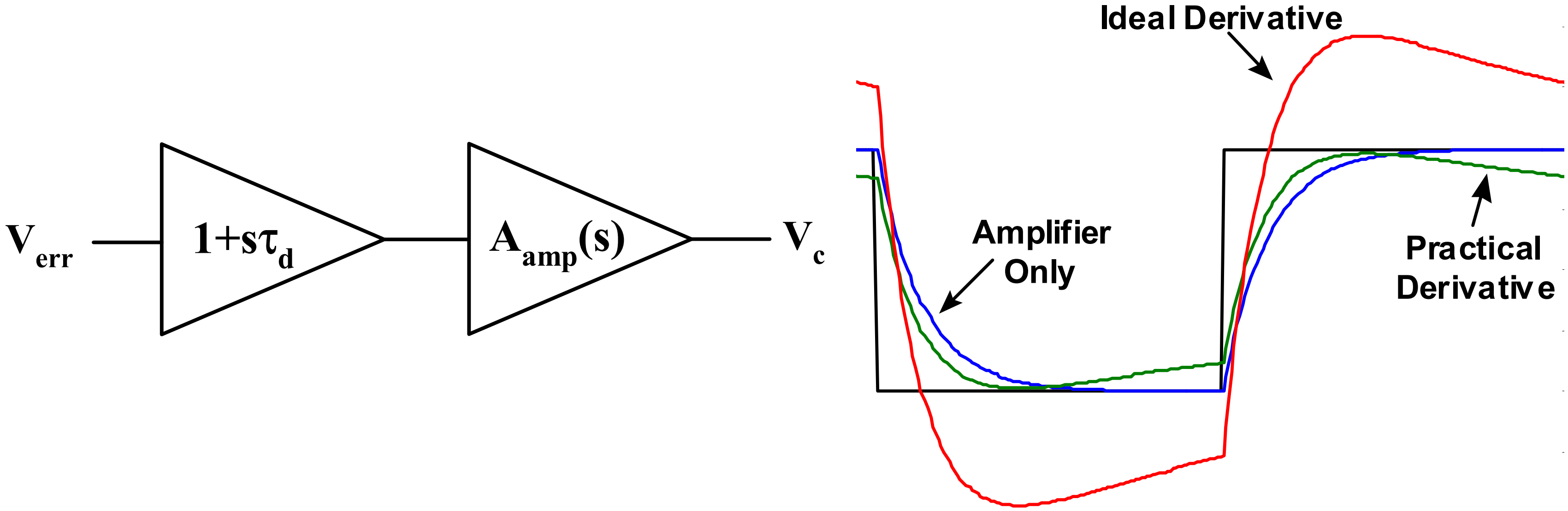
- For optimal response to noise at output, feedback bandwidth is critical



- For non-linear loop, this translates into low t_{delay}

- Can we exploit comparator's properties to improve effective delay?

