ESE532: System-on-a-Chip Architecture

Day 26: December 3, 2018
Defect Tolerance

Today

- Reliability Challenges
- Defect Tolerance
  - Memories
  - Interconnect
  - FPGA
- FPGA Variation and Energy
  - (time permitting)

Message

- At small feature sizes, not viable to demand perfect fabrication of billions of transistors on a chip
- Modern ICs are like snowflakes
  - Everyone is different, changes over time
- Reconfiguration allows repair
  - Finer grain → higher defect rates
  - Tolerate variation → lower energy

Intel Xeon Phi Offerings

Part #	Cores
7290F	72
7250F	68
7230F	64

http://www.intel.com/content/www/us/en/products/processors/xeon-phi/xeon-phi-processors.html

Intel Xeon Phi Offerings

Part #	Cores
7290F	72
7250F	68
7230F	64

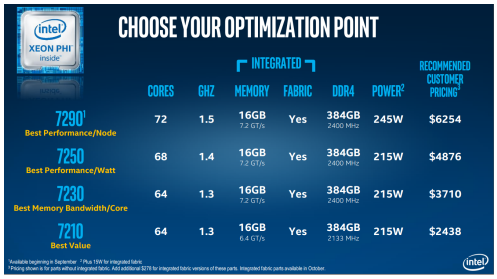
Is Intel producing 3 separate chips?

Preclass 1 and Intel Xeon Phi Offerings

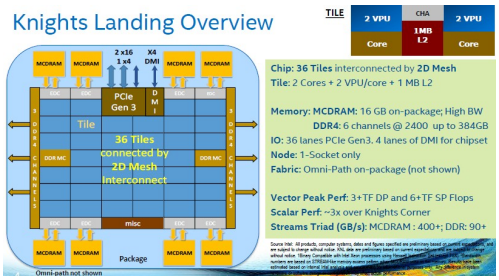
Part #	Cores
7290F	72
7250F	68
7230F	64

Cost ratio between 72 and 64 processor assuming fixed mm^2 per core?

Intel Xeon Phi Pricing



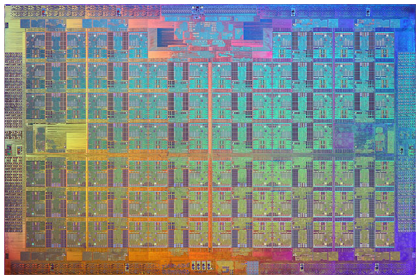
Intel Knights Landing



https://www.nextplatform.com/2016/06/20/intel-knights-landing-yields-big-bang-buck-jump/

[Intel, Micro 2016]

Knights Landing Xeon Phi



[Intel, Micro 2016]

What's happening?

- Fabricated chip has 76 cores
- Not expect all to work
- Selling based on functional cores
  - 72, 68, 64
- Charge premium for high core counts
  - Don't yield as often, people pay more
- Do see design to accommodate defects

https://www.nextplatform.com/2016/08/22/intel-tweaking-xeon-phi-deep-learning/

[Intel, Micro 2016]

Warmup Discussion

- Where else do we guard against defects today?
  - Where do we accept imperfection today?

Motivation: Probabilities

- Given:
  - N objects
  - P_g yield probability
- What's the probability for yield of composite system of N items? [Preclass 2]
  - Assume iid (independent, identically distributed) faults
  - P(N items good) = $(P_g)^N$

Probabilities

- $P_{all\_good}(N) = (P_g)^N$
- P=0.999999

N	$P_{all\_good}(N)$
10^4	
10^5	
10^6	
10^7	

Probabilities

- $P_{all\_good}(N) = (P_g)^N$
- P=0.999999

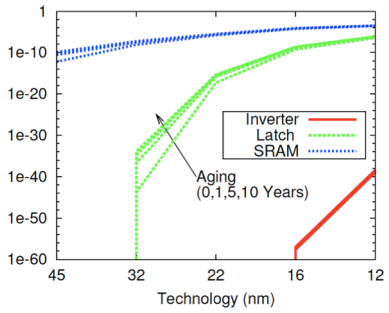
N	$P_{all\_good}(N)$
10^4	0.99
10^5	0.90
10^6	0.37
10^7	0.000045

Simple Implications

- As N gets large
  - must either increase reliability
  - …or start tolerating failures
- N
  - memory bits
  - disk sectors
  - wires
  - transmitted data bits
  - processors
  - transistors
  - molecules

As devices get smaller, failure rates increase
chemists think P=0.95 is good
As devices get faster, failure rate increases

Failure Rate Increases



[Nassif / DATE 2010]

Quality Required for Perfection?

