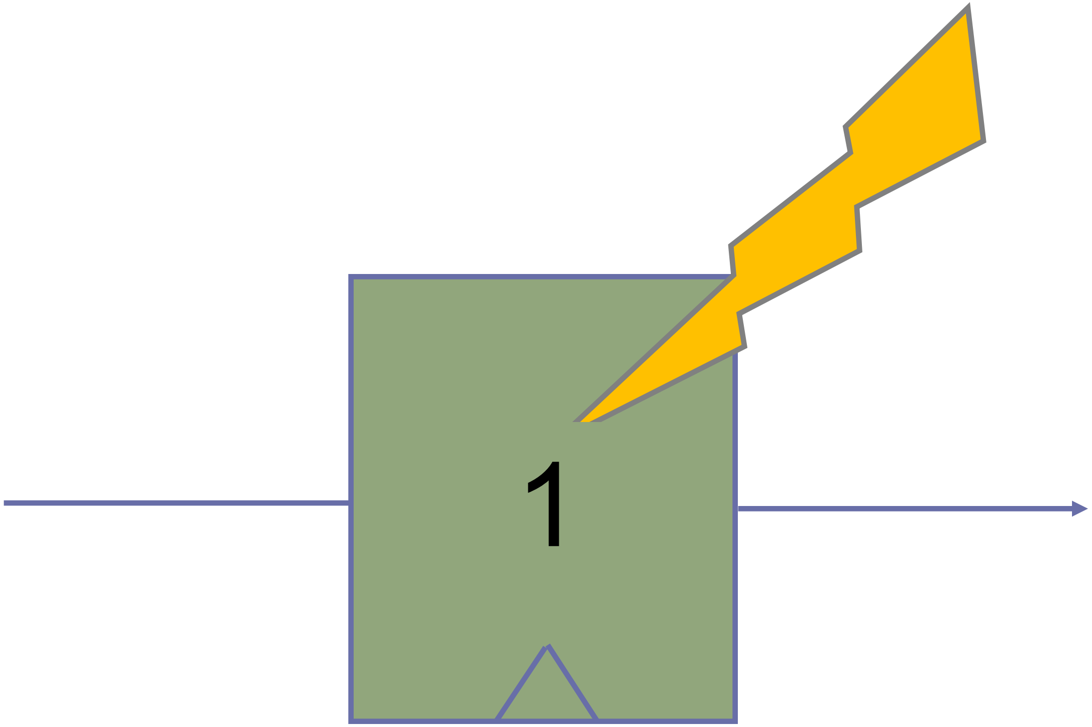
Reliable Architectures

Mengjia Yan
Computer Science & Artificial Intelligence Lab
M.I.T.

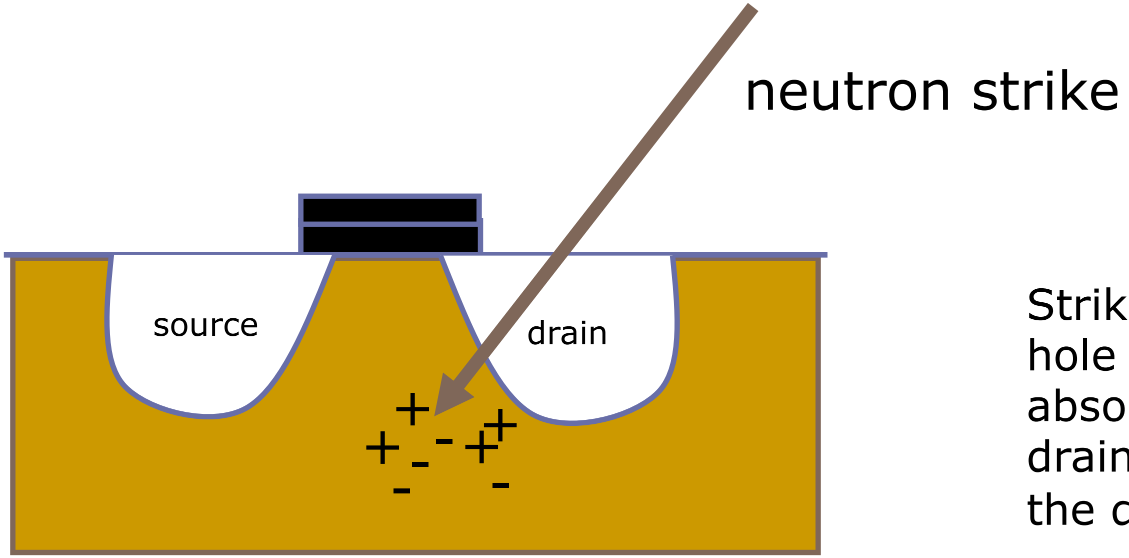
Many of the slides in this presentation are from public presentations made by Joel Emer for the AVF work

Event Changes State of a Single Bit



- Hard Error – Changes that are permanent
- Soft Error – Changes that are not permanent

Impact of Neutron Strike on a Si Device

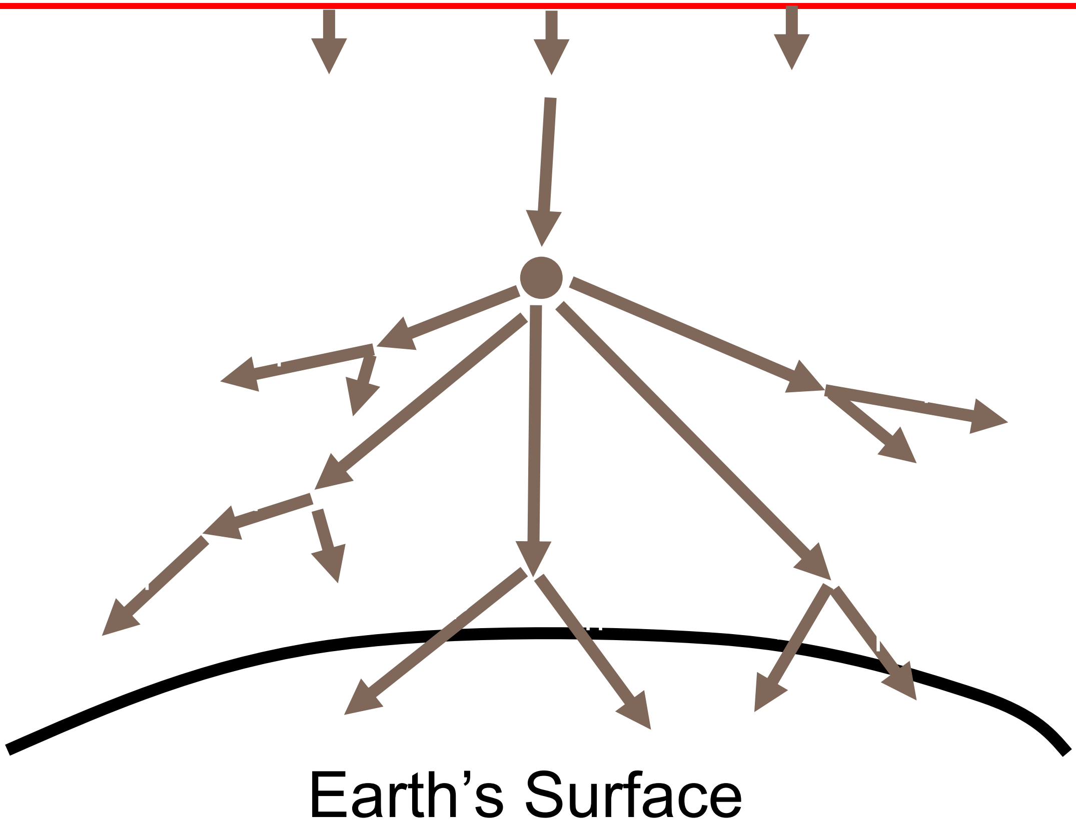


Transistor Device

Strikes release electron & hole pairs that can be absorbed by source & drain to alter the state of the device

- Secondary source of upsets: Alpha particles from packaging

Cosmic Rays Come From Deep Space



- Neutron flux is higher at higher altitudes
  - 3–5x increase in Denver at 5,000 feet
  - 100x increase in airplanes at 30,000+ feet

Basics of Charge Generation

Cosmic rays of >1GeV result in neutrons of >1MeV

Energy (eV)	**Electron-Hole Pairs**	**Charge (Femtocoulombs)**
3.6eV	1	$3.2\text{x}10^{-4}$
1MeV	$\sim 2.8\text{x}10^{5}$	~44
1GeV	$\sim 2.8\text{x}10^{8}$	$\sim 44\text{x}10^{3}$

In 2010:

- Critical charge on a DRAM: ~25 fCoulomb
- Critical charge on an SRAM: <4 fCoulomb

