ECE/CS 250
Computer Architecture

Multicore and Multithreaded Processors
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Multicore and Multithreaded Processors

- Why multicore?
- Thread-level parallelism
- Multithreaded cores
- Multiprocessors
- Design issues
- Examples

Readings

- Patterson and Hennessy
  - Chapter 6
  - At least one recent research paper!

Why Multicore?

- Why is everything now multicore?
  - This is a fairly new trend
- Reason #1: Running out of "ILP" that we can exploit
  - Can't get much better performance out of a single core that's running a single program at a time
- Reason #2: Power/thermal constraints
  - Even if we wanted to just build fancier single cores at higher clock speeds, we'd run into power and thermal obstacles
- Reason #3: Moore's Law
  - Lots of transistors → what else are we going to do with them?
  - Historically: use transistors to make more complicated cores with bigger and bigger caches
  - But this strategy has run into problems

How do we keep multicores busy?

- Single core processors exploit ILP
- Multicore processors exploit TLP: thread-level parallelism
- What's a thread?
  - A program can have 1 or more threads of control
  - Each thread has own PC
  - All threads in a given program share resources (e.g., memory)
- OK, so where do we find more than one thread?
- Option #1: Multiprogrammed workloads
  - Run multiple single-threaded programs at same time
- Option #2: Explicitly multithreaded programs
  - Create a single program that has multiple threads that work together to solve a problem

Parallel Programming

- How do we break up a problem into sub-problems that can be worked on by separate threads?
- ICQ: How would you create a multithreaded program that searches for an item in an array?
- ICQ: How would you create a multithreaded program that sorts a heap?

- Fundamental challenges
  - Breaking up the problem into many reasonably sized tasks
    - What if tasks are too small? Too big? Too few?
  - Minimizing the communication between threads
    - Why?

Writing a Parallel Program

- Compiler can turn sequential code into parallel code
  - Just as soon as the Cleveland Indians win the World Series
- Can use an explicitly parallel language or extensions to an existing language
  - Map/reduce (Google), Hadoop
  - Pthreads
  - Java threads
  - Message passing interface (MPI)
  - CUDA
  - OpenCL
  - High performance Fortran (HPF)
  - Etc.

Parallel Program Challenges

- Parallel programming is HARD!
  - Why?
- Problem: #cores is increasing, but parallel programming isn't getting easier → how are we going to use all of these cores???

HPF Example

```
forall(i=1:100, j=1:200){
   MyArray[i,j] = X[i-1, j] + X[i+1, j];
}
```

// "forall" means we can do all i,j combinations in parallel
// I.e., no dependences between these operations

Some Problems Are "Easy" to Parallelize

- Database management system (DBMS)
- Web search (Google)
- Graphics
- Some scientific workloads (why?)
- Others??

Multicore and Multithreaded Processors

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Multithreaded Cores

- So far, our core executes one thread at a time
- Multithreaded core: execute multiple threads at a time
- Old idea … but made a big comeback fairly recently
- How do we execute multiple threads on same core?
  - Coarse-grain switching
  - Fine-grain switching
  - Simultaneous multithreading (SMT) → "hyperthreading" (Intel)
- Benefits?
  - Better instruction throughput
    - Greater resource utilization
    - Tolerates long latency events (e.g., cache misses)
  - Cheaper than multiple complete cores

Multiprocessors

- Multiprocessors have been around a long time … just not on a single chip
  - Mainframes and servers with 2-64 processors
  - Supercomputers with 100s or 1000s of processors
- Now, multiprocessor on a single chip
  - "multicore processor" (sometimes "chip multiprocessor")
- Why does "single chip" matter so much?
  - ICQ: What's fundamentally different about having a multiprocessor that fits on one chip vs. on multiple chips?

Multicore and Multithreaded Processors

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Multiprocessor Microarchitecture

- Many design issues unique to multiprocessors
  - Interconnection network
  - Communication between cores
  - Memory system design
  - Others?

Interconnection Networks

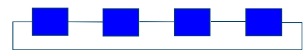
- Networks have many design aspects
  - We focus on one design aspect here (topology) → see ECE 552 (CS 550) and ECE 652 (CS 650) for more on this
- Topology is the structure of the interconnect
  - Geometric property → topology has nice mathematical properties
- Direct vs Indirect Networks
  - Direct: All switches attached to host nodes (e.g., mesh)
  - Indirect: Many switches not attached to host nodes (e.g., tree)

Direct Topologies: k-ary d-cubes

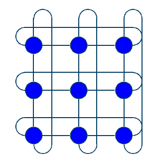
- Often called k-ary n-cubes
- General class of regular, direct topologies
  - Subsumes rings, tori, cubes, etc.
- d dimensions
  - 1 for ring
  - 2 for mesh or torus
  - 3 for cube
  - Can choose arbitrarily large d, except for cost of switches
- k switches in each dimension
  - Note: k can be different in each dimension (e.g., 2,3,4-ary 3-cube)

Examples of k-ary d-cubes (for N cores)

- 1D Ring = k-ary 1-cube
  - d = 1 [always]
  - k = N [always] = 4 [here]
  - Ave dist = ?



- 2D Torus = k-ary 2-cube
  - d = 2 [always]
  - k = $\log_d N$ (always) = 3 [here]
  - Ave dist = ?



k-ary d-cubes in Real World

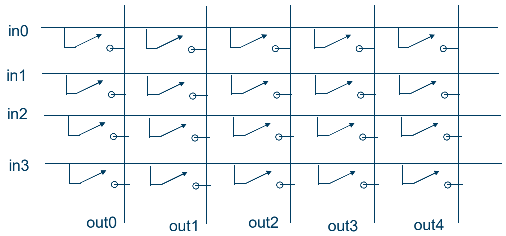
- Compaq Alpha 21364 (and 21464, R.I.P.)
  - 2D torus (k-ary 2-cube)
- Cray T3D and T3E
  - 3D torus (k-ary, 3-cube)
- Intel's MIC (formerly known as Larrabee)
  - 1D ring
- Intel's SandyBridge (one flavor of core i7)
  - 2D mesh

Indirect Topologies

- Indirect topology – most switches not attached to nodes
- Some common indirect topologies
  - Crossbar
  - Tree
  - Butterfly
- Each of the above topologies comes in many flavors

Indirect Topologies: Crossbar

- Crossbar = single switch that directly connects n inputs to m outputs
  - Logically equivalent to m n:1 muxes
- Very useful component that is used frequently



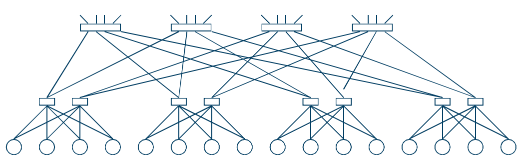
Indirect Topologies: Trees

- Indirect topology – most switches not attached to nodes
- Tree: send message up from leaf to closest common ancestor, then down to recipient

- N host nodes at leaves
- k = branching factor of tree (k=2 → binary tree)
- d = height of tree = $\log_k N$

Indirect Topologies: