# Improving Error-Resilience of Emerging Multi-Value Technologies

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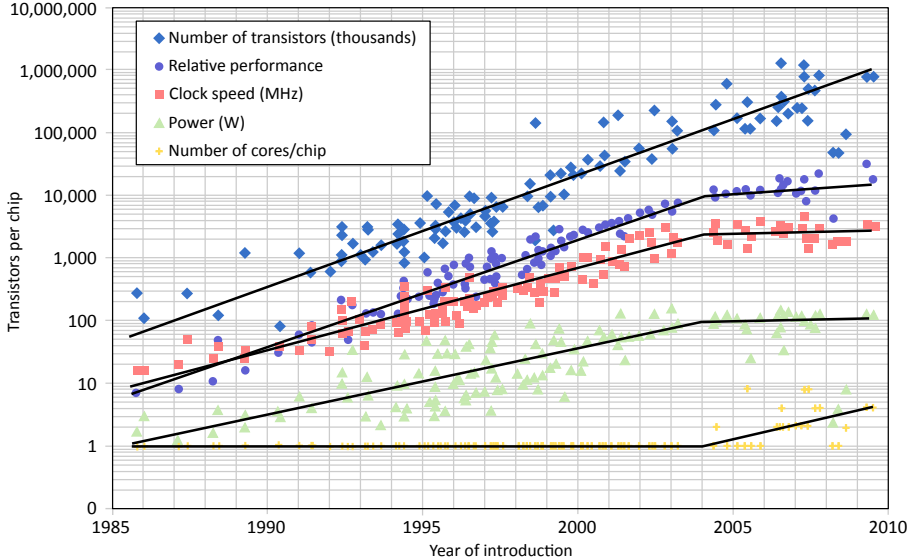
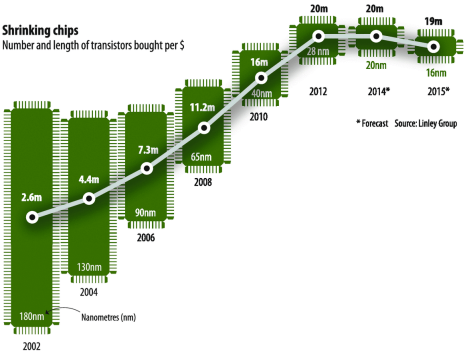
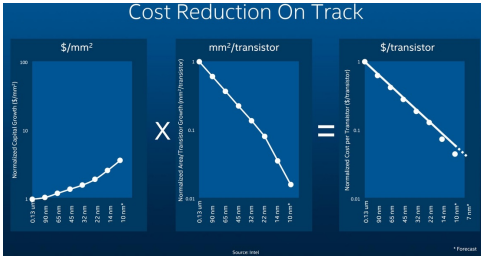
# Moore's Law Struggling with CMOS




[1] National Research Council, "The Future of Computing Performance: Game Over or Next Level?", 2011.

# Moore's Law

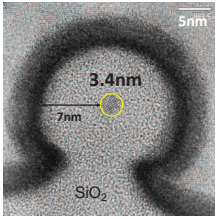


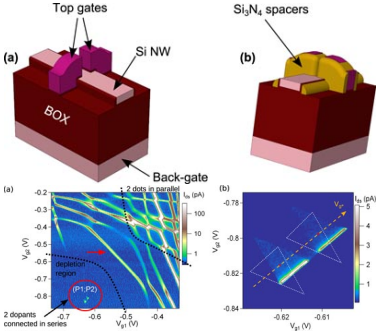



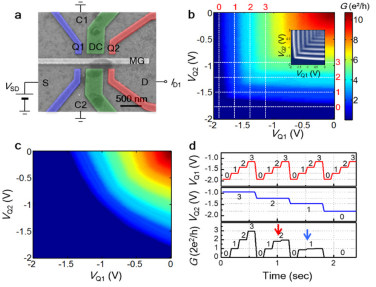

[1] The economist, "A golden rule of microchips appears to be coming to an end", Nov. 18, 2013.

[2] Vivek Singh, Intel, "Moore's Law at 50: No End in Sight", DAC 2015 keynote.

# Emerging Technologies to the Rescue?



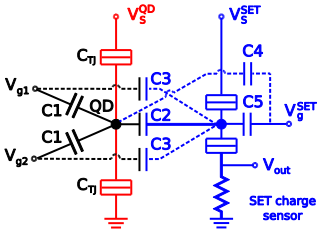



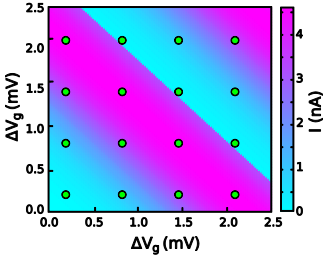

[1] R. Lavieville et al., "350K Operating Silicon Nanowire Single Electron/Hole Transistors Scaled Down to 3.4nm Diameter and 10nm Gate Length" EUROSOI-ULIS, Jan., 2015.

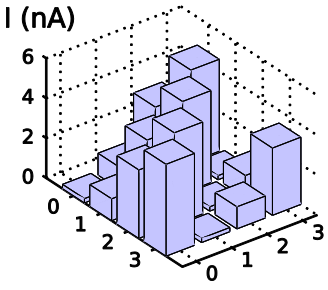
[2] X. Jehl et al., "The coupled atom transistor" Journal of Physics: Condensed Matter, 2015.

[3] M. Seo et al., "Multi-valued logic gates based on ballistic transport in quantum point contacts" Scientific Reports, 4, 2014.

# Quantum Dot SET Half Adder

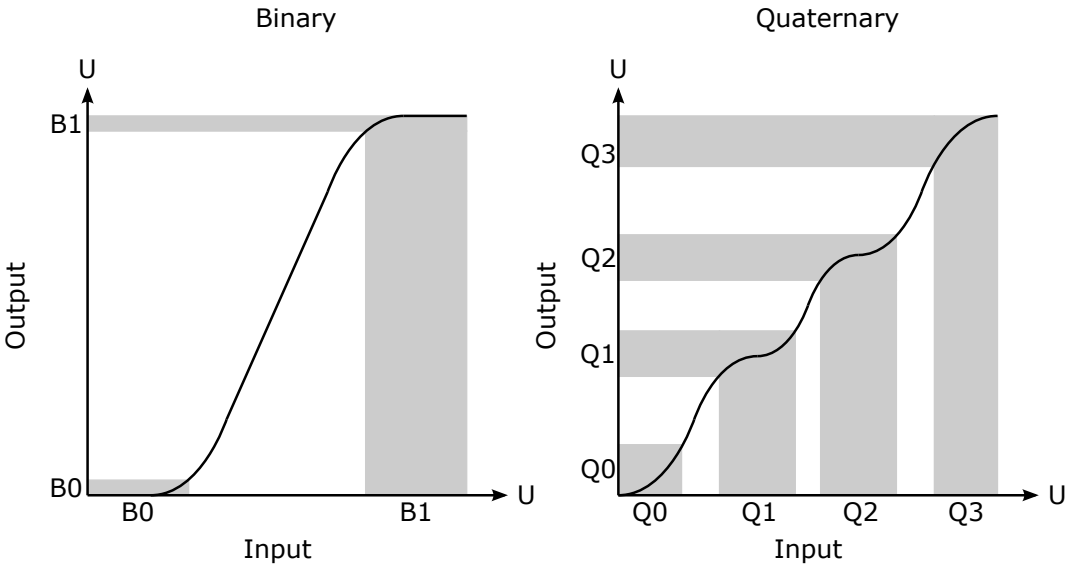



[1] M.V. Klymenko and F. Remacle, University of Liège.

# Multi-Valued Logic



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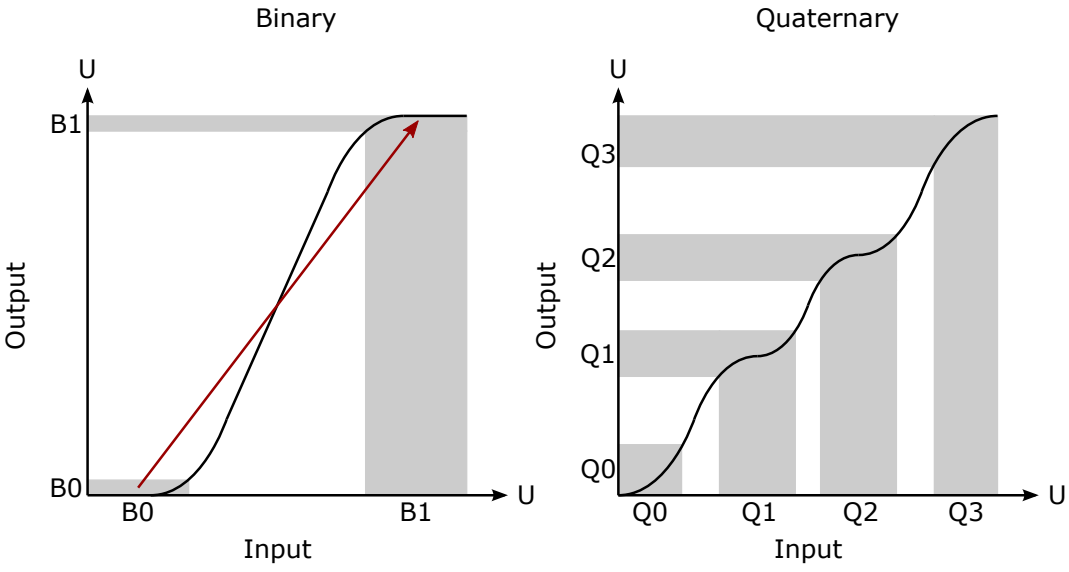

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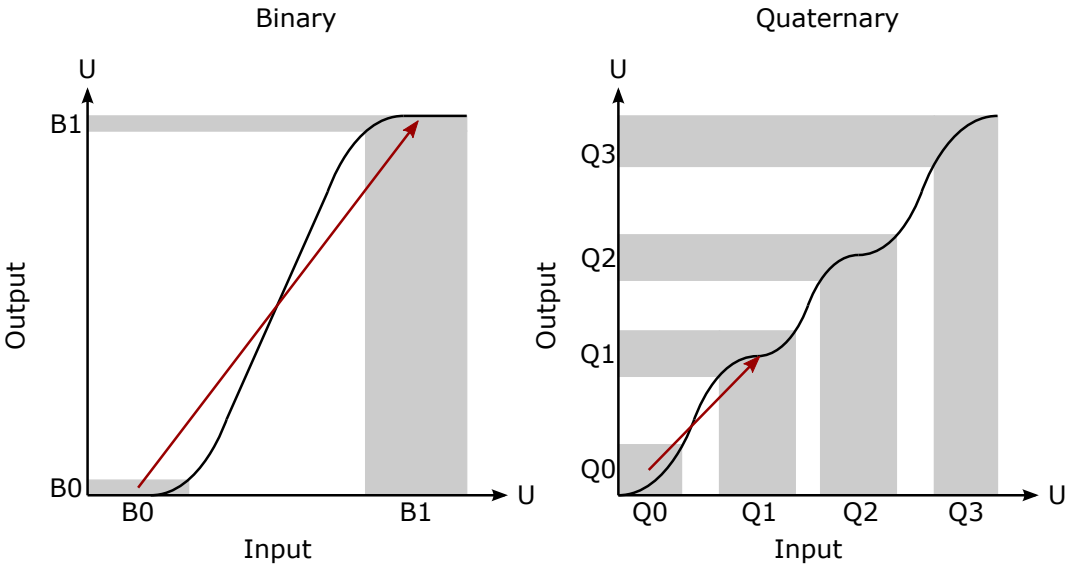

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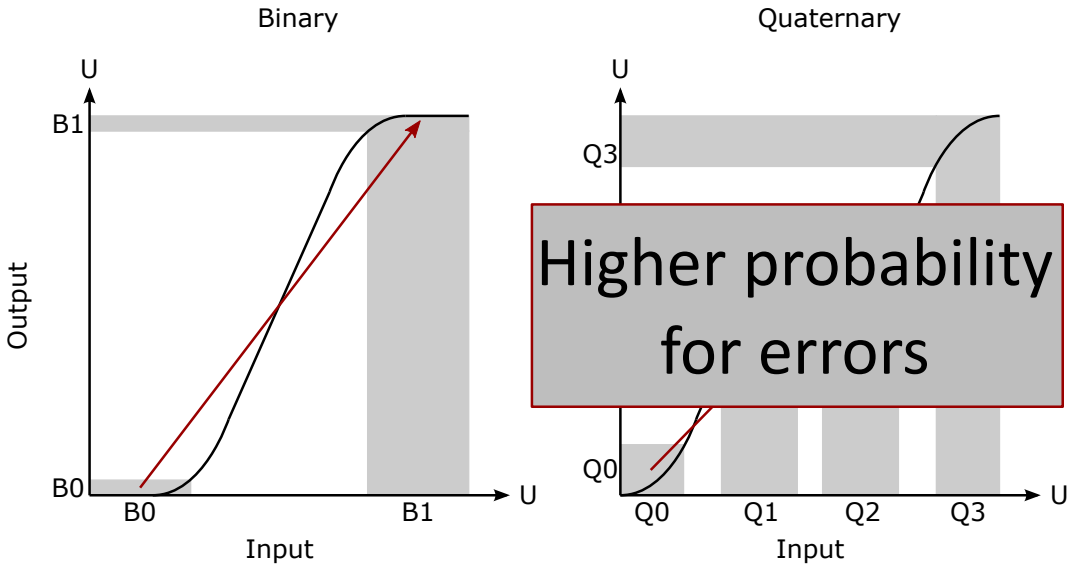

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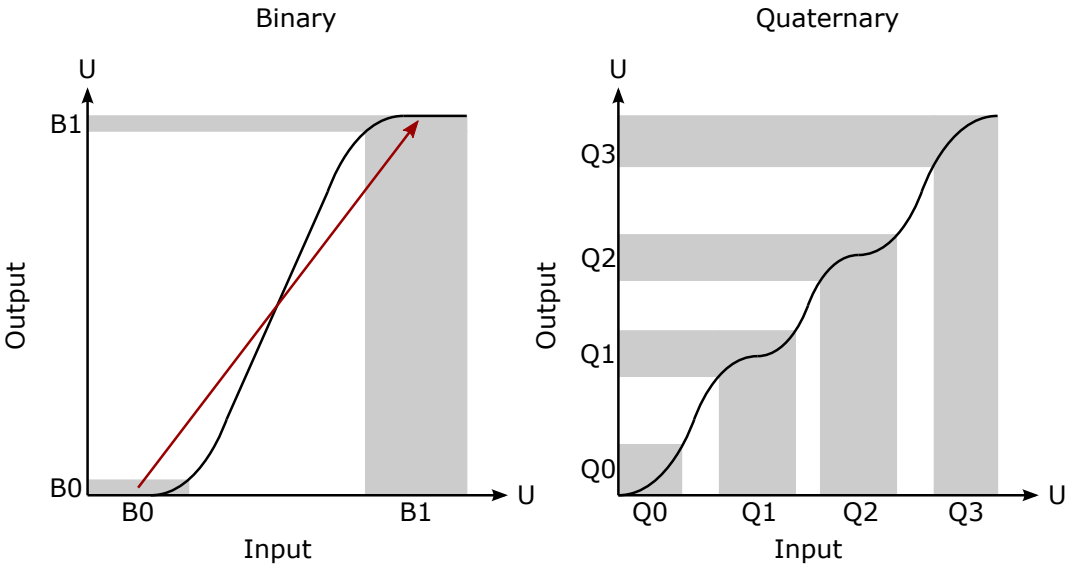

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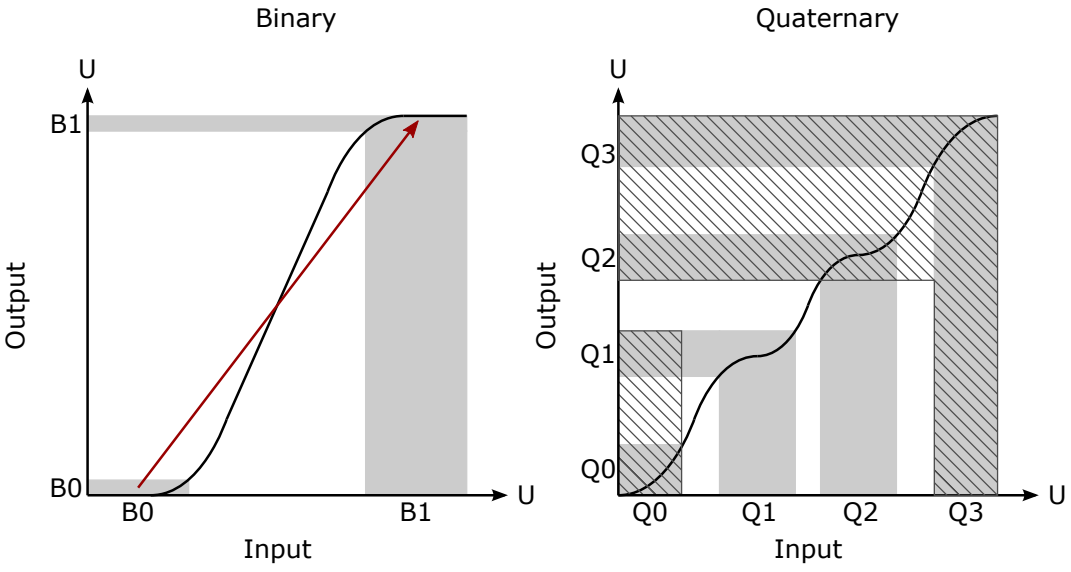

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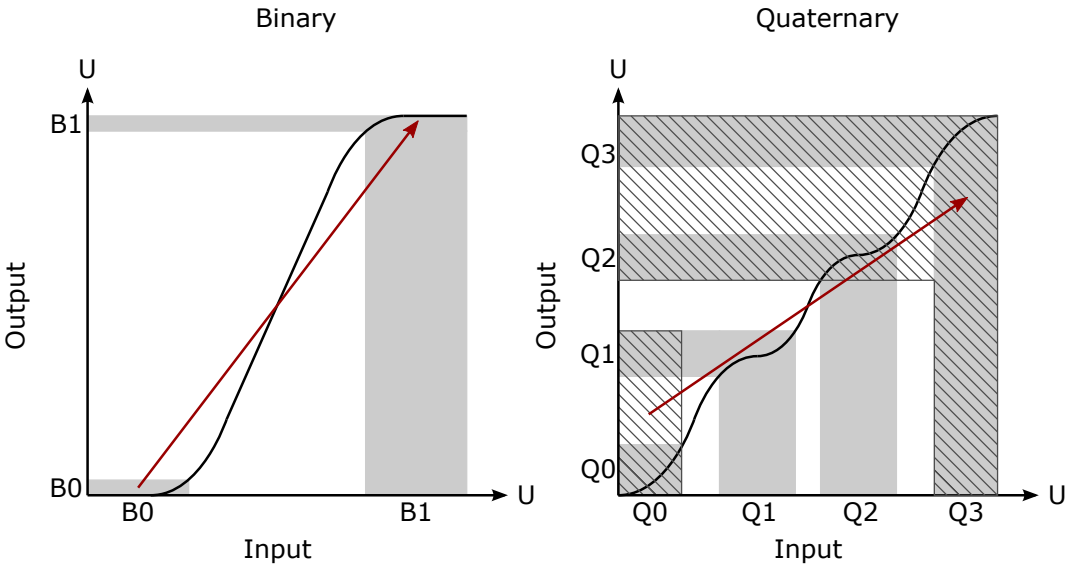

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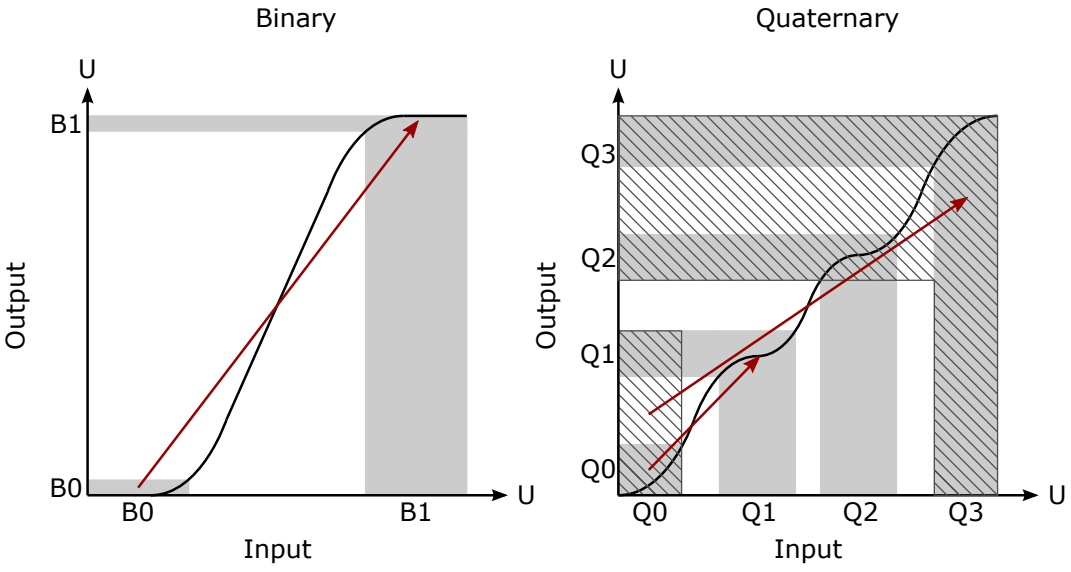

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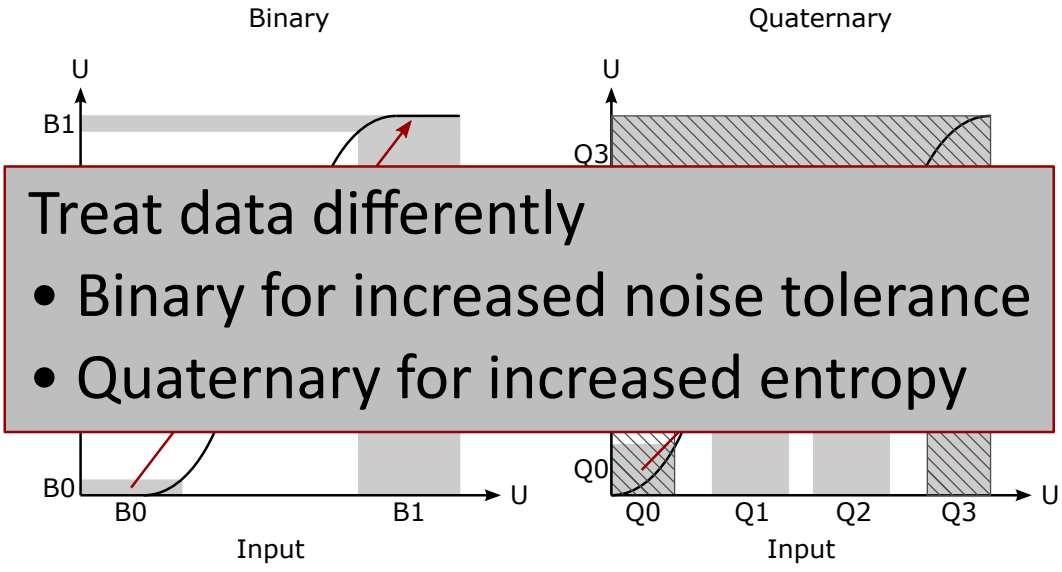



Treat data differently

- Binary for increased noise tolerance
- Quaternary for increased entropy

# Dual-Mode Gates

OR

| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 1 | 2 | 3 |
| 1 | 1 | 1 | 3 | 3 |
| 2 | 2 | 3 | 2 | 3 |
| 3 | 3 | 3 | 3 | 3 |

AND

| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 1 | 0 | 1 |
| 2 | 0 | 0 | 2 | 2 |
| 3 | 0 | 1 | 2 | 3 |

XOR

| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 1 | 2 | 3 |
| 1 | 1 | 0 | 3 | 2 |
| 2 | 2 | 3 | 0 | 1 |
| 3 | 3 | 2 | 1 | 0 |

MAX

| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 1 | 2 | 3 |
| 1 | 1 | 1 | 2 | 3 |
| 2 | 2 | 2 | 2 | 3 |
| 3 | 3 | 3 | 3 | 3 |

MIN

| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 1 | 1 | 1 |
| 2 | 0 | 1 | 2 | 2 |
| 3 | 0 | 1 | 2 | 3 |

INV

| A | $\overline{A}$ |
|---|---|
| 0 | 3 |
| 1 | 2 |
| 2 | 1 |
| 3 | 0 |

# Dual-Mode Adder?

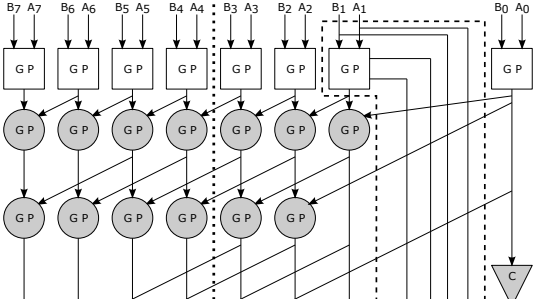
HA

| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 1 | 2 | 3 |
| 1 | 1 | 2 | 3 | 0 |
| 2 | 2 | 3 | 0 | 1 |
| 3 | 3 | 0 | 1 | 2 |

FA (carry=1)

| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 0 |
| 1 | 2 | 3 | 0 | 1 |
| 2 | 3 | 0 | 1 | 2 |
| 3 | 0 | 1 | 2 | 3 |

# Carry-Lookahead Adder



# Dual-Mode Adder

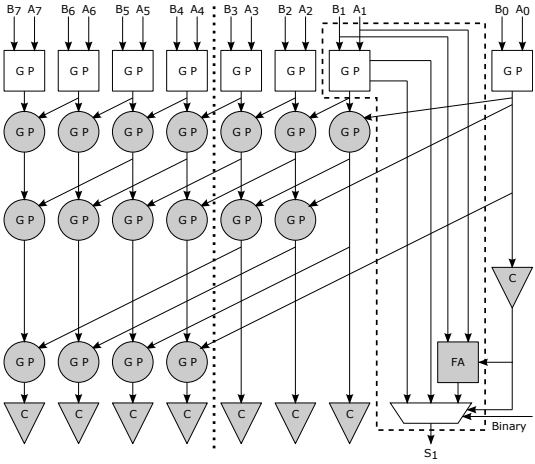
HA

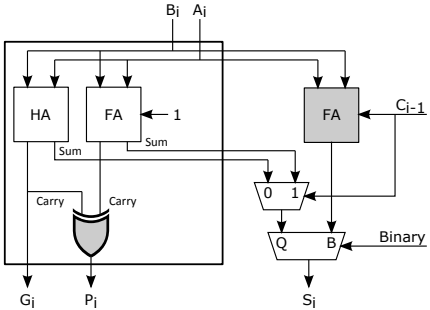
| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 1 |
| 2 | 0 | 0 | 1 | 1 |
| 3 | 0 | 1 | 1 | 1 |

FA (carry=1)

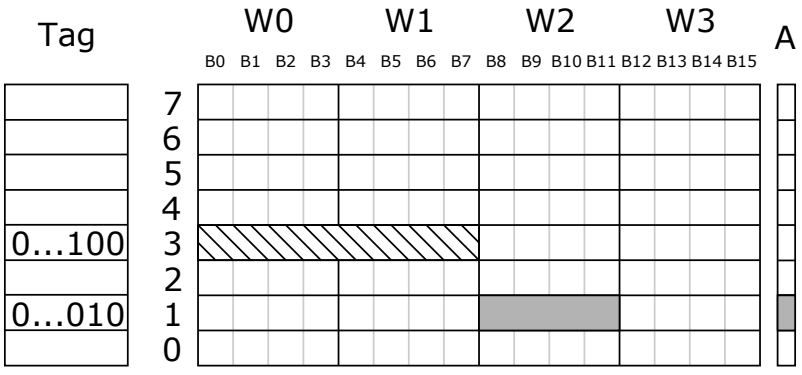
| B \ A | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 |
| 1 | 0 | 0 | 1 | 1 |
| 2 | 0 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 |