Cosmic Ray Strikes: Evidence & Reaction

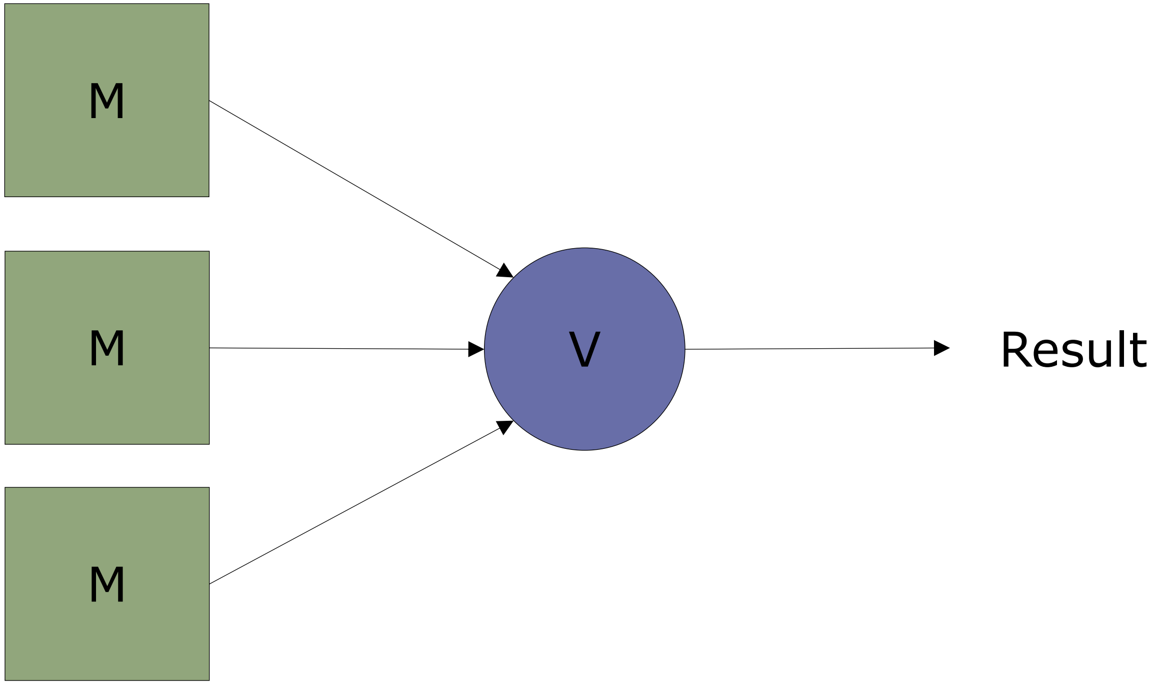
- Publicly disclosed incidences
  - Error logs in large servers, E. Normand, “Single Event Upset at Ground Level,” IEEE Trans. on Nucl Sci, Vol. 43, No. 6, Dec 1996.
  - Sun Microsystems found cosmic ray strikes on L2 cache with defective error protection caused Sun’s flagship servers to crash, R. Baumann, IRPS Tutorial on SER, 2000.
  - Cypress Semiconductor reported in 2004 a single soft error brought a billion-dollar automotive factory to a halt once a month, Zielger & Puchner, “SER – History, Trends, and Challenges,” Cypress, 2004.
  - In 2003, a "single-event upset" was blamed for an electronic voting error in Schaerbeekm, Belgium. A bit flip in the electronic voting machine added 4,096 extra votes to one candidate.

Physical solutions are hard

- Shielding?
  - No practical absorbent (e.g., approximately > 10 ft of concrete)
  - This is unlike Alpha particles which are easily blocked
- Technology solution?
  - Partially-depleted SOI of some help, effect on logic unclear
  - Fully-depleted SOI may help, but is challenging to manufacture
  - FinFETs are showing significantly lower vulnerability
- Circuit-level solution?
  - Radiation-hardened circuits can provide 10x improvement with significant penalty in performance, area, cost
  - 2–4x improvement may be possible with less penalty

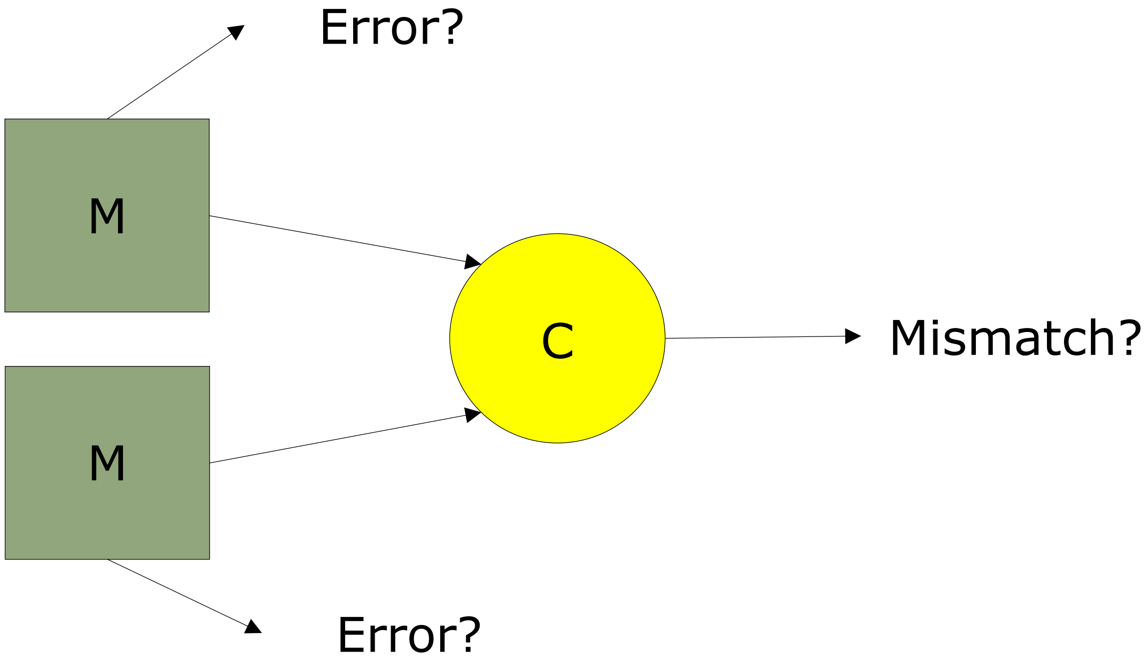
Triple Modular Redundancy

(Von Neumann, 1956)



V does a majority vote on the results

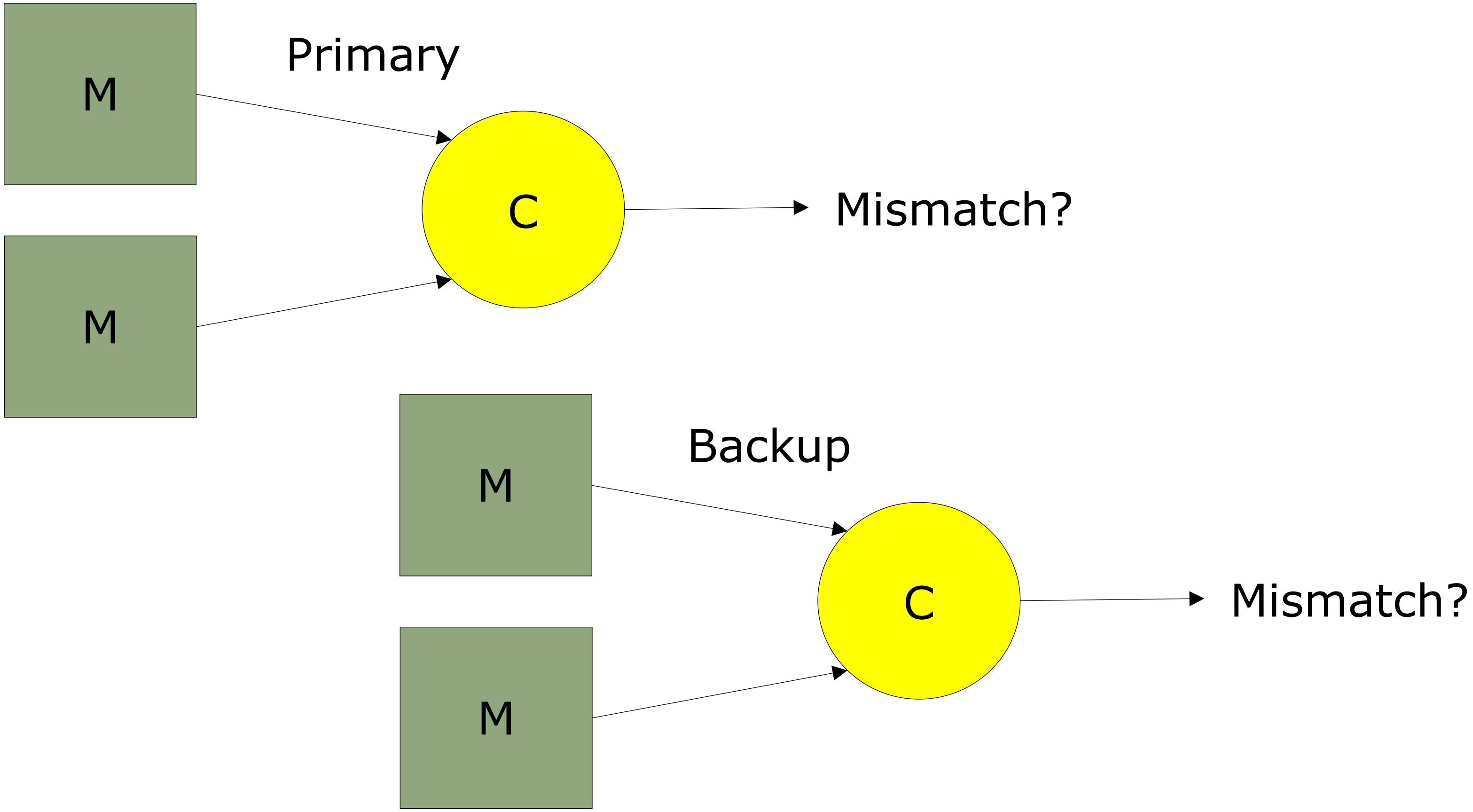
Dual Modular Redundancy
(e.g., BINAC 1949, Stratus 1982)



- Processing stops on mismatch
- Error signal used to decide which processor be used to restore state to other

