CIS 501
Computer Architecture

Unit 10: Hardware Multithreading

This Unit: Multithreading (MT)

Application		
OS		
Compiler	Firmware	
CPU	I/O	
Memory		
Digital Circuits		
Gates & Transistors		
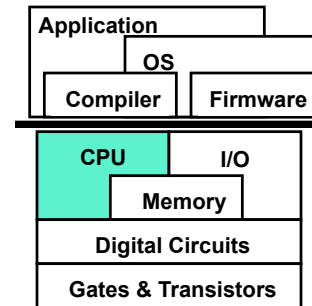
- Why multithreading (MT)?
  - Utilization vs. performance
- Three implementations
  - Coarse-grained MT
  - Fine-grained MT
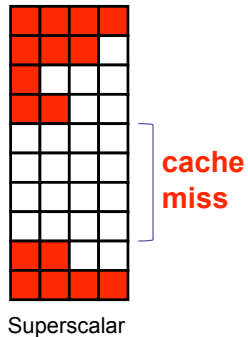 - Simultaneous MT (SMT)

Readings

- H+P
  - Chapter 3.5-3.6

- Paper
  - Tullsen et al., "Exploiting Choice…"

Performance And Utilization

- Performance (IPC) important
- Utilization (actual IPC / peak IPC) important too

- Even moderate superscalars (e.g., 4-way) not fully utilized
  - Average sustained IPC: 1.5–2 → < 50% utilization
    - Mis-predicted branches
    - Cache misses, especially L2
    - Data dependences

- **Multi-threading (MT)**
  - Improve utilization by multi-plexing multiple threads on single CPU
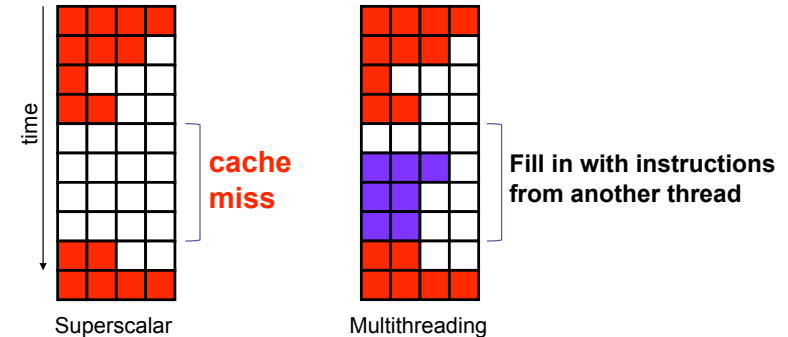 - One thread cannot fully utilize CPU? Maybe 2, 4 (or 100) can

Superscalar Under-utilization

- Time evolution of issue slot
  - 4-issue processor

cache miss

Superscalar

Simple Multithreading

- Time evolution of issue slot
  - 4-issue processor

time

cache miss

Fill in with instructions from another thread

Superscalar   Multithreading

- Where does it find a thread? Same problem as multi-core
  - Same shared-memory abstraction

Latency vs Throughput

- **MT trades (single-thread) latency for throughput**
  - – Sharing processor degrades latency of individual threads
  - + But improves aggregate latency of both threads
  - + Improves utilization
- Example
  - Thread A: individual latency=10s, latency with thread B=15s
  - Thread B: individual latency=20s, latency with thread A=25s
  - Sequential latency (first A then B or vice versa): 30s
  - Parallel latency (A and B simultaneously): 25s
  - – MT slows each thread by 5s
  - + But improves total latency by 5s
- **Different workloads have different parallelism**
  - SpecFP has lots of ILP (can use an 8-wide machine)
  - Server workloads have TLP (can use multiple threads)

# MT Implementations: Similarities

- How do multiple threads share a single processor?
  - Different sharing mechanisms for different kinds of structures
  - Depend on what kind of state structure stores

- **No state**: ALUs
  - Dynamically shared
- **Persistent hard state (aka "context")**: PC, registers
  - Replicated
- **Persistent soft state**: caches, bpred
  - Dynamically partitioned (like on a multi-programmed uni-processor)
    - TLBs need thread ids, caches/bpred tables don't
  - Exception: **ordered "soft" state** (BHR, RAS) is replicated
- **Transient state**: pipeline latches, ROB, RS
  - Partitioned … somehow

MT Implementations: Differences

- Main question: **thread scheduling policy**
  - When to switch from one thread to another?
- Related question: **pipeline partitioning**
  - How exactly do threads share the pipeline itself?

- Choice depends on
  - What kind of latencies (specifically, length) you want to tolerate
  - How much single thread performance you are willing to sacrifice

- Three designs
  - Coarse-grain multithreading (CGMT)
  - Fine-grain multithreading (FGMT)
  - Simultaneous multithreading (SMT)

The Standard Multithreading Picture

- Time evolution of issue slots
  - Color = thread

Superscalar   CGMT   FGMT   SMT
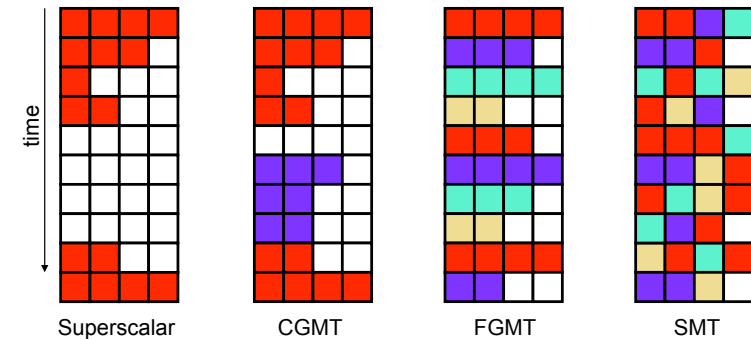
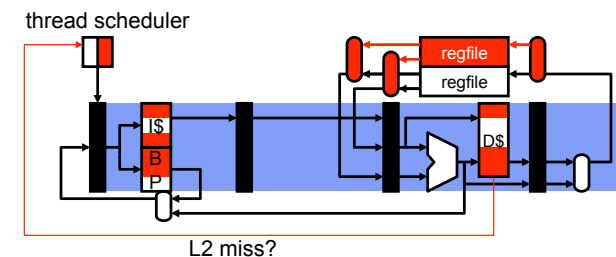# Coarse-Grain Multithreading (CGMT)

- **Coarse-Grain Multi-Threading (CGMT)**
  - + Sacrifices very little single thread performance (of one thread)
  - – Tolerates only long latencies (e.g., L2 misses)
  - Thread scheduling policy
    - Designate a "preferred" thread (e.g., thread A)
    - Switch to thread B on thread A L2 miss
    - Switch back to A when A L2 miss returns
  - Pipeline partitioning
    - None, flush on switch
    - – Can't tolerate latencies shorter than twice pipeline depth
    - Need short in-order pipeline for good performance

 - Example: IBM Northstar/Pulsar

CGMT
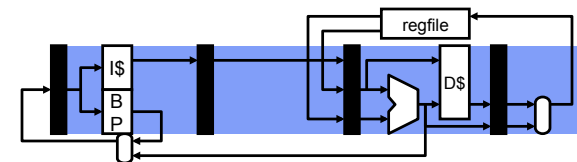
- CGMT

Fine-Grain Multithreading (FGMT)

- **Fine-Grain Multithreading (FGMT)**
  - – Sacrifices significant single thread performance
  - + Tolerates latencies (e.g., L2 misses, mispredicted branches, etc.)
  - Thread scheduling policy
    - Switch threads every cycle (round-robin), L2 miss or no
  - Pipeline partitioning
    - Dynamic, no flushing
    - Length of pipeline doesn't matter so much
  - – Need a lot of threads
  - Extreme example: Denelcor HEP
    - So many threads (100+), it didn't even need caches
    - Failed commercially
  - Not popular today
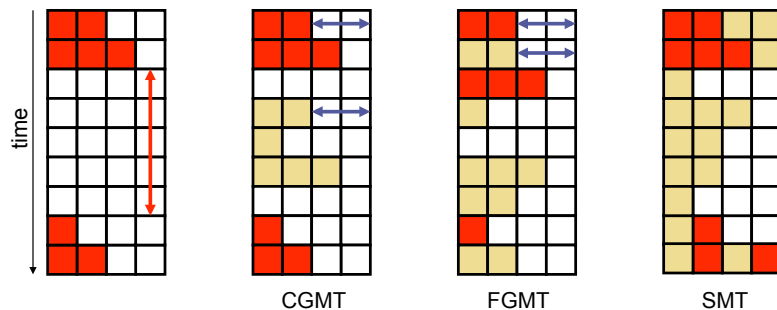   - Many threads → many register files

