Motivation for Multithreaded Architectures

Processors not executing code at their hardware potential
- late '70's: performance lost to memory latency
- '90's: performance not in line with the increasingly complex parallel hardware as well
- increase in instruction issue bandwidth
- increase in number of functional units
- out-of-order execution
- techniques for decreasing/hiding branch & memory latencies
- Still, processor utilization was decreasing & instruction throughput not increasing in proportion to the issue width

Motivation for Multithreaded Architectures

Major cause is the lack of instruction-level parallelism in a single executing thread

Therefore the solution has to be more general than building a smarter cache or a more accurate branch predictor

Multithreading

Traditional multithreaded processors hardware switch to a different context to avoid processor stalls

Two styles of traditional multithreading
1. coarse-grain multithreading
   - switch on a long-latency operation (e.g., L2 cache miss)
   - another thread executes while the miss is handled
   - modest increase in instruction throughput
     - doesn’t hide latency of short-latency operations
     - no switch if no long-latency operations
     - need to fill the pipeline on a switch
     - potentially no slowdown to the thread with the miss
     - if stall is long & switch back fairly promptly
   - HEP, IBM RS64 III

2. fine-grain multithreading
   - can switch to a different thread each cycle (usually round robin)
   - hides latencies of all kinds
   - larger increase in instruction throughput but slows down the execution of each thread
   - Cray (Tera) MTA

Multithreaded Processors

Multithreaded processors can increase the pool of independent instructions & consequently address multiple causes of processor stalling
- holds processor state for more than one thread of execution
  - registers
  - PC
- each thread’s state is a hardware context
- execute the instruction stream from multiple threads without software context switching
- utilize thread-level parallelism (TLP) to compensate for a lack in ILP
### Comparison of Issue Capabilities

#### Superscalar horizontal waste

- Threads can switch to different threads each cycle.
- Switches to ready threads only.
- Up to 128 hardware contexts.
  - Lots of latency to hide, mostly from the multi-hop interconnection network.
  - Average instruction latency for computation: 22 cycles (i.e., 22 instruction streams needed to keep functional units busy).
  - Average instruction latency including memory: 120 to 200 cycles (i.e., 120 to 200 instruction streams needed to hide all latency, on average).
  - Processor state for all 128 contexts.
  - GPRs (total of 4K registers!).
  - Status registers (includes the PC).
  - Branch target registers/stream.

#### Traditional Multithreading

- Issues multiple instructions from a single thread each cycle.
- No processor-side data caches.
  - Increases the latency for data accesses but reduces the variation between ops.
  - To avoid having to keep caches coherent.
  - Memory-side buffers instead.
  - L1 & L2 instruction caches.
  - Instruction accesses are more predictable & have no coherency problem.
  - Prefetch fall-through & target code.

#### SMT

- Issues multiple instructions from multiple threads each cycle.
- No hardware context switching.
- Same-cycle multithreading.
- Huge boost in instruction throughput with less degradation to individual threads.

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### Cray (Tera) MTA

#### Goals

- The appearance of uniform memory access.
- Lightweight synchronization.
- Heterogeneous parallelism.

#### Interesting features

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**Cray (Tera) MTA**

**Interesting features**
- Trade-off between avoiding memory bank conflicts & exploiting spatial locality for data
  - conflicts:
    - memory distributed among hardware contexts
    - memory addresses are randomized to avoid conflicts
    - want to fully utilize all memory bandwidth
    - good unit stride performance
    - replicate instructions in multiple memory banks
  - locality:
    - run-time system can confine consecutive virtual addresses to a single (close-by) memory unit
    - used mainly for the stack

**Run-time support**
- number of executing threads
  - protection domains: group of threads executing in the same virtual address space
  - RT sets the maximum number of thread contexts (instruction streams) a domain is allowed (compiler estimate)
  - domain can create & kill threads within that limit, depending on its need for them

**Simultaneous multithreaded (SMT) processors** combine designs from:
- out-of-order superscalar processors
- traditional multithreaded processors

The combination enables a processor
- that issues & executes instructions from multiple threads simultaneously
  - > converting TLP to ILP
- in which threads share almost all hardware resources

**Compiler support**
- VLIW instructions
  - memory/ arithmetic/ branch
  - load/ store architecture
  - need a good code scheduler
- memory dependence look-ahead
  - field in a memory instruction that specifies the number of independent memory ops that follow
  - guarantees nonstalling instruction choice
  - improves memory parallelism
- handling branches
  - special instruction to store a branch target in a register before the branch is executed
  - can start prefetching the target code

**Cray (Tera) MTA**

**Interesting features**
- tagged memory
  - indirectly set full/ empty bits to prevent data races
    - prevents a consumer/ producer from loading/ overwriting a value before a producer/ consumer has written/ read it
    - set to empty when producer instruction starts executing
      - consumer instructions block if try to read the producer value
      - set to full when producer writes value
        - consumers can now read a valid value
        - explicitly set full/ empty bits for thread synchronization
          - primarily used accessing shared data
            - lock: read memory location & set to empty
            - other readers are blocked
            - unlock: write & set to full

**Interesting features**
- no paging
  - want pages pinned down in memory
    - page size is 256MB
- forward bit
  - memory contents interpreted as a pointer & dereferenced
  - used for GC & null reference checking
- user-mode trap handlers
  - lighter weight
  - used for fatal exceptions, overflow, normalizing floating point numbers
  - not used for protection - user might override the RT
  - designed for user-written trap handlers, but too complicated for users

**SMT: The Executive Summary**
Performance Implications

Multiprogramming workload
- 2.5X on SPEC95, 4X on SPEC2000
Parallel programs
- ~1.7X on SPLASH2
Commercial databases
- 2-3X on TPC B; 1.5X on TPC D
Web servers & OS
- 4X on Apache and Digital Unix

Does this Processor Sound Familiar?

Technology transfer =>
- 2-context Intel Hyperthreading
- 4-context IBM Power5
- 2-context Sun UltraSPARC on a 4-processor CMP
- 4-context Compaq 21464
- network processor & mobile device start-ups
- others in the wings

An SMT Architecture

Three primary goals for this architecture:
1. Achieve significant throughput gains with multiple threads
2. Minimize the performance impact on a single thread executing alone
3. Minimize the microarchitectural impact on a conventional out-of-order superscalar design

Implementing SMT

No special hardware for scheduling instructions from multiple threads
- use the out-of-order renaming & instruction scheduling mechanisms
- physical register pool model
- renaming hardware eliminates false dependences both within a thread (just like a superscalar) & between threads

How it works:
- map thread-specific architectural registers onto a pool of thread-independent physical registers
- operands are thereafter called by their physical names
- an instruction is issued when its operands become available & a functional unit is free
- instruction scheduler not consider thread IDs when dispatching instructions to functional units (unless threads have different priorities)

From Superscalar to SMT

Extra pipeline stages for accessing thread-shared register files
- 8 threads * 32 registers + renaming registers

SMT instruction fetcher (iCOUNT)
- fetch from 2 threads each cycle
- count the number of instructions for each thread in the pre-execution stages
- pick the 2 threads with the lowest number
- in essence fetching from the two highest throughput threads
From Superscalar to SMT

Per-thread hardware
• small stuff
  • all part of current out-of-order processors
  • none endangers the cycle time
• other per-thread processor state, e.g.,
  • program counters
  • return stacks
  • thread identifiers, e.g., with BTB entries, TLB entries
• per-thread bookkeeping for, e.g.,
  • instruction queue flush
  • instruction retirement
  • trapping

This is why there is only a 15% increase to Alpha 21464 chip area.

Implementing SMT

Thread-shared hardware:
• fetch buffers
• branch prediction structures
• instruction queues
• functional units
• active list
• all caches & TLBs
• store buffers & MSHRs

This is why there is little single-thread performance degradation (~1.5%).

Architecture Research

Concept & potential of Simultaneous Multithreading: ISCA ’95 & ISCA 25th Anniversary Anthology
Designing the microarchitecture: ISCA ’96
• straightforward extension of out-of-order superscalars
I-fetch thread chooser: ISCA ’96
• 40% faster than round-robin
The lockbox for cheap synchronization: HPCA ’98
• orders of magnitude faster
• can parallelize previously unparallelizable codes

OS Research

Analysis of OS behavior on SMT: ASPLOS ’00
• Kernel-kernel conflicts in IS & DS & branch mispredictions ameliorated by SMT instruction issue + thread-sharing in HW

OS/runtime support for mini-threads: HPCA ’03
• dedicated server: recompile OS for fewer registers
• multiprogrammed environment: multiple versions

OS/runtime support for executing threaded programs: ISCA ’98 & PPoPP ’03
• page mapping, stack offsetting, dynamic memory allocation, synchronization
Others are Now Carrying the Ball

Fault detection & recovery
Thread-level speculation
Instruction & data prefetching
Instruction issue hardware design
Thread scheduling & thread priority
Single-thread execution
Profiling executing threads
SMT-CMP hybrids
Power considerations

SMT Collaborators

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For more info on SMT:
http://www.cs.washington.edu/research/smt