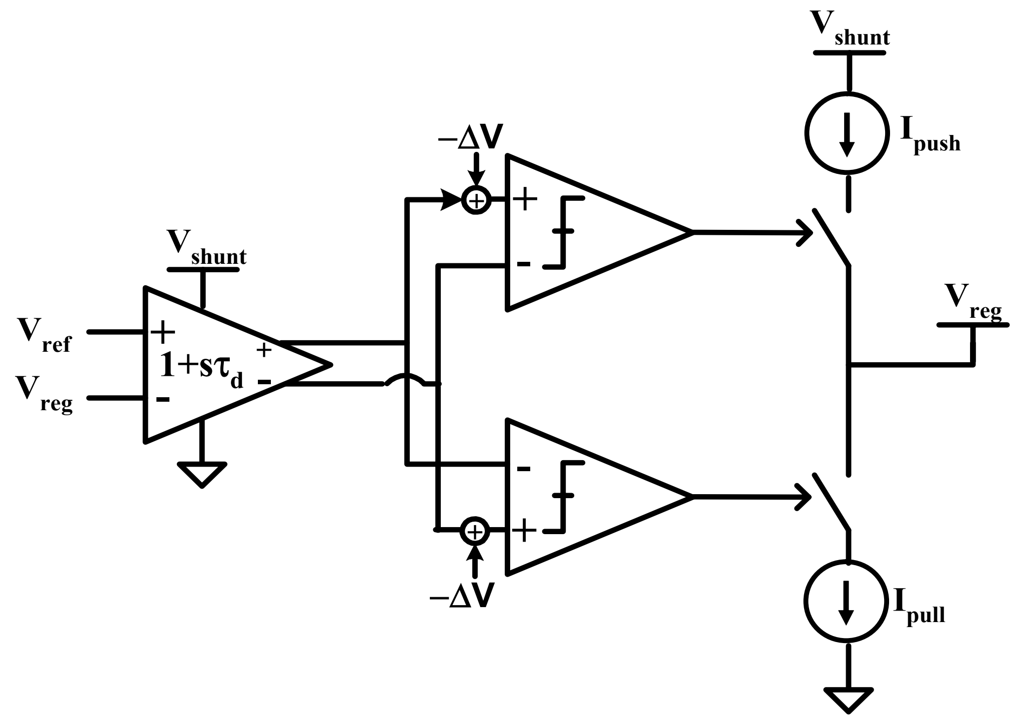
Linear Loop with Derivative Control



- **Addition of $s\tau_d$ to input cancels some of the phase shift from limited amplifier bandwidth**
- **But, implementing derivative behavior (without inductors) requires reduction of DC gain**
  - **Limits usefulness in a linear loop**

Derivative Feedback with Comparators

- **As long as comparators swing full-rail**
  - **Only shape of TF in front of comparators matters**
  - **"Gain" is restored by the comparators**

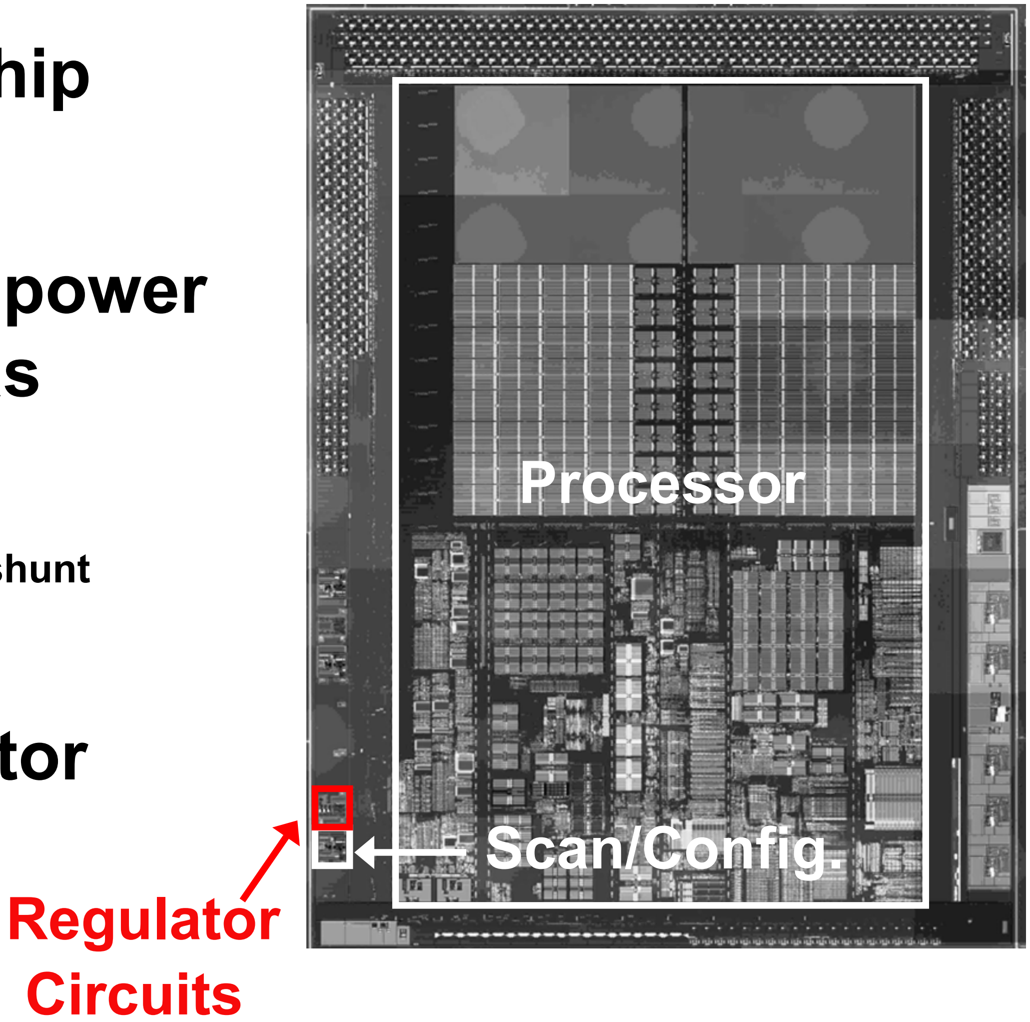


- **Net effect of derivative: reduces impact of t_{delay}**

- **Similar to sliding mode control**
  - **But region of sliding behavior is small**

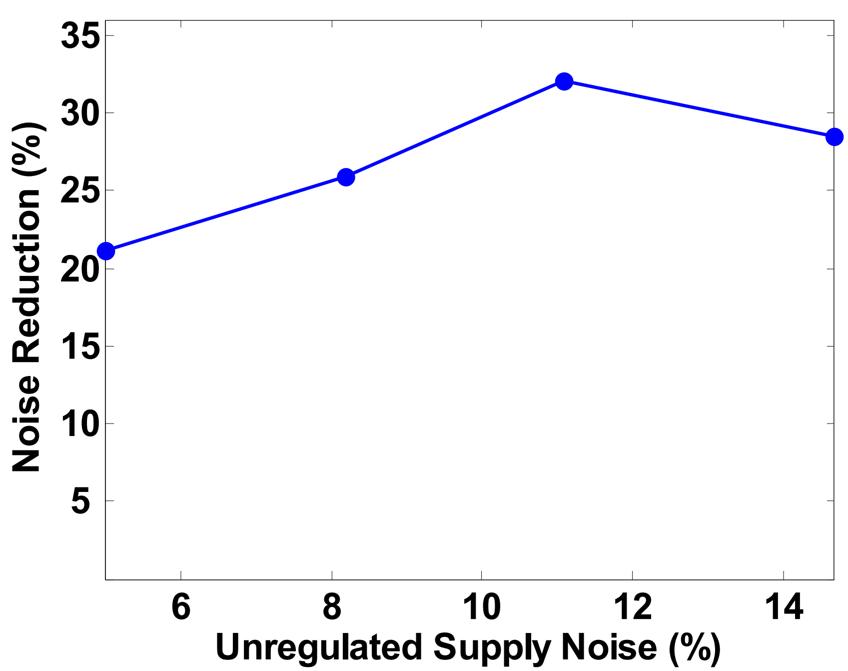
Test-Chip Details

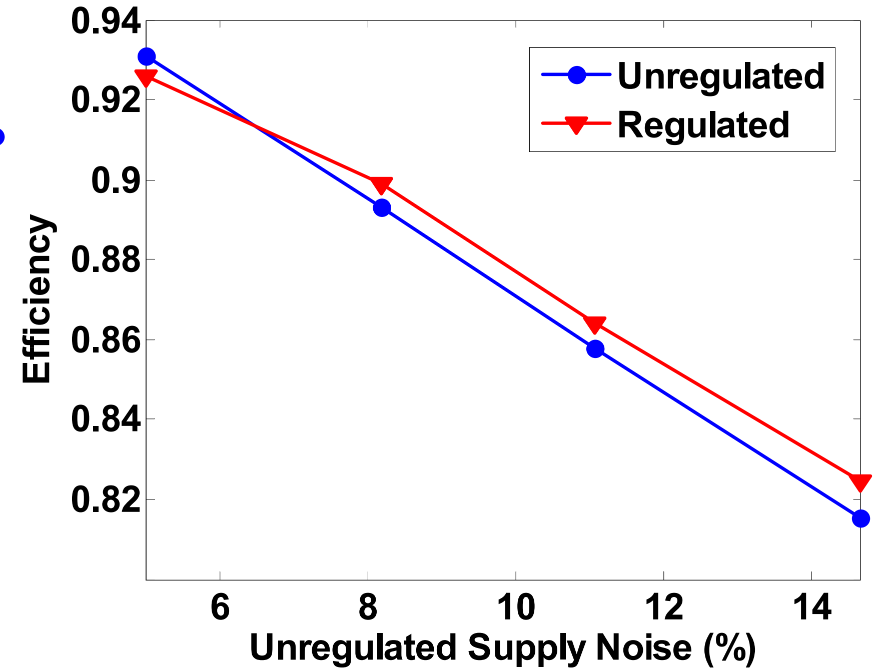
- **65nm SOI AMD test-chip**
- **Regulator uses same power distribution scheme as processor**
  - **With reallocation for V_{shunt}**
- **On-chip noise generator and perf. monitor for testing**



E. Alon and M. Horowitz, "Integrated Regulation for Energy-Efficient Digital Circuits," ***IEEE Journal of Solid-State Circuit*****, Aug. 2008.**

Measured Results

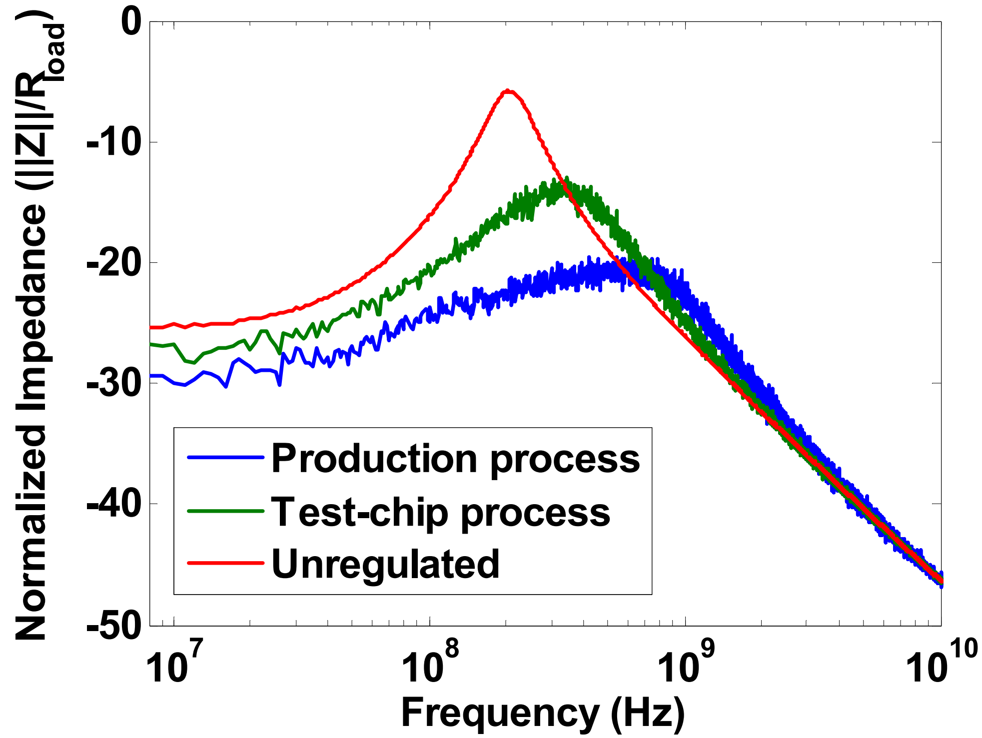




- **Regulator reduces broadband noise by ~30%**
- **Total power dissipation actually reduced by up to ~1.4%**

Impedance with Faster Process

- **Process was in development**
  - **Low device f_t**
- **Measurement matches simulation with slower devices**



- **Expect to reach ~50% noise and ~4% power reduction in production process with higher f_t**

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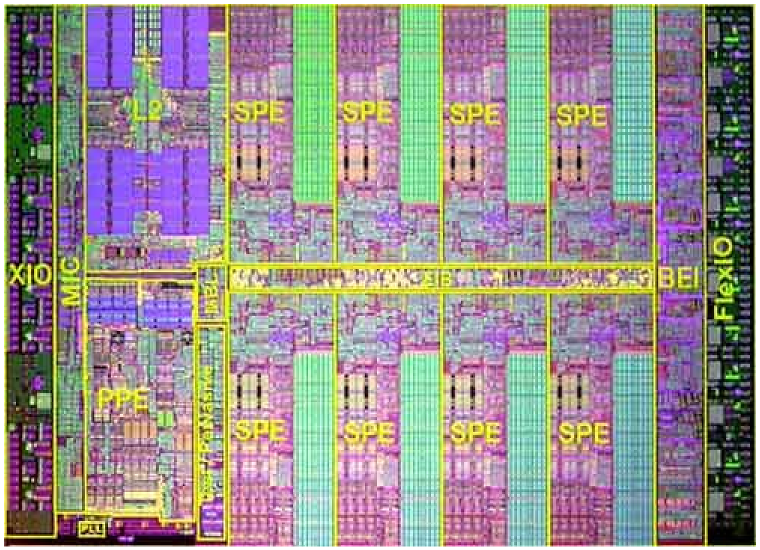
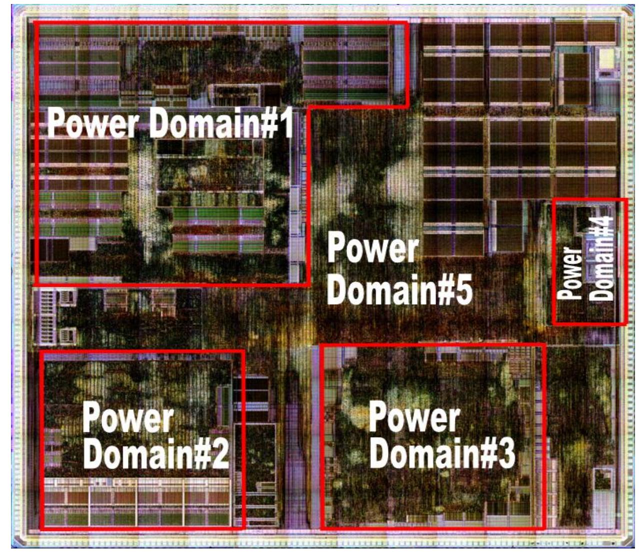
Need for Local Power Supplies

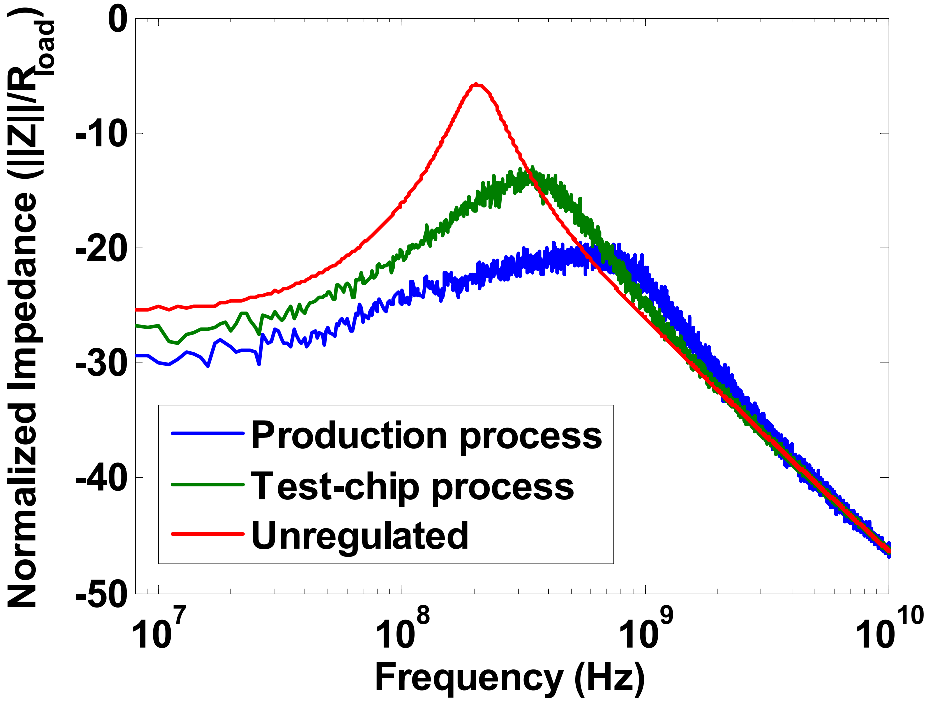


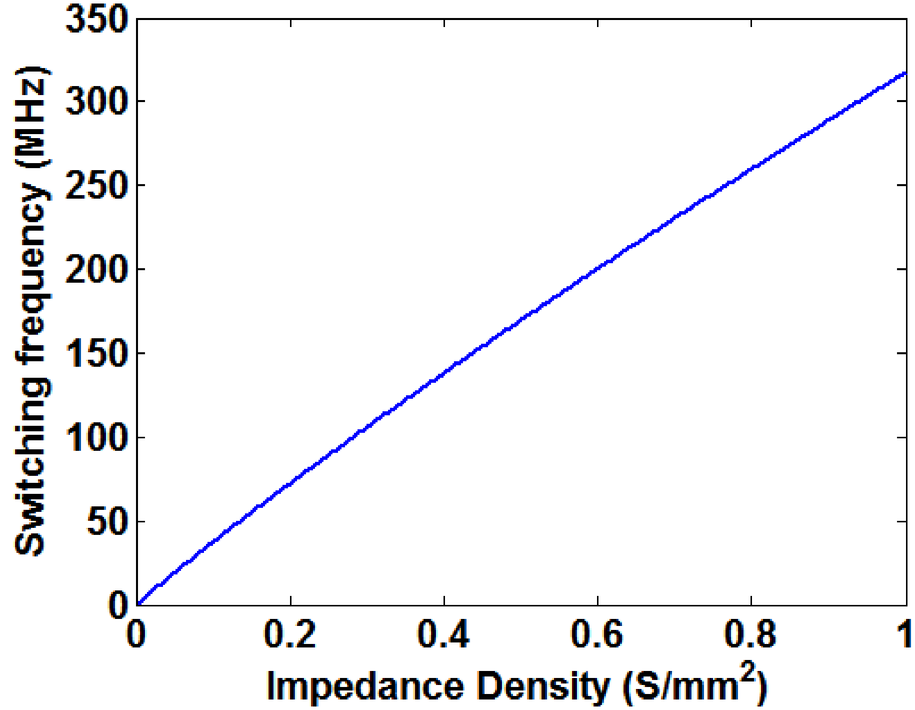


- **Clear need for many, local supply voltages**
  - **Per core supply, dynamic voltage supplies for SRAM, etc.**