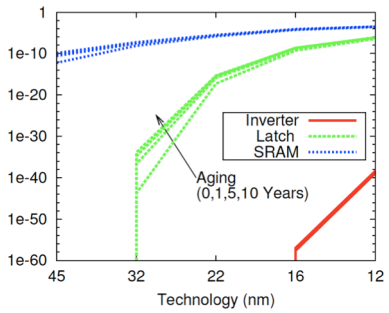
- How high must P_g be to achieve 90% yield on a collection of 10^{11} devices?

[preclass 4]

$$(P_g)^{10^{11}} > 0.9$$

$$P_g > 1 - 10^{-12}$$

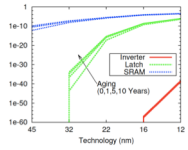
Failure Rate Increases



[Nassif / DATE 2010]

Challenge

- Feature size scales down (S)
- Capacity (area) → increases ($1/S^2$)
  - N increase
- Reliability per device goes down
  - P_g decrease
- P(N items good) = $(P_g)^N$



Defining Problems

Three Problems

1. **Defects:** Manufacturing imperfection
   - Occur before operation; persistent
     - Shorts, breaks, bad contact
2. **Transient Faults:**
   - Occur during operation; transient
     - node X value flips: crosstalk, ionizing particles, bad timing, tunneling, thermal noise
3. **Lifetime "wear" defects**
   - Parts become bad during operational lifetime
     - Fatigue, electromigration, burnout….
   - …slower
     - NBTI, Hot Carrier Injection

In a Nut-shell…

Shekhar Bokar
Intel Fellow
Micro37 (Dec.2004)

100 BT integration capacity

20 BT unusable (variations)

10 BT will fail over time

Intermittent failures

Yet, deliver high performance in the power & cost envelope

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Defect Rate

- Device with 10^{11} elements (100BT)
- 3 year lifetime = 10^8 seconds
- Accumulating up to 10% defects
- 10^{10} defects in 10^8 seconds
  - →1 new defect every 10ms
- At 10GHz operation:
  - One new defect every 10^8 cycles
  - $P_{newdefect}=10^{-19}$

First Step to Recover

Admit you have a problem
(observe that there is a failure)

Detection

- How do we determine if something wrong?
  - Some things easy
    - ….won't start
  - Others tricky
    - …one **and** gate computes False & True→True
- Observability
  - can see effect of problem
  - some way of telling if defect/fault present

Detection

- Coding
  - space of legal values << space of all values
  - should only see legal
  - *e.g.* parity, ECC (Error Correcting Codes)
- Explicit test (defects, recurring faults)
  - ATPG = Automatic Test Pattern Generation
  - Signature/BIST=Built-In Self-Test
  - POST = Power On Self-Test
- Direct/special access
  - test ports, scan paths

Coping with defects/faults?

- **Key idea: redundancy**
- Detection:
  - Use redundancy to detect error
- Mitigating: use redundant hardware
  - Use spare elements in place of faulty elements (defects)
  - Compute multiple times so can discard faulty result (faults)

Defect Tolerance

Three Problems

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Two Models

- Disk Drives (defect map)
- Memory Chips (perfect chip)

Disk Drives

- Expose defects to software
  - software model expects defects
    - Create table of good (bad) sectors
  - manages by masking out in software
    - (at the OS level)
    - Never allocate a bad sector to a task or file
  - yielded capacity varies

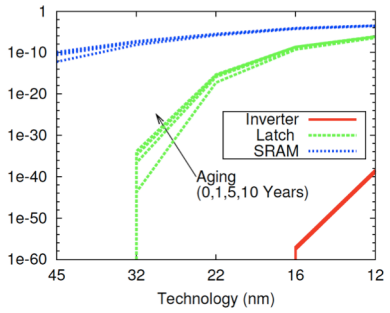
Memory Chips

- Provide model in **hardware** of perfect chip
- Model of perfect memory at capacity X
- Use redundancy in hardware to provide perfect model
- Yielded capacity fixed
  - discard part if not achieve

Example: Memory

- Correct memory:
  - N slots
  - each slot reliably stores last value written
- Millions, billions, etc. of bits…
  - have to get them all right?

Failure Rate Increases



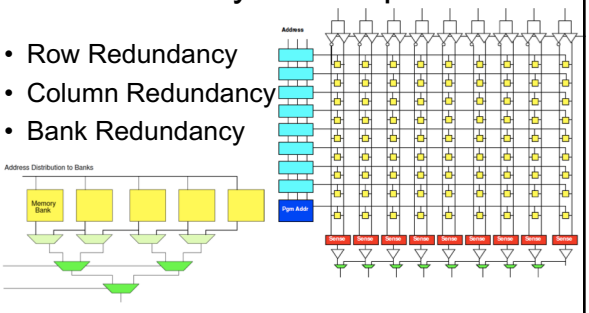
[Nassif / DATE 2010]

Memory Defect Tolerance

- Idea:
  - few bits may fail
  - provide more raw bits
  - configure so yield what looks like a perfect memory of specified size

Memory Techniques

- Row Redundancy
- Column Redundancy
- Bank Redundancy



Yield M of N

- Preclass 5: Probability of yielding 3 of 5 things?
  - Symbolic?
  - Numerical for P_g=0.9?

Yield M of N

- P(M of N) = P(yield N)
  + (N choose N-1) P(exactly N-1)
  + (N choose N-2) P(exactly N-2)…
  + (N choose N-M) P(exactly N-M)…
  [think binomial coefficients]

M of 5 example

- $1*P^5 + 5*P^4(1-P)^1+10P^3(1-P)^2+10P^2(1-P)^3+5P^1(1-P)^4 + 1*(1-P)^5$
- Consider P=0.9
  - $1*P^5$ 0.59
  - $5*P^4(1-P)^1$ 0.33
  - $10P^3(1-P)^2$ 0.07
  - $10P^2(1-P)^3$ 0.008
  - $5P^1(1-P)^4$ 0.00045
  - $1*(1-P)^5$ 0.00001

M=5 P(sys)=0.59
M=4 P(sys)=0.92
M=3 P(sys)=0.99
Can achieve higher system yield than individual components!

Possible Yield of 76 cores@ P=0.9

Processors Yield	Prob Exact	Prob at least
76	0.001	0.001
75	0.004	0.005
74	0.016	0.020
73	0.041	0.061
72	0.079	0.140
71	0.119	0.259
70	0.148	0.407
69	0.156	0.562
68	0.141	0.704
67	0.112	0.816
66	0.079	0.895
65	0.050	0.945
64	0.028	0.973

Possible Yield of 76 cores@ P=0.9

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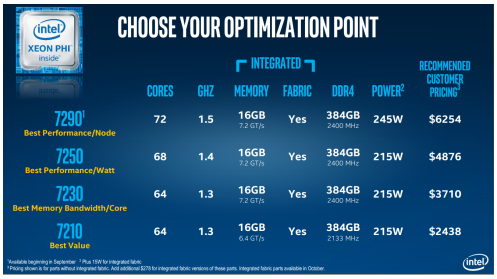
64	0.973

Out of 100 chips, how many?