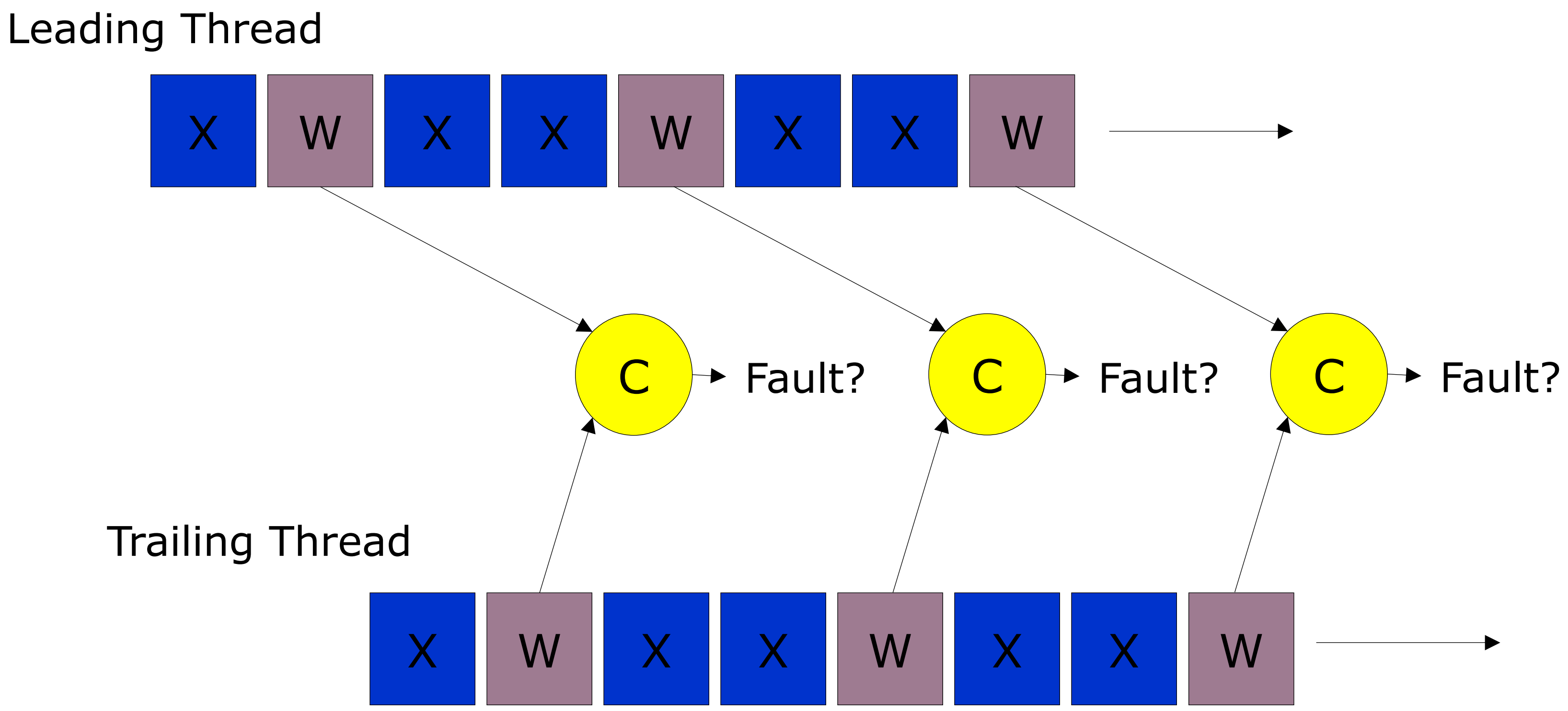
Pair and Spare Lockstep

(e.g., Tandem, 1975)



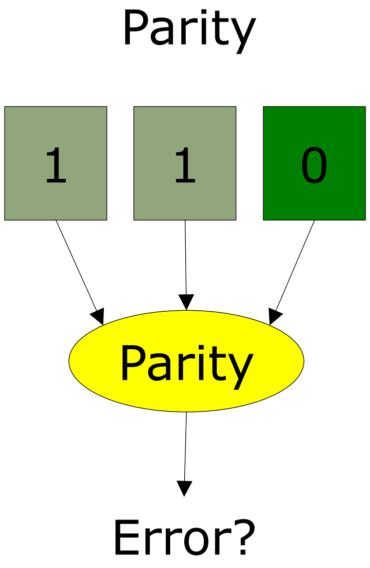
- Primary creates periodic checkpoints
- Backup restarts from checkpoint on mismatch

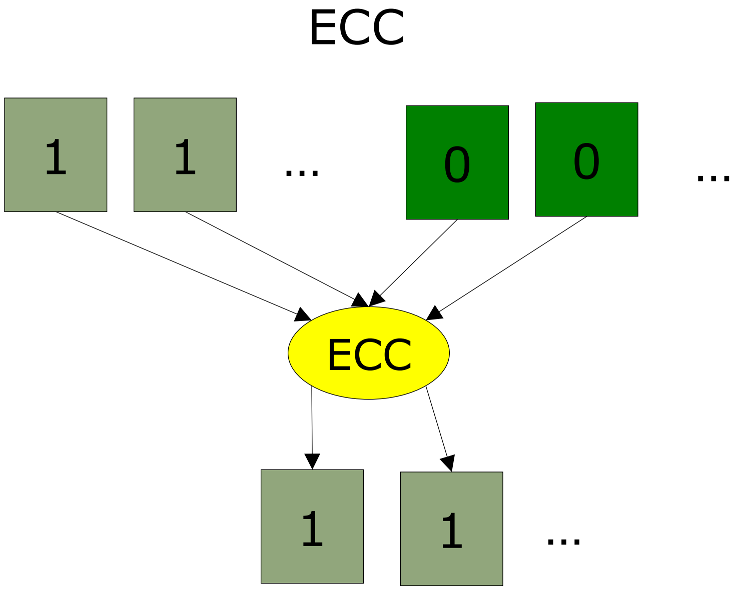
Redundant Multithreading
(e.g., Reinhardt, Mukherjee, 2000)



- Writes are checked

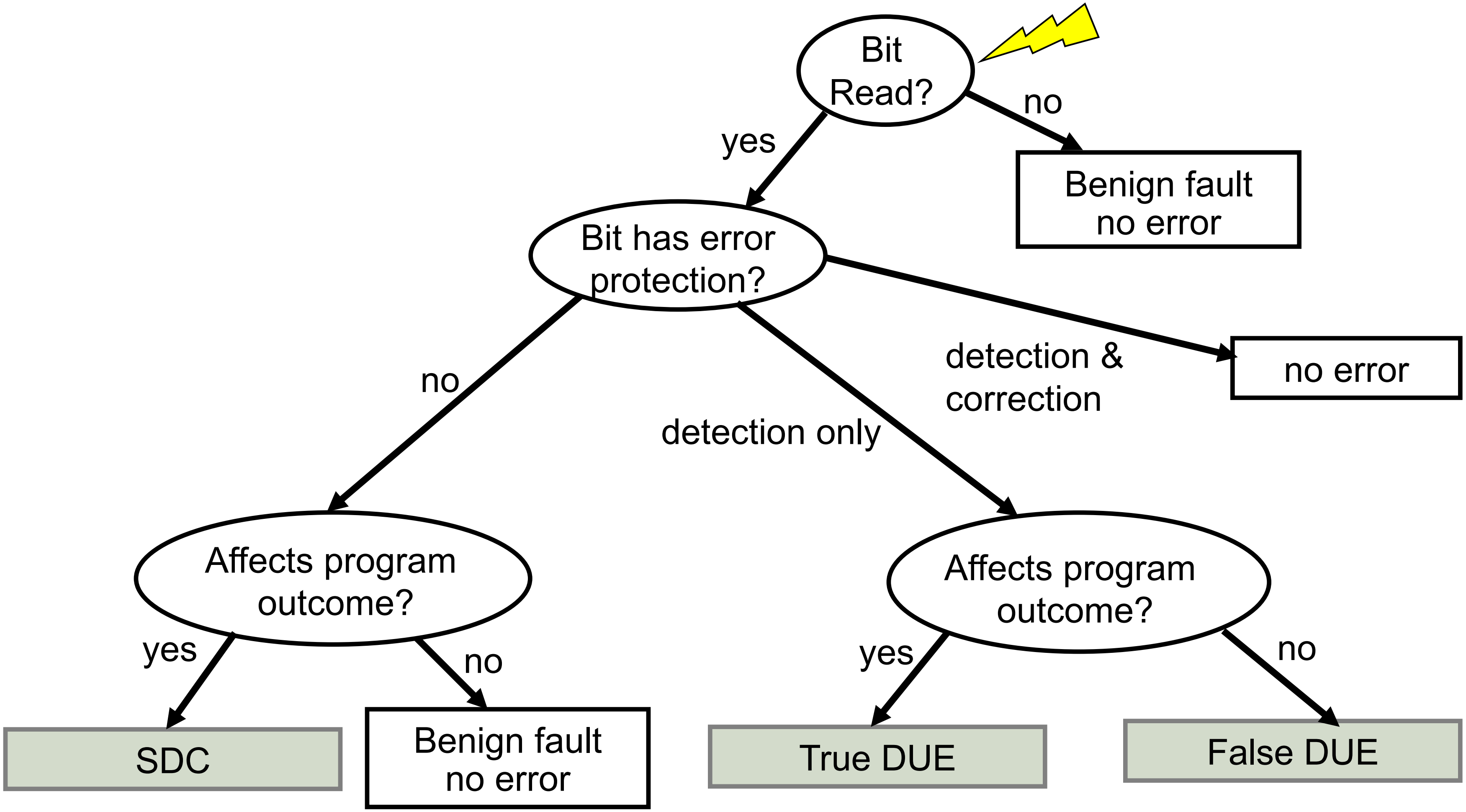
Component Protection





- Fujitsu SPARC in 130 nm technology (ISSCC 2003)
  - 80% of 200k latches protected with parity

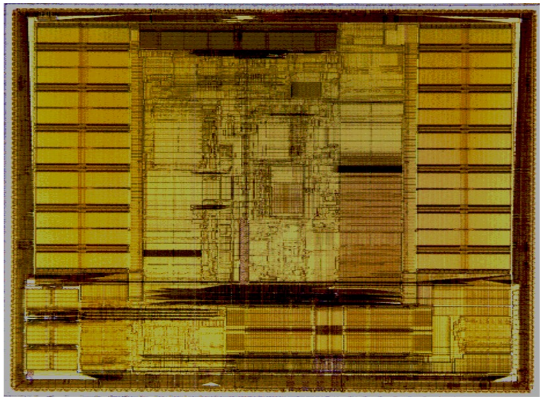
Strike on a bit (e.g., in register file)



SDC = Silent Data Corruption, DUE = Detected Unrecoverable Error

Metrics

- Interval-based
  - MTTF = Mean Time to Failure
  - MTTR = Mean Time to Repair
  - MTBF = Mean Time Between Failures = MTTF + MTTR
  - Availability = MTTF / MTBF
- Rate-based
  - FIT = Failure in Time = 1 failure in a billion hours
  - 1 year MTTF = 10^9 / (24 * 365) FIT = 114,155 FIT
  - SER FIT = SDC FIT + DUE FIT