# Carry-Lookahead Adder



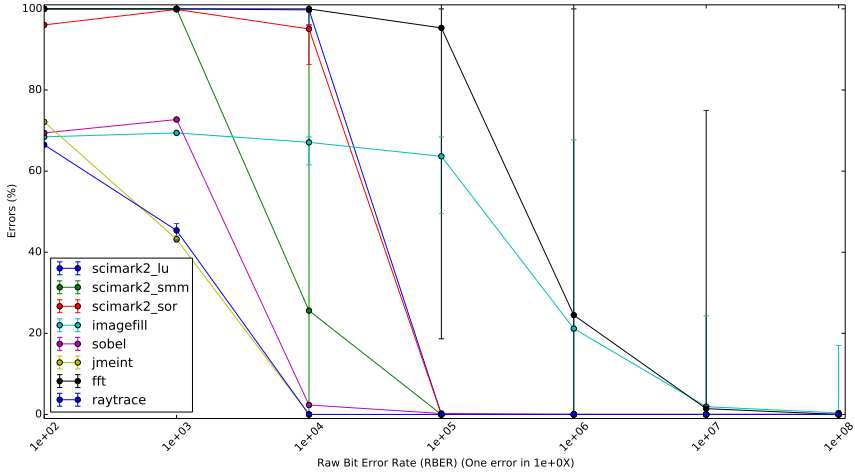
# Dual-Mode Caches



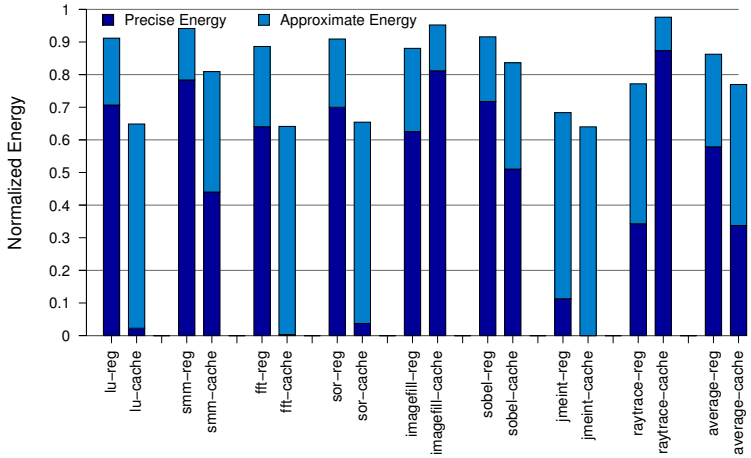
# Evaluation

- EnerJ
  - Implemented our own Cache Model
  - New Error Models
- Eight benchmarks
- Energy Estimation
  - Gate Equivalents
  - CACTI

# Results — Errors



# Results — Energy




- 32% average energy reduction for the register file
- 36% average energy reduction for the L1 cache
- 18% average energy reduction for arithmetic

# Results — L1 DC Miss Rate

| Benchmark | Original (%) | Approximate (%) | Improvement (%) |
|---|---|---|---|
| lu | 5.11 | 2.67 | 48% |
| smm | 7.00 | 4.36 | 38% |
| fft | 15.91 | 0.004 | 100% |
| sor | 2.13 | 1.08 | 49% |
| imagefill | 17.26 | 11.62 | 33% |
| sobel | 0.10 | 0.05 | 50% |
| jmeint | 1.30 | 0.65 | 50% |
| raytrace | 0.50 | 0.25 | 50% |

# Summary

- We live in interesting times
  - CMOS scaling is reaching its end
  - Emerging devices have new characteristics
- Continued scaling leads to unreliable devices
  - Approximate computing
  - Trading power and performance against precision
- Multi-value devices
  - Dual-mode architecture
  - Binary format for reliable operations
  - Quaternary format for efficient operations

# Thank You for Listening