Sell with 72:
Sell with 68:
Sell with 64:
Discard:

Intel Xeon Phi Pricing



Repairable Area

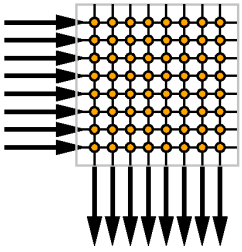
- Not all area in a RAM is repairable
  - memory bits spare-able
  - io, power, ground, control not redundant

Repairable Area

- P(yield) = P(non-repair) * P(repair)
- P(non-repair) = P^{Nnr}
  - $N_{nr} << N_{total}$
  - $P > P_{repair}$
    - e.g. use coarser feature size
    - Differential reliability
- P(repair) ~ P(yield M of N)

Consider a Crossbar

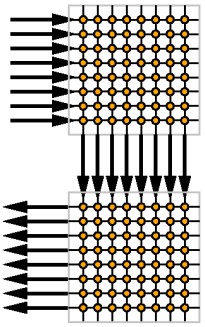
- Allows us to connect any of N things to each other
  - E.g.
    - N processors
    - N memories
    - N/2 processors
    + N/2 memories



Crossbar Buses and Defects

- Two crossbar multibus
- Wires may fail
- Switches may fail

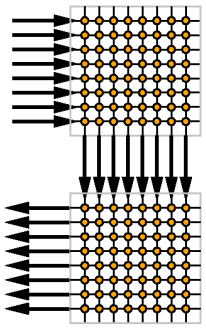
- How tolerate
  - Wire failures between crossbars?
  - Switch failures?



Crossbar Buses and Defects

- Two crossbars
- Wires may fail
- Switches may fail

- Provide more wires
  - Any wire fault avoidable
    - M choose N



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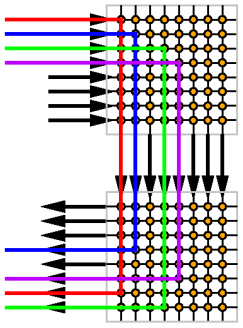

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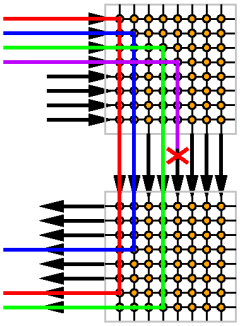
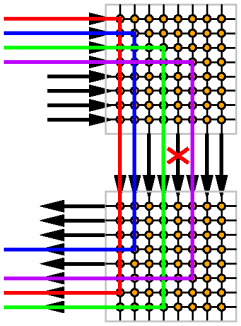


Crossbar Buses and Faults

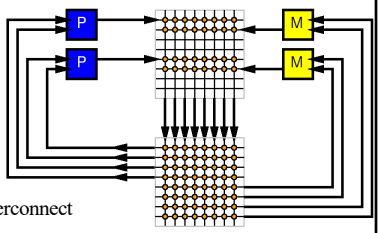
- Two crossbars
- Wires may fail
- Switches may fail

- Provide more wires
  - Any wire fault avoidable
    - M choose N
  - Same idea



Simple System

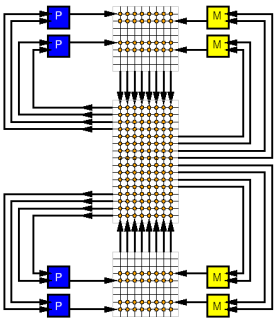
- P Processors
- M Memories
- Wires



Memory, Compute, Interconnect

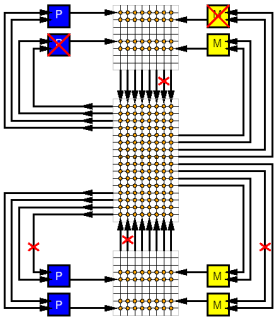
Simple System w/ Spares

- P Processors
- M Memories
- Wires
- Provide spare
  - Processors
  - Memories
  - Wires



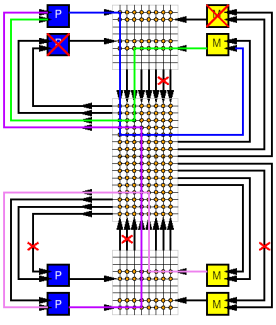
Simple System w/ Defects

- P Processors
- M Memories
- Wires
- Provide spare
  - Processors
  - Memories
  - Wires
- ...and defects