Hypothetical Example

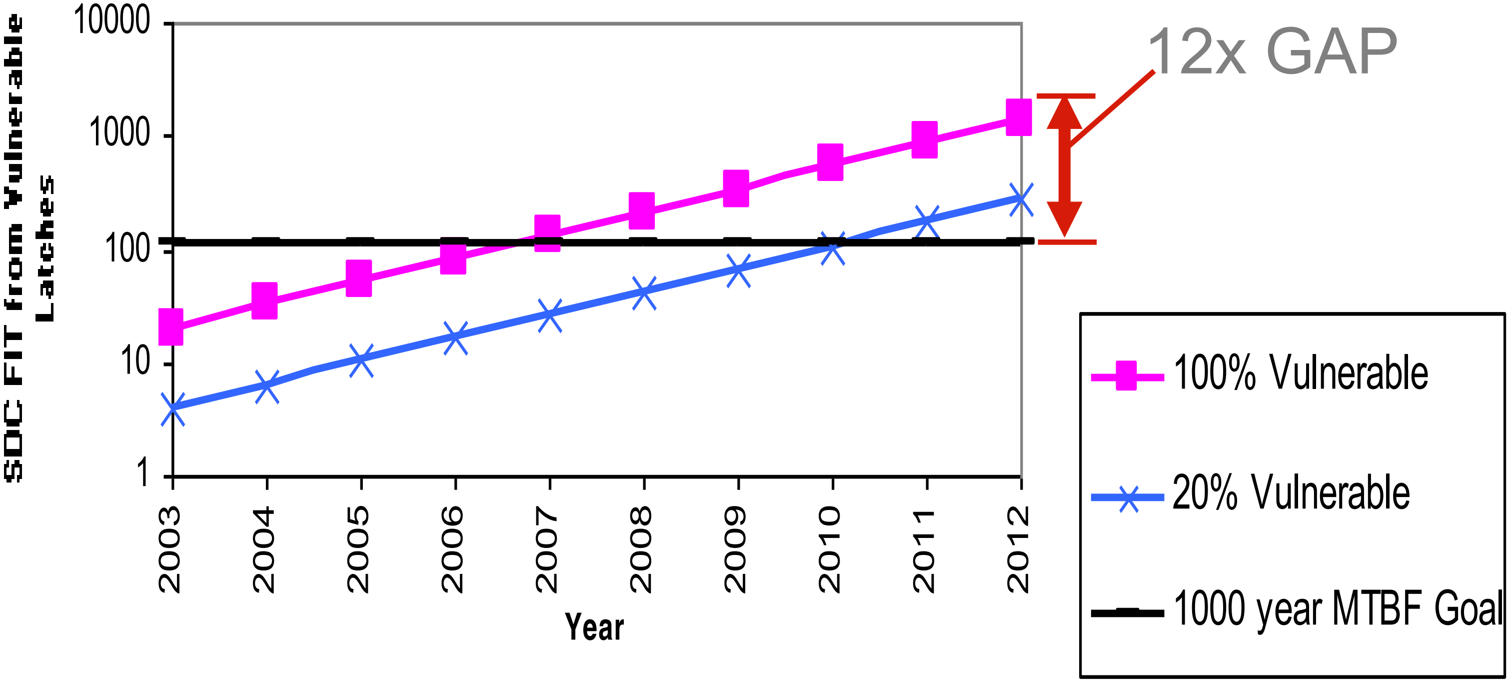
Cache: 0 FIT

\+ IQ: 100K FIT

\+ FU: 58K FIT

Total of 158K FIT

Number of Vulnerable Bits Growing with Moore’s Law



Typical SDC goal: 1000 year MTBF
Typical DUE goal: 10-25 year MTBF

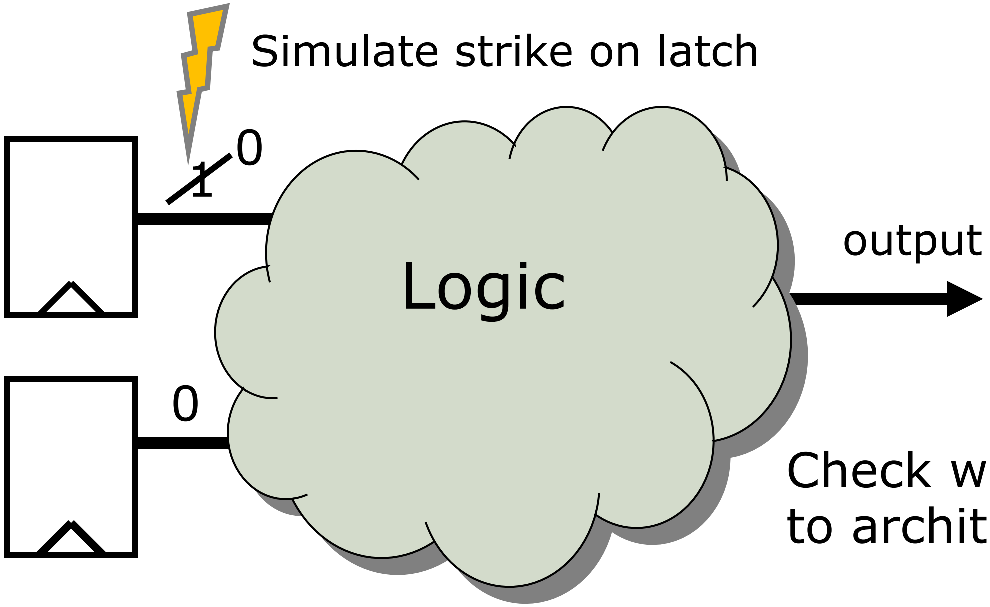
Architectural Vulnerability Factor (AVF)

$$\text{AVF}_{\text{bit}} = \text{Probability Bit Matters}$$

$$= \frac{\text{\# of Visible Errors}}{\text{\# of Bit Flips from Particle Strikes}}$$

$$\text{FIT}_{\text{bit}} = \text{intrinsic FIT}_{\text{bit}} * \text{AVF}_{\text{bit}}$$

Statistical Fault Injection (SFI) with RTL



Simulate strike on latch

Check whether fault propagates to architectural state

+ Naturally characterizes all logical structures

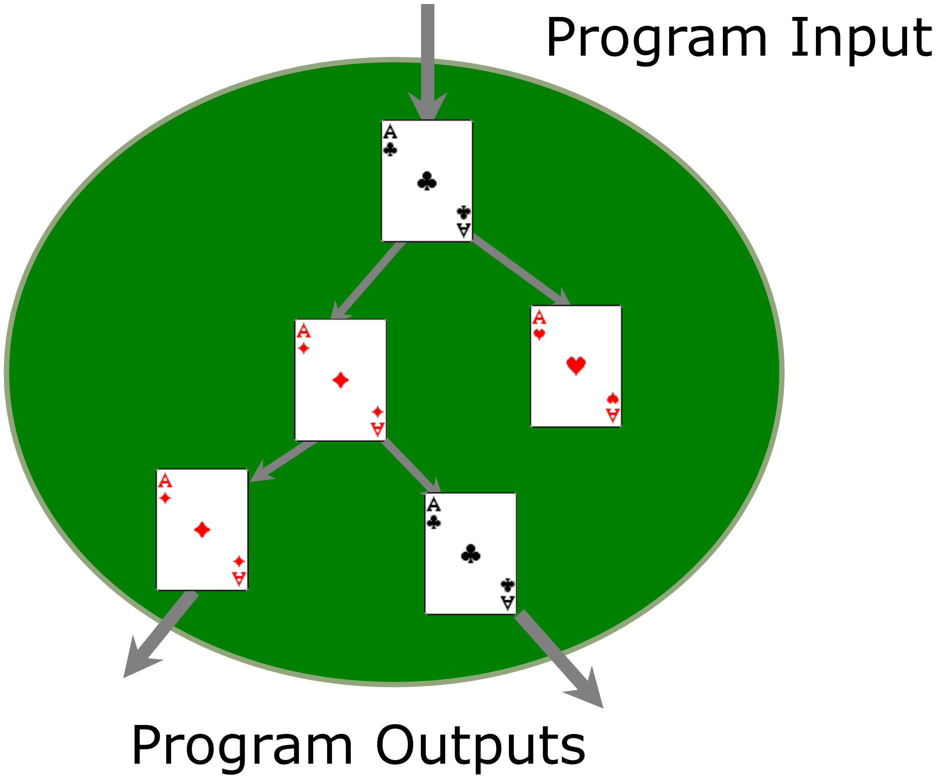
- RTL not available until late in the design cycle
- Numerous experiments to flip all bits
- Generally done at the chip level
  - Limited structural insight

Architectural Vulnerability Factor Does a bit matter?

- Branch Predictor

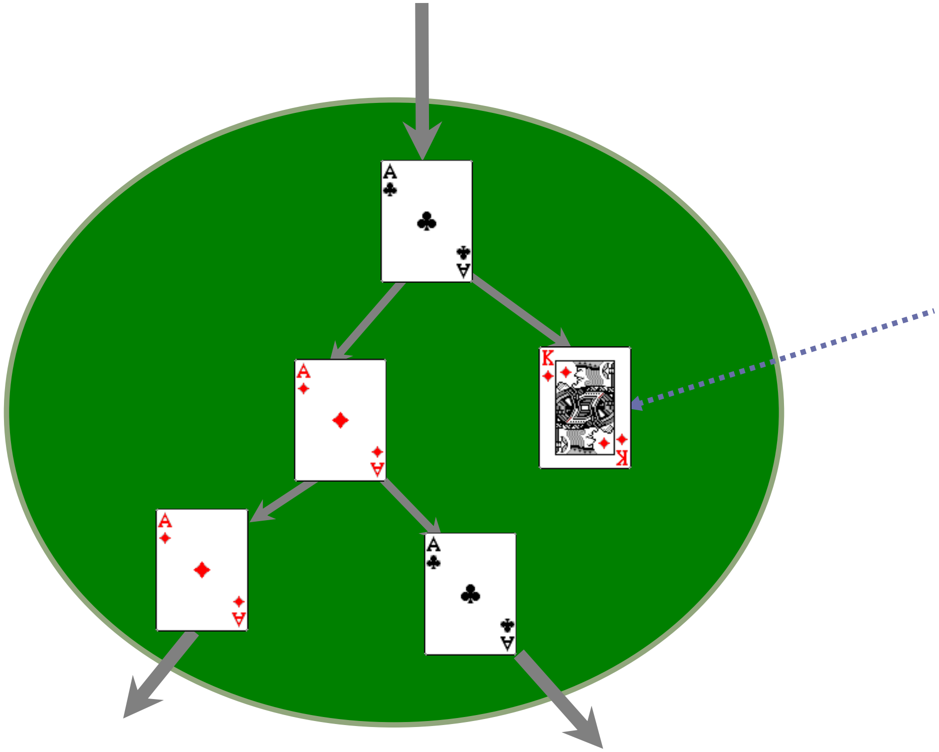
- Program Counter

Architecturally Correct Execution (ACE)



- ACE path requires only a subset of values to flow correctly through the program's data flow graph (and the machine)
- Anything else (un-ACE path) can be derated away

Example of un-ACE instruction: Dynamically Dead Instruction



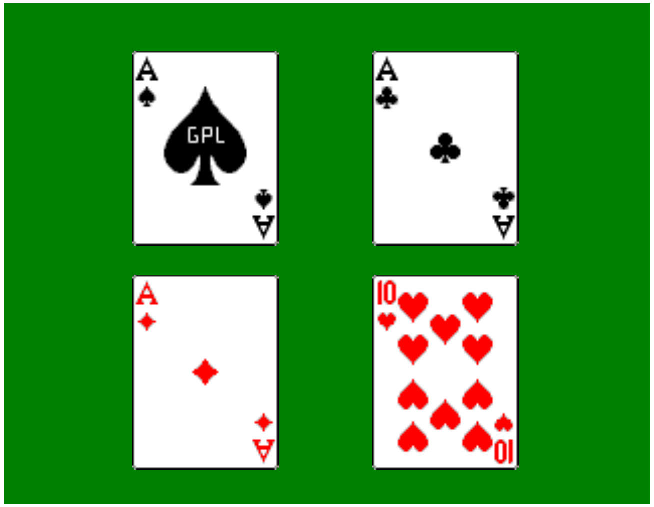
Dynamically Dead Instruction

- Most bits of an un-ACE instruction do not affect program output

Vulnerability of a structure

AVF = fraction of cycles a bit contains ACE state

T = 4



ACE% = 3/4

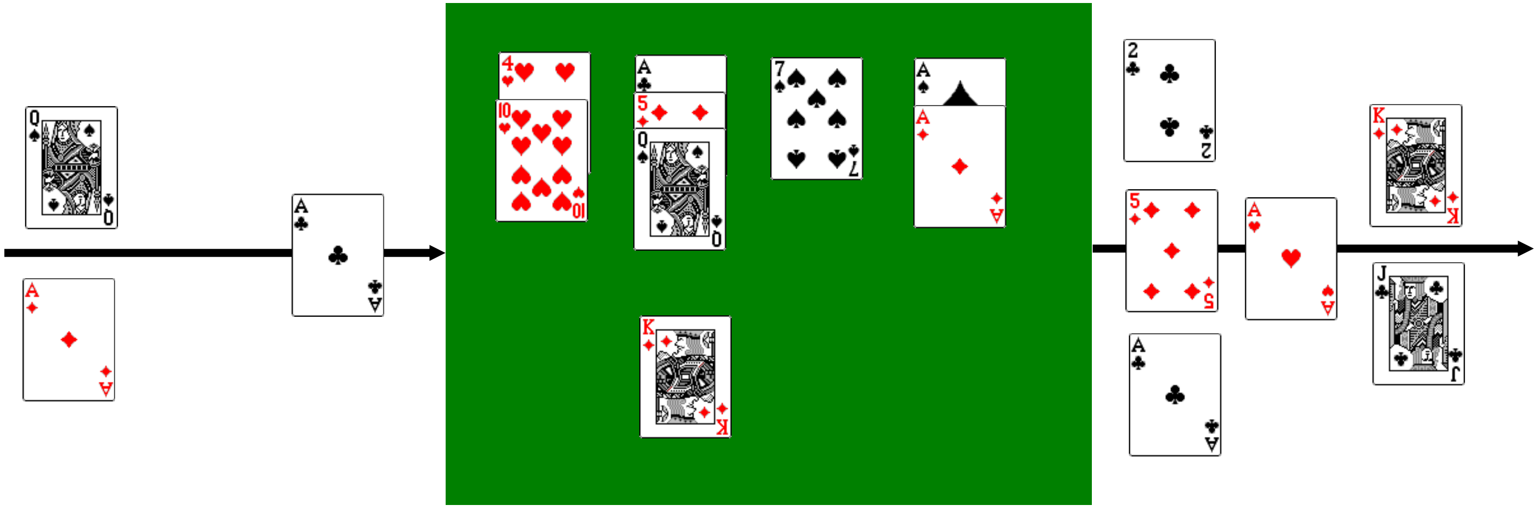
Vulnerability of a structure

AVF = fraction of cycles a bit contains ACE state

$$= \frac{(2 + 1 + 0 + 3) / 4}{4}$$

$$= \frac{\text{Average number of ACE bits in a cycle}}{\text{Total number of bits in the structure}}$$

Little’s Law for ACEs



$$\overline{N}_{ace} \square \overline{T}_{ace} \times \overline{L}_{ace}$$

$$AVF \square \frac{\overline{N}_{ace}}{N_{total}}$$

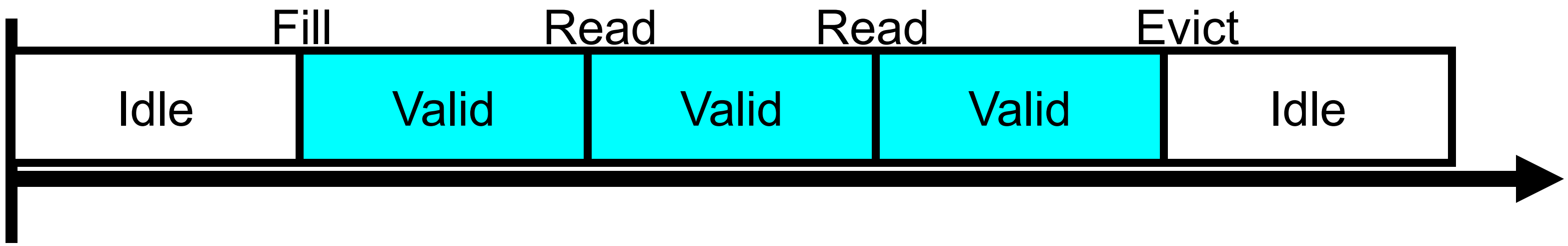
Computing AVF

- Approach is conservative
  - Assume every bit is ACE unless proven otherwise
- Data Analysis using a Performance Model
  - Prove that data held in a structure is un-ACE
- Timing Analysis using a Performance Model
  - Tracks the time this data spent in the structure

ACE Lifetime Analysis (1)

(e.g., write-through data cache)

- **Idle is unACE**

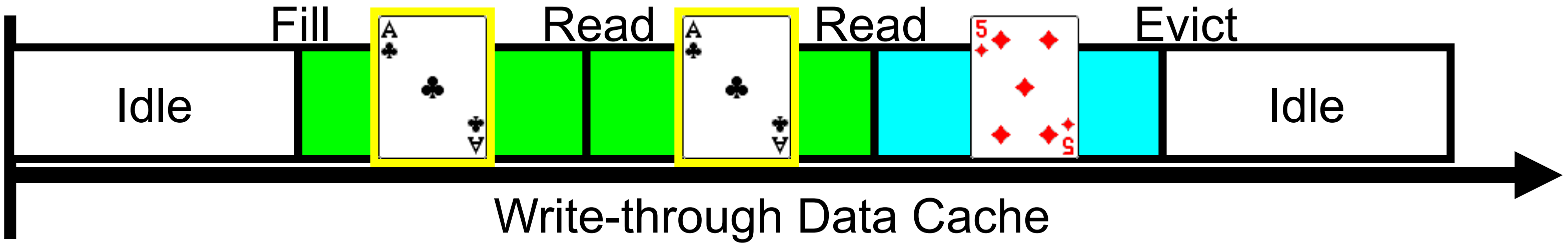


- Assuming all time intervals are equal
- For 3/5 of the lifetime the bit is valid
- Gives a measure of the structure’s utilization
  - Number of useful bits
  - Amount of time useful bits are resident in structure
  - Valid for a particular trace

ACE Lifetime Analysis (2)

(e.g., write-through data cache)

- **Valid is not necessarily ACE**

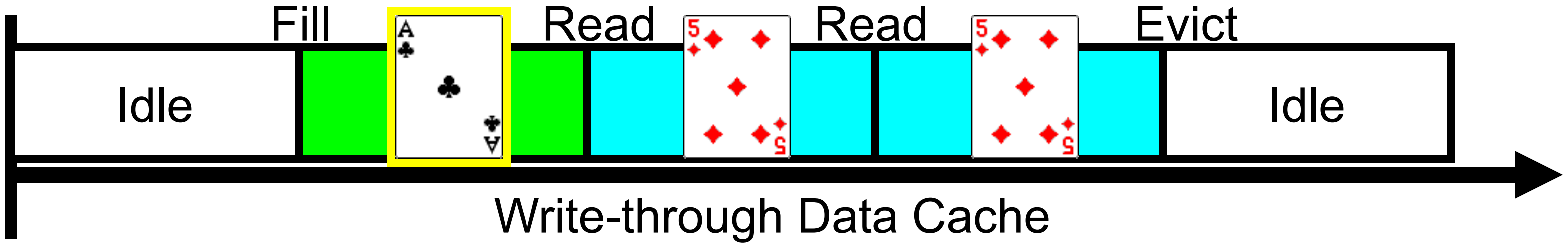


- ACE % = AVF = 2/5 = 40%
- Example Lifetime Components
  - ACE: fill-to-read, read-to-read
  - unACE: idle, read-to-evict, write-to-evict

ACE Lifetime Analysis (3)

(e.g., write-through data cache)

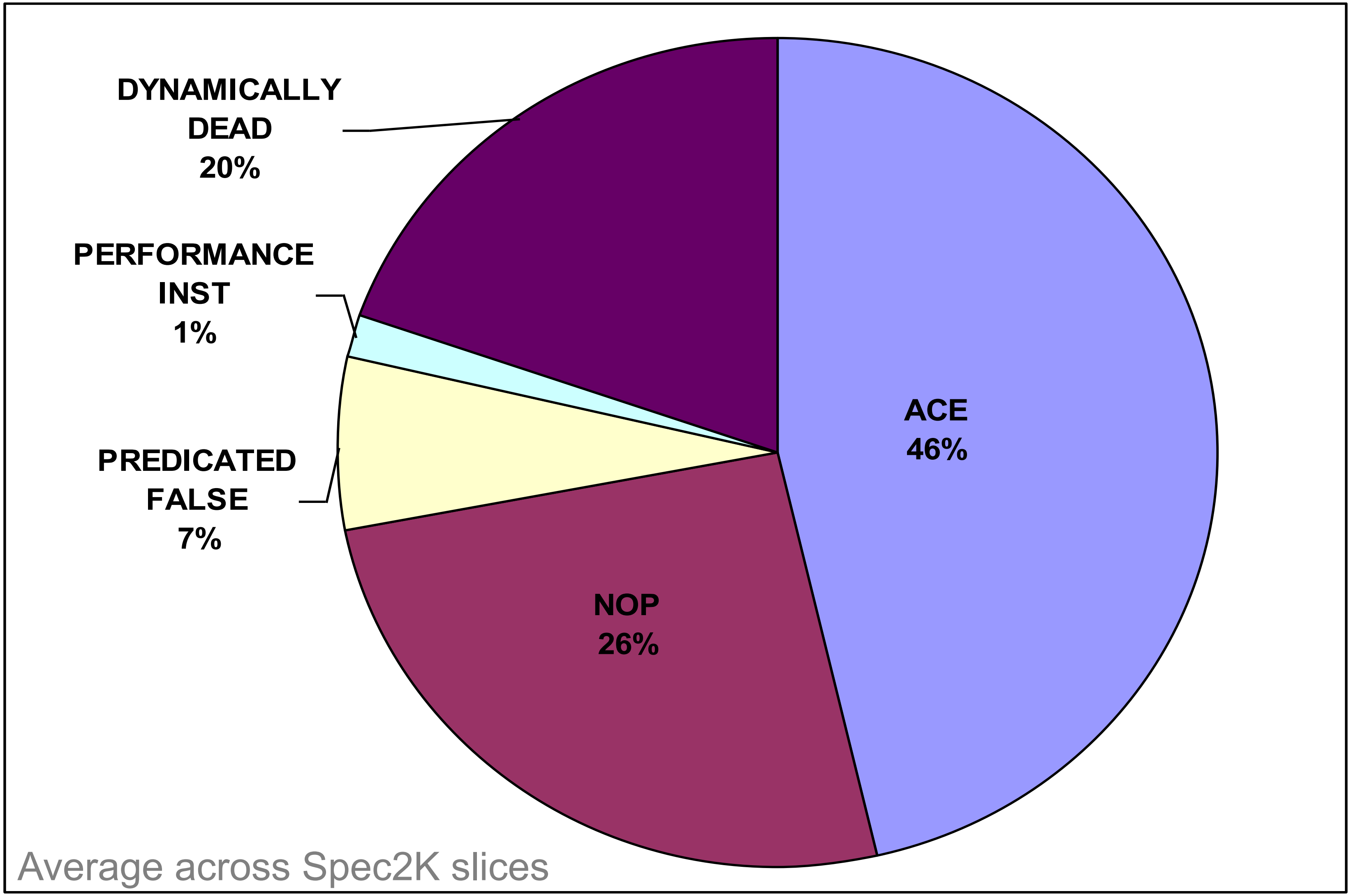
- **Data ACEness is a function of instruction ACEness**



- Second Read is by an unACE instruction

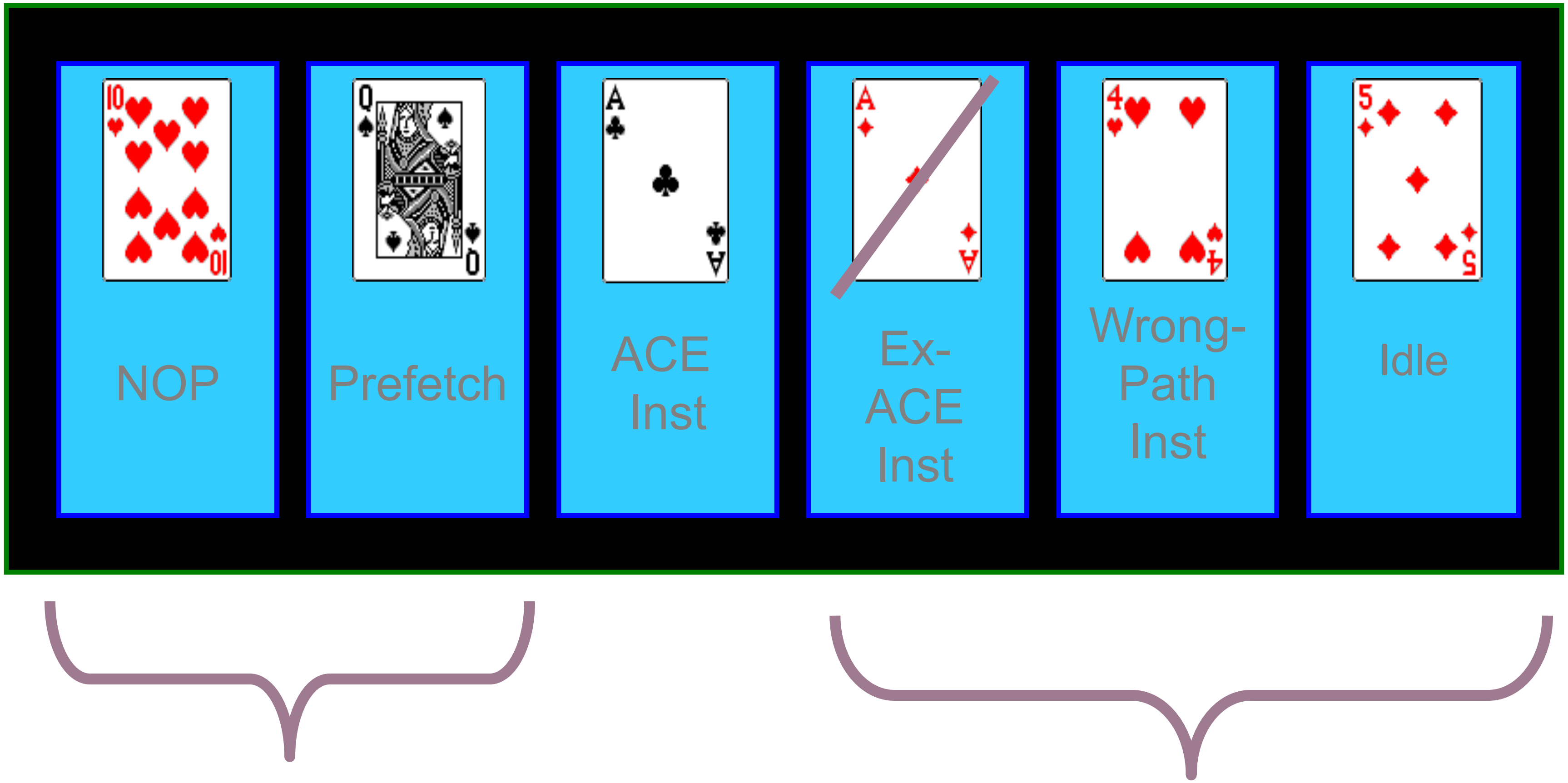
- AVF = 1/5 = 20%

Dynamic Instruction Breakdown



Average across Spec2K slices

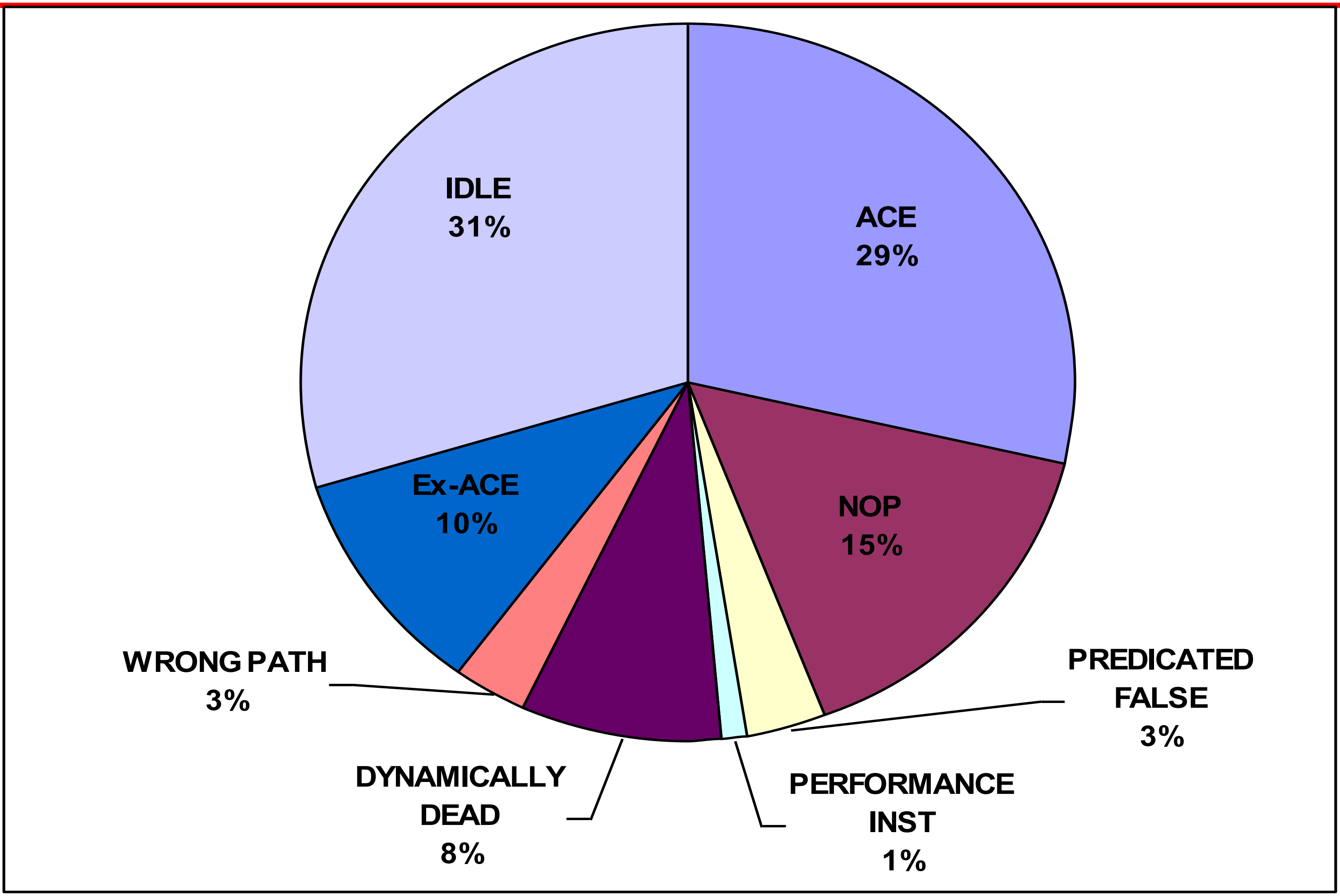
Mapping ACE & un-ACE Instructions to the Instruction Queue