Fine-Grain Multithreading

- FGMT
  - **Multiple threads in pipeline at once**
  - (Many) more threads
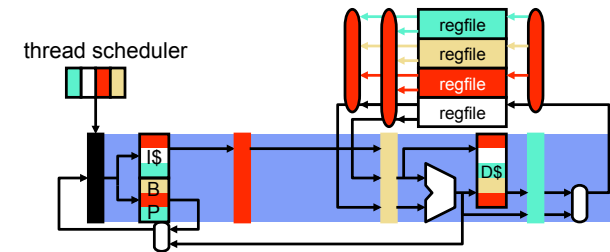
# Vertical and Horizontal Under-Utilization

- FGMT and CGMT reduce **vertical under-utilization**
  - Loss of all slots in an issue cycle
- Do not help with **horizontal under-utilization**
 - Loss of some slots in an issue cycle (in a superscalar processor)

Simultaneous Multithreading (SMT)

- What can issue insns from multiple threads in one cycle?
  - Same thing that issues insns from multiple parts of same program...
  - ...out-of-order execution

- **Simultaneous multithreading (SMT)**: OOO + FGMT
  - Aka **"hyper-threading"**
  - Observation: once insns are renamed, scheduler doesn't care which thread they come from (well, for non-loads at least)
  - Some examples
    - IBM Power5: 4-way issue, 2 threads
    - Intel Pentium4: 3-way issue, 2 threads
    - Intel "Nehalem": 4-way issue, 2 threads
    - Alpha 21464: 8-way issue, 4 threads (canceled)
    - Notice a pattern? #threads (T) * 2 = #issue width (N)

# Simultaneous Multithreading (SMT)
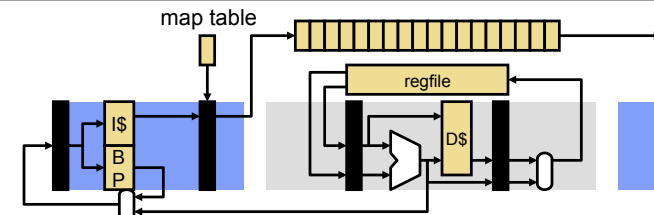
- SMT
 - Replicate map table, share (larger) physical register file
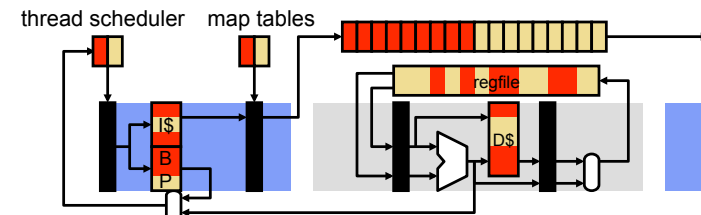
SMT Resource Partitioning

- Physical regfile and insn buffer entries shared at fine-grain
  - Physically unordered and so fine-grain sharing is possible
- How are physically ordered structures (ROB/LSQ) shared?
  - Fine-grain sharing (below) would entangle commit (and squash)
  - Allowing threads to commit independently is important
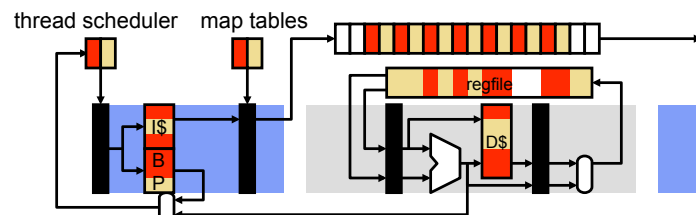
Static & Dynamic Resource Partitioning