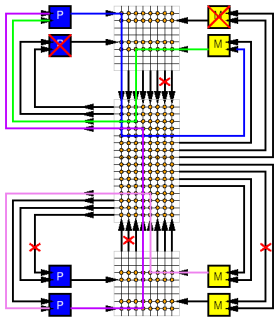
Simple System Repaired

- P Processors
- M Memories
- Wires
- Provide spare
  - Processors
  - Memories
  - Wires
- Use crossbar to switch together good processor and memories



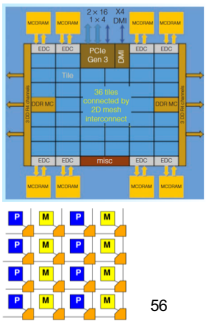
Simple System Repaired

- What are the costs?
  - Area
  - Energy
  - Delay



In Practice

- Crossbars are inefficient
- Use switching networks with
  - Locality
  - Segmentation
- …but basic idea for sparing is the same



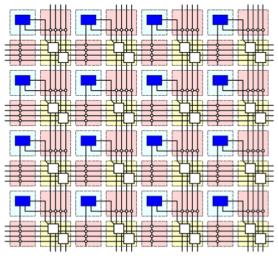
FPGAs

Modern FPGA

- Has 10,000 to millions of LUTs
- Hundreds to thousands of
  - Memory banks
  - Multipliers
- Reconfigurable interconnect

XC7Z020

- 6-LUTs: 53,200
- DSP Blocks: 220
  - 18x25 multiply, 48b accumulate
- Block RAMs: 140
  - 36Kb
  - Dual port
  - Up to 72b wide



Modern FPGA

- Has 10,000 to millions of gates
- Hundreds to thousands of
  - Memory banks
  - Multipliers
- Reconfigurable interconnect

- If a few resources don't work
  - avoid them

Granularity

- How do transistors compare between 6-LUT and 64b processor core?
  - [qualitative or ballpark]

Granularity

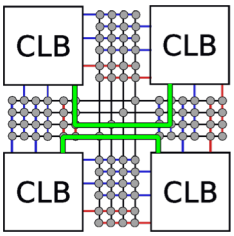
- Consider two cases
  - Knight's Bridge with 76 64b processors
  - FPGA with 1 Million 6-LUTs
- 10 defects (bad transistors)
- How much capacity lost?
  - Knight's Bridge?
  - 1M 6-LUT FPGA?

Observe

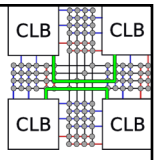
- Finer granularity sparing
  - Lose fewer resources per defect
    - Losing processor vs. losing 6-LUT
    - Losing memory row vs. losing entire memory bank
  - Pay more for reconfiguration
- Finer grained designs
  - Tolerate higher defect rates

Interconnect Defects

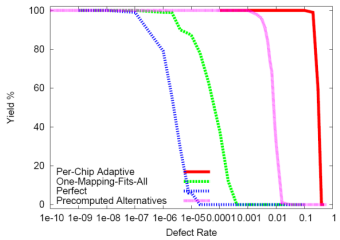
- Route around interconnect defects



Defect-Level Viable with FPGAs



- Fine-grained repair
- Avoiding routing defects
  - Tolerates >20% switch defects



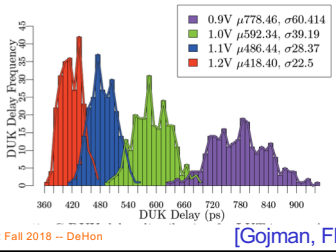
[Rubin/unpublished]

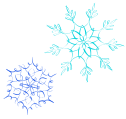
FPGAs Variation and Energy

(if time permits)

Variation

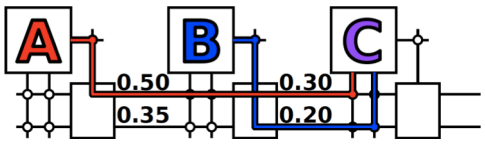
- Modern ICs are like Snowflakes
  - Each one is different