Architectural un-ACE

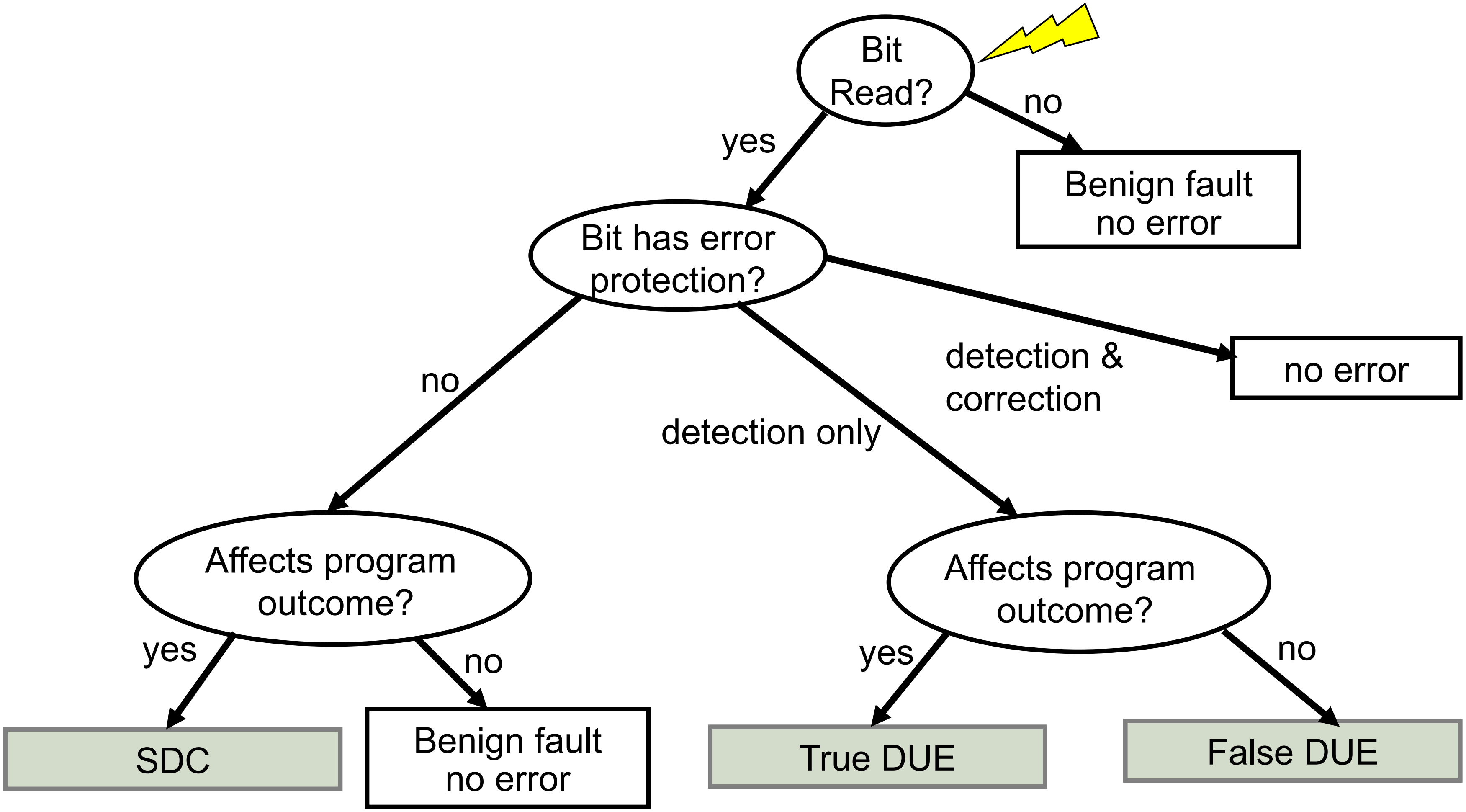
Micro-architectural un-ACE

Instruction Queue



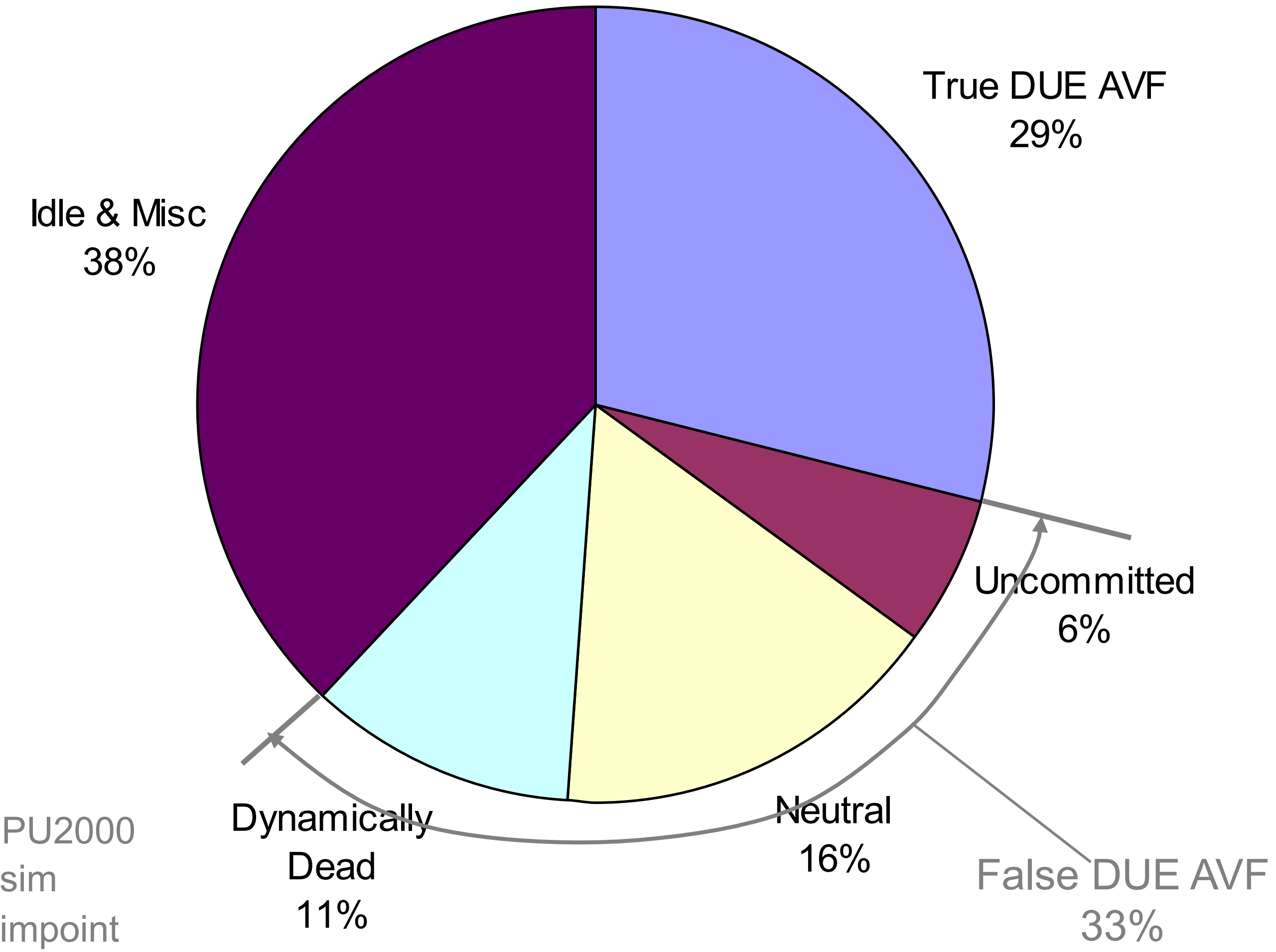
ACE percentage = AVF = 29%

Strike on a bit (e.g., in register file)



SDC = Silent Data Corruption, DUE = Detected Unrecoverable Error

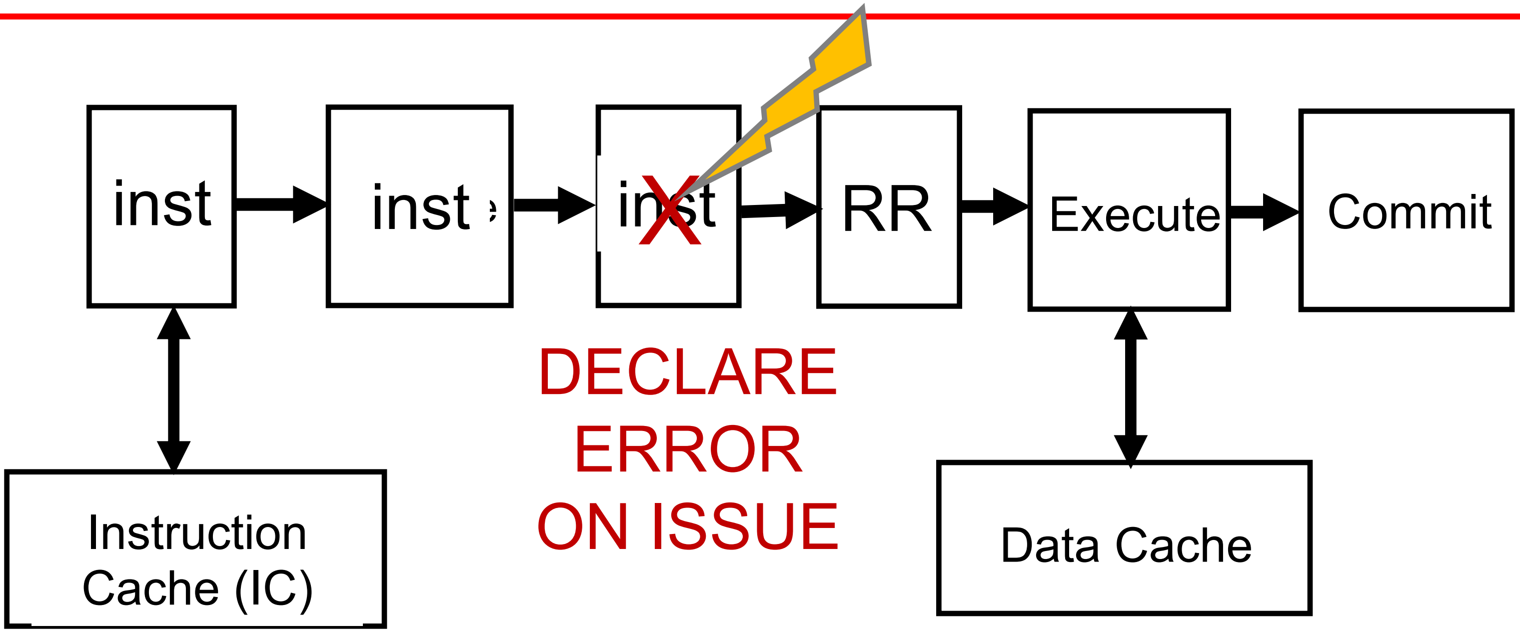
DUE AVF of Instruction Queue with Parity



