Reliable Computing I

Lecture 10: Re-execution

Instructor: Mehdi Tahoori
Today’s Lecture

- Re-Execution techniques
  - RESO
  - Multithreading
Re-Execution

- Replicate the actions on a module either
  - on the same module (temporal redundancy) or
  - on spare modules (temporal & spatial redundancy)
- Good for detecting and/or correcting transient faults
  - Transient error will only affect one execution
- Analogy from real life: calling to confirm a reservation
- Can implement this at many different levels
  - ALU
  - Thread context
  - Processor
  - System
Re-Execution with Shifted Operands (RESO)

- Re-execute the same arithmetic operations, but with shifted operands (question: why shift?)
- Goal: detect errors in ALU
- Example: shift left by 2
  - Simplified example: we’re ignoring wraparound

\[
\begin{array}{c}
0 & 0 & 1 & 0 \\
+ & 1 & 0 & 0 & 1 \\
\hline
1 & 0 & 1 & 0 \\
\end{array}
\quad
\begin{array}{c}
1 & 0 & X & X \\
+ & 0 & 1 & X & X \\
\hline
1 & 1 & X & X \\
\end{array}
\]

- By comparing output bit 0 of the first execution and output bit 2 of the shifted re-execution, we detect an error in the ALU, since they should be equal
Re-Execution With a Twist

- After adding $A + B = C$, then compute $C - B$
  - If we don’t get $A$, there’s a problem
- What new types of faults/errors does this detect?
- How general is this approach?
  - I.e., how many operations are reversible?
  - Can we extend this to higher-level operations (algorithms)?
- The devil is in the details (corner cases)
  - Overflow, underflow, divide by zero, etc.
- This type of execution checking is more frequently performed at the software level … why?
Re-Execution with Processes

- Use redundant process to detect errors
- If we only have one CPU with a single-threaded core, we must execute two processes sequentially and then compare their results. If they differ, there’s an error.
  - Problem: slowdown factor = 2
- In a multicore, we can execute copies of the same process simultaneously on 2 cores and have them periodically compare their results
  - Most modern processors are multicore “Chip Multi Processor” (CMP)
  - Almost no slowdown, except for comparisons
  - Disadvantages: the opportunity cost and power/energy cost of not using that other core to perform non-redundant work
  - Is this an FER approach? (hint: what happens if an error occurs?)
Re-Execution with Threads

- Use redundant threads to detect/correct errors
  - A thread is like a process, except that multiple threads can share the same address space
- Many current microprocessors (Intel, AMD, IBM), are multithreaded (“hyperthreaded”, if you work for Intel)
  - Each processor can run multiple processes or multiple threads of the same process (i.e., it has multiple thread contexts)
- Can re-execute a program on multiple thread contexts, just like with multiple processors
  - Better performance than re-execution with multiple processors, since the comparison can be performed on-chip
  - Less opportunity cost to use extra thread context than extra processor
Fault Detection via Lockstepping (HP Himalaya)

Replicated Microprocessors + Cycle-by-Cycle Lockstepping
Fault Detection via Simultaneous Multithreading

Input Replication

Output Comparison

Memory covered by ECC
RAID array covered by parity
Servernet covered by CRC

Without lockstepping: Transient redundancy is not guaranteed!
→ Solution in later slides

Replicated Microprocessors + Cycle-by-Cycle Lockstepping
Recap: Simultaneous Multithreading (SMT)

Example: Alpha 21464, Intel Northwood, many more recent architectures

(More details on threading in lectures from CAPP, Prof. Karl)
# Redundant Multithreading (RMT)

- **RMT = Multithreading + Fault Detection (& Recovery)**

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<th>Redundant Multithreading (RMT)</th>
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| Chip Multiprocessor (CMP) | Multiple Threads running on CMP | Chip-Level Redundant Threading (CRT) |
Sphere of Replication

- Two copies of each architecturally visible thread
  - Co-scheduled on SMT core
  - Compare results: signal fault if different
Basic Pipeline

Both leading & trailing threads would go through this pipeline
Load Value Queue (LVQ)

- Keep threads on same path despite I/O or MP writes
- Out-of-order load issue possible
Store Queue Comparator (STQ)

- Store Queue Comparator
  - Compares outputs to data cache
  - Catch faults before propagating to rest of system
Branch Outcome Queue (BOQ)

- **Branch Outcome Queue**
  - Forward leading-thread branch targets to trailing fetch
  - 100% prediction accuracy in absence of faults
Line Prediction Queue (LPQ)

- Alpha 21464 fetches chunks using line predictions
- Chunk = contiguous block of 8 instructions
SRT Performance

- One logical thread → two hardware contexts
  - Performance degradation = 30%
  - Per-thread store queue buys extra 4%
- Two logical threads → four hardware contexts
  - Average slowdown increases to 40%
  - Only 32% with per-thread store queues

SRT = Simultaneous Redundant Threading
Redundant Multithreading (RMT)

RMT = Multithreading + Fault Detection (& Recovery)

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Chip-Level Redundant Threading

- SRT typically more efficient than splitting one processor into two half-size CPUs
- What if you already have two CPUs? = Multicore
  - Conceptually easy to run these in lock-step
    - Benefit: full physical redundancy
    - Costs:
      - Changed hardware design
      - Latency through centralized checker logic
      - Overheads (misspeculation etc.) incurred twice
- CRT combines best of SRT & lockstepping
  - Only requires multithreaded CMP cores
- With per-thread store queues, ~13% improvement over lockstepping with 8-cycle checker latency
Chip-Level Redundant Threading

CPU A

Leading Thread A

Trailing Thread B

CPU B

Trailing Thread A

Leading Thread B

LVQ

LPQ

Stores