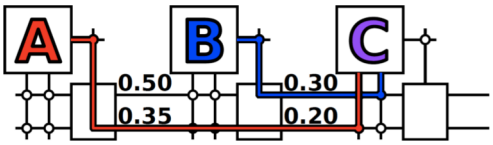
[Gojman, FPGA2013]

Variation Challenge



- Use of high V_{th} resource forces high supply voltage (V_{dd}) to meet timing requirement
- Delay: CV/I and I goes as $(V_{dd}-V_{th})^2$

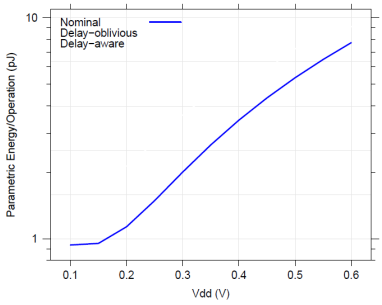
Component-Specific



- Use defect idea to avoid high V_{th} resource
- Allow lower supply voltage (V_{dd}) to meet timing requirement
- Delay: CV/I and I goes as $(V_{dd}-V_{th})^2$

Energy vs V_{dd} (des)

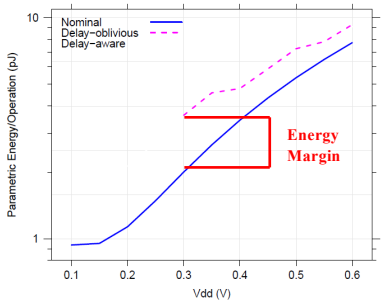
- Nominal uses minimum size



[Mehta, FPGA 2012]

Energy vs V_{dd} (des)

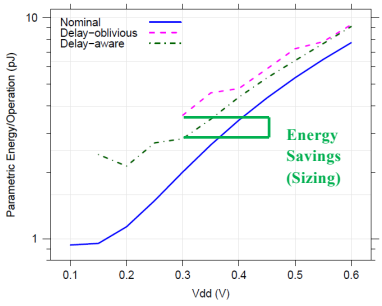
- Nominal uses minimum size



[Mehta, FPGA 2012]

Energy vs V_{dd} (des)

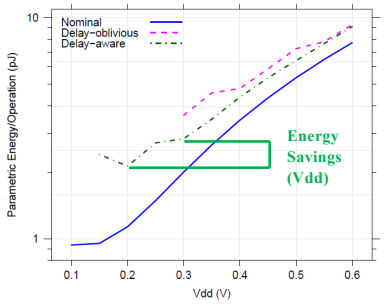
- Nominal uses minimum size
- Delay-aware routing reduces energy margins
  1. Smaller sizes



[Mehta, FPGA 2012]

Energy vs V_{dd} (des)

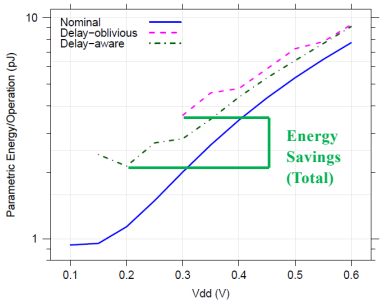
- Nominal uses minimum size
- Delay-aware routing reduces energy margins
  1. Smaller sizes
  2. Lower voltages



[Mehta, FPGA 2012]

Energy vs V_{dd} (des)

- Nominal uses minimum size
- Delay-aware routing reduces energy margins
  1. Smaller sizes
  2. Lower voltages
  3. Less Leakage



[Mehta, FPGA 2012]

Big Ideas

- At small feature sizes, not viable to demand perfect fabrication of billions of transistors on a chip
- Modern ICs are like snowflakes
  - Everyone is different, changes over time
- Reconfiguration allows repair
  - Finer grain → higher defect rates
  - Tolerate variation → lower energy

Admin

- Project due Friday
  - Reminder turin
    - Report
    - Code
    - Bitstsream, elf, decoder (see supplement)
  - Current sender will send largest files