CPU2000
Asim
Simpoint
Itanium®2-like

Coping with Wrong-Path Instructions

(assume parity-protected instruction queue)

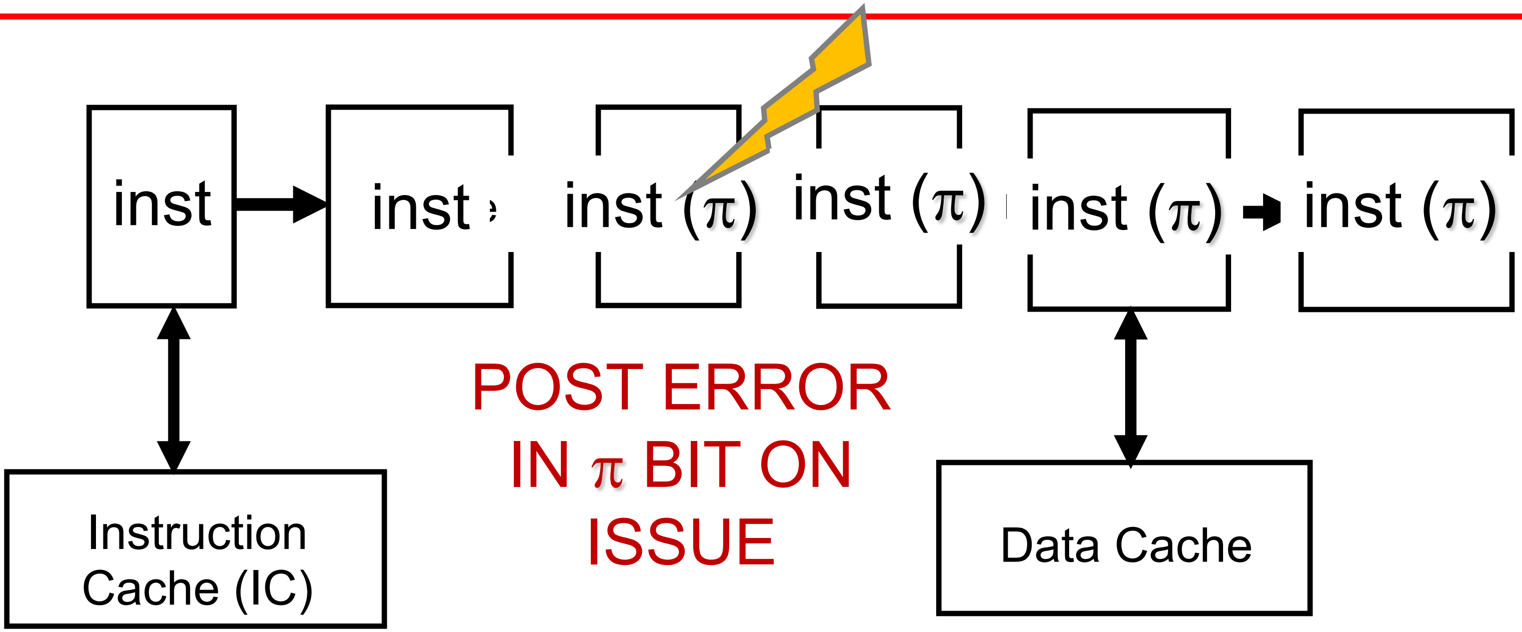


DECLARE ERROR ON ISSUE

- Problem: not enough information at issue

The π (Possibly Incorrect) Bit

(assume parity-protected instruction queue)



POST ERROR IN π BIT ON ISSUE

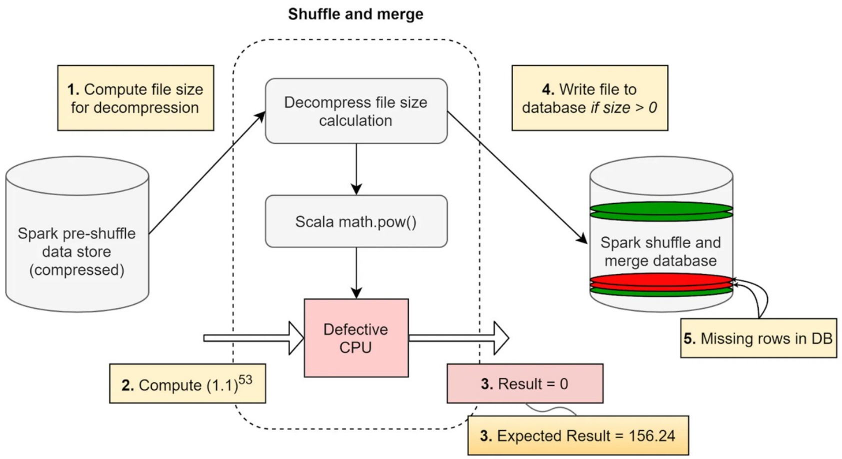
At commit point, declare error only if not wrong-path instruction and π bit is set

Sources of False DUE in an Instruction Queue

- Instructions with uncommitted results
  - e.g., wrong-path, predicated-false
  - solution: π (possibly incorrect) bit till commit
- Instruction types neutral to errors
  - e.g., no-ops, prefetches, branch predict hints
  - solution: anti-π bit
- Dynamically dead instructions
  - instructions whose results will not be used in future
  - solution: π bit beyond commit

Reliability Problems in 2020s

- Silent Data Corruption (SDC)
  - Cloud companies noticed SDC is a widespread problem for large-scale infrastructure systems.
  - "Cores that don't count" by Google, HotOS, 2021
  - "Silent data corruption at Scale" by Facebook, Arxiv, 2021
- Problems
  - Long error detection latencies: taking days to weeks
  - Scalability



Example errors:

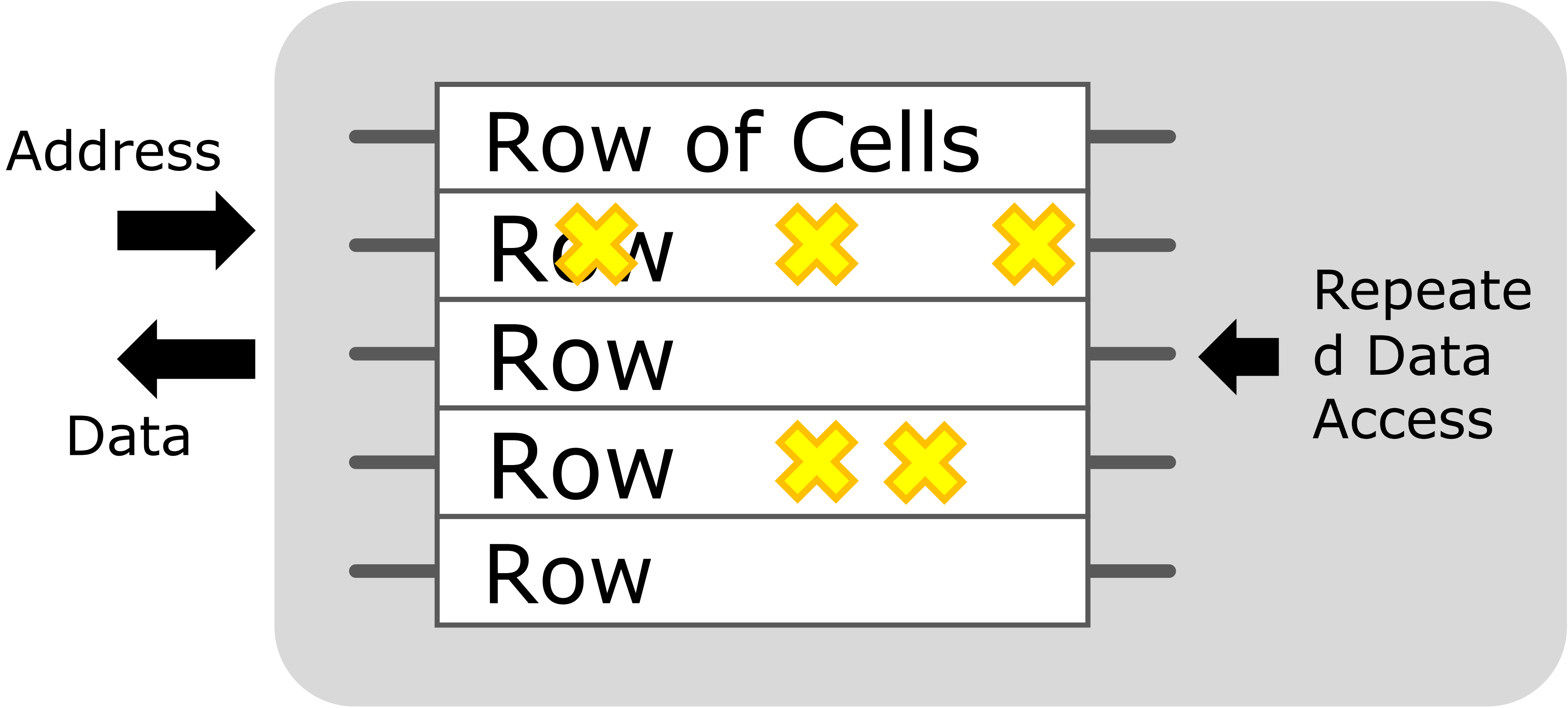
$Int\,[(1.1)^{3}] = 0\,,\ expected = 1$

$Int\,[(1.1)^{107}] = 32809\,,\ expected = 26854$

$Int\,[(1.1)^{-3}] = 1\,,\ expected = 0$

Reliability Problems in 2020s

- Rowhammer: Repeatedly accessing a row enough times can cause disturbance errors in nearby rows



Thank you!

Next Lecture:
Transactional Memory