- **Static partitioning** (below)
  - T equal-sized contiguous partitions
  - ± No starvation, sub-optimal utilization (fragmentation)
- **Dynamic partitioning**
  - P > T partitions, available partitions assigned on need basis
  - ± Better utilization, possible starvation
  - ICOUNT: fetch policy prefers thread with fewest in-flight insns
- Couple both with larger ROBs/LSQs
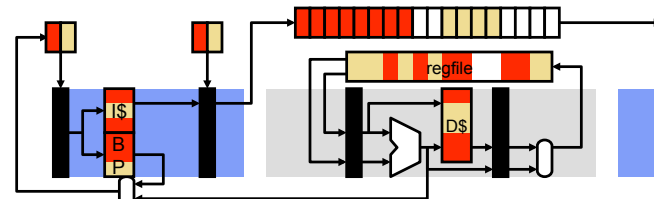
Multithreading Issues

- Shared soft state (caches, branch predictors, TLBs, etc.)
- Key example: **cache interference**
  - General concern for all MT variants
  - Can the working sets of multiple threads fit in the caches?
  - Shared memory SPMD threads help here
    + Same insns → share I$
    + Shared data → less D$ contention
    - MT is good for workloads with shared insn/data
  - To keep miss rates low, SMT might need a larger L2 (which is OK)
    - Out-of-order tolerates L1 misses

- Large physical register file (and map table)
  - physical registers = (**#threads** * #arch-regs) + #in-flight insns
  - map table entries = (**#threads** * #arch-regs)

Notes About Sharing Soft State

- Caches are shared naturally…
  - Physically-tagged: address translation distinguishes different threads
- … but TLBs need explicit thread IDs to be shared
  - Virtually-tagged: entries of different threads indistinguishable
  - Thread IDs are only a few bits: enough to identify on-chip contexts
- Thread IDs make sense on BTB (branch target buffer)
  - BTB entries are already large, a few extra bits / entry won't matter
  - Different thread's target prediction → automatic mis-prediction
- … but not on a BHT (branch history table)
  - BHT entries are small, a few extra bits / entry is huge overhead
  - Different thread's direction prediction → mis-prediction not automatic
- Ordered soft-state should be replicated
  - Examples: Branch History Register (BHR), Return Address Stack (RAS)
  - Otherwise it becomes meaningless… Fortunately, it is typically small

Multithreading vs. Multicore

- If you wanted to run multiple threads would you build a…
  - A multicore: multiple separate pipelines?
  - A multithreaded processor: a single larger pipeline?
- **Both will get you throughput on multiple threads**
  - Multicore core will be simpler, possibly faster clock
  - SMT will get you better performance (IPC) on a single thread
    - SMT is basically an ILP engine that converts TLP to ILP
    - Multicore is mainly a TLP (thread-level parallelism) engine
- **Do both**
  - Sun's Niagara (UltraSPARC T1)
  - 8 processors, each with 4-threads (non-SMT threading)
  - 1Ghz clock, in-order, short pipeline (6 stages or so)
  - Designed for power-efficient "throughput computing"

Research: Speculative Multithreading

- **Speculative multithreading**
  - Use multiple threads/processors for **single-thread performance**
  - Speculatively parallelize sequential loops, that might not be parallel
    - Processing elements (called PE) arranged in logical ring
    - Compiler or hardware assigns iterations to consecutive PEs
    - Hardware tracks logical order to detect mis-parallelization
  - Techniques for doing this on non-loop code too
    - Detect reconvergence points (function calls, conditional code)
  - Effectively chains ROBs of different processors into one big ROB
    - Global commit "head" travels from one PE to the next
    - Mis-parallelization flushes one PEs, but **not all** PEs
  - Also known as split-window or "Multiscalar"
  - Not commercially available yet…
    - But it is the "biggest idea" from academia not yet adopted

Research: Multithreading for Reliability

- Can multithreading help with reliability?
  - Design bugs/manufacturing defects? No
  - Gradual defects, e.g., thermal wear? No
  - Transient errors? Yes

- **Staggered redundant multithreading (SRT)**
  - Run two copies of program at a slight stagger
  - Compare results, difference? Flush both copies and restart
  - – Significant performance overhead

Multithreading Summary

- Latency vs. throughput
- Partitioning different processor resources
- Three multithreading variants
  - Coarse-grain: no single-thread degradation, but long latencies only
  - Fine-grain: other end of the trade-off
  - Simultaneous: fine-grain with out-of-order
- Multithreading vs. chip multiprocessing