### Link Surroundings

- Links integrated onto 1V, 100A processors
  - Required $|Z_{\text{supply}}| < 1 \text{ m}\Omega$ for ~100mV supply noise
- Link supply (ground) often shared...

![90nm Itanium Processor Core](image)

**Measured Supply Noise**

### Series Regulator Requirements

- Low drop-out voltage
  - Efficiency $\leq \frac{V_{\text{reg}}}{V_{\text{dd}}}$
  - Need to budget for $V_{\text{dd}}$ droops too
- High PSRR across a broad range of frequencies
  - Intrinsic supply rejection of load (e.g., ring oscillator) may be very low

### On-Chip Regulation

- Many links regulate supplies of critical blocks
- Good/bad regulator design can make or break the link

### Regulator Types

- Switching vs. linear
  - (“Easy” vs. “Not easy” to integrate)
- Linear: series vs. shunt
  - (Isolation vs. impedance)
Compensation Techniques

- How do these two techniques achieve stability?
- What are the implications of that on PSRR?

Miller Compensation

RC Compensation

Dominant Pole: Amplifier vs. Output

Optimizing Regulator PSRR

- For fixed amplifier GBW, find “best” PSRR by trading between gain and bandwidth
- Define PSRR as inverse of max. sensitivity
- Similar results if minimize $\sigma_{\text{Vref}}/\sigma_{\text{Vout}}$ with white noise on $V_{\text{dd}}$

Small Signal Model for Supply Noise

Optimal Amplifier Design

- For clarity, normalize amplifier gain and bandwidth:
  - Amplifier bandwidth relative to output pole: $\omega_a = \kappa \cdot \omega_o$
  - Normalized gain-bandwidth: $\text{GBW} = \kappa \cdot A_a$
- If open loop gain $(A_aA_o) > 1$, optimal allocation is:
  $$\kappa = \sqrt{\frac{1}{2}} A_a \cdot \text{GBW}$$
  $$A_a = \sqrt{\frac{1}{2}} \text{GBW}/A_a$$
What This Really Means

Implications

• With optimal allocation:
  \[ \text{PSRR} \propto \frac{1}{\sqrt{A_g \cdot \text{GBW}}} \]

• To improve PSRR by 2x, both amplifier gain and bandwidth increase by 2x

• In other words, required gain-bandwidth scales with \( \text{PSRR}^2 \)
  • Tradeoff steep – any way to improve?

Towards an Improved Solution

• With \( \omega_o = 2\pi \cdot 100\text{MHz} \) and \( A_o = 3 \)

<table>
<thead>
<tr>
<th>GBW</th>
<th>( \omega_o )</th>
<th>( A_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (100MHz)</td>
<td>2\pi·212MHz</td>
<td>0.47</td>
</tr>
<tr>
<td>10 (1GHz)</td>
<td>2\pi·670MHz</td>
<td>1.49</td>
</tr>
<tr>
<td>100 (10GHz)</td>
<td>2\pi·2.1GHz</td>
<td>4.71</td>
</tr>
</tbody>
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• “Amplifier” in many cases is just acting like a (high-bandwidth) wire...

Source-Follower-Based Regulator

“Practical” Issue #1
Practical Issue #2

Common-Source Has Issues Too...

Typical Design

Local Negative Feedback

- Local feedback efficiently trades gain for bandwidth
- Next lecture: use local f/b to drastically improve PSRR...