- **But, can't sacrifice supply impedance**
  - **Makes external DC-DC conversion difficult (split planes)**

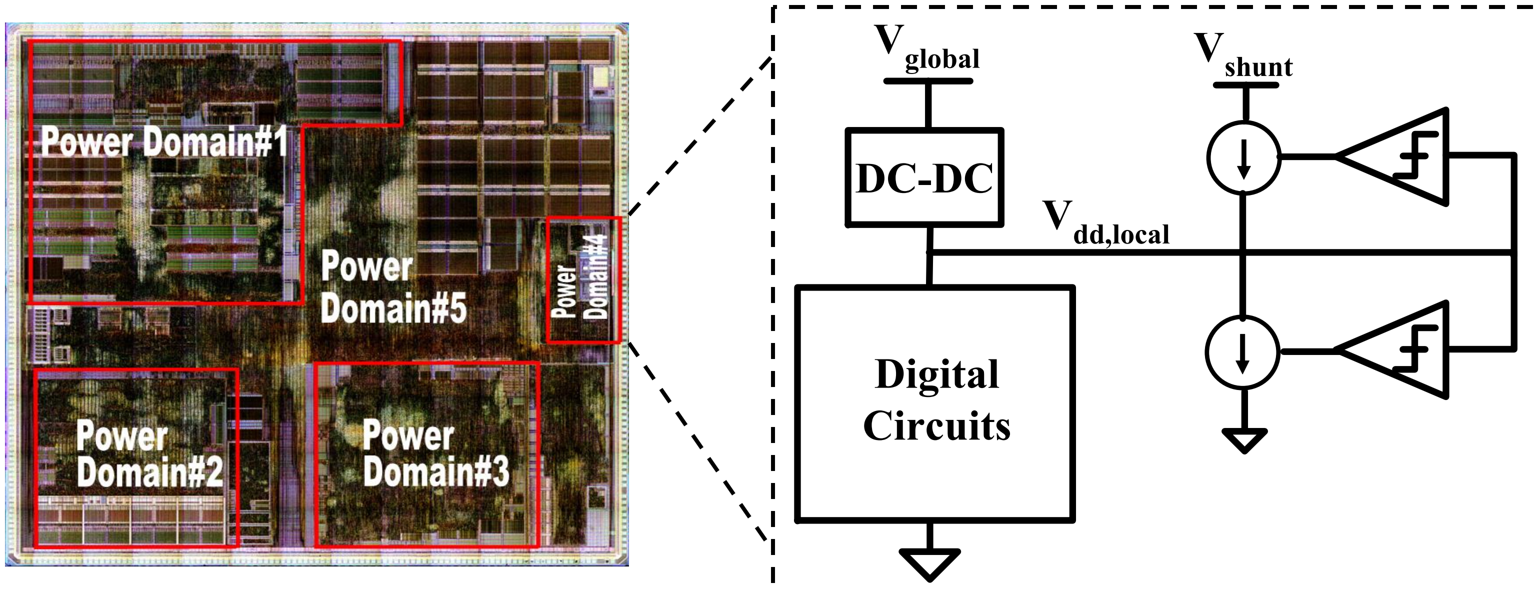
Converter Impedance and Efficiency





- Supply noise very broadband…
  - Significant noise content up to ~1GHz
- Operate integrated switching converter at ~2GHz?
  - Inefficient and impractical…

Proposed Power Delivery Architecture



- Split delivery of DC power from AC impedance
  - DC-DC creates local supply
  - Parallel regulator handles transients (maintains V_{min})

- Key question becomes conversion efficiency of integrated DC-DC

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Conclusions

- **Supply impedance is a key consideration in chip power delivery**

- **Digital circuits care about V_{min}**
  - **Can leverage this to build power-neutral linear regulator**
  - **Measured 30% noise reduction and actually improved power by ~1.4%**

- **Leverage efficient delivery of low impedance for integrated converters**
  - **Low dynamic impedance and high efficiency hard to attain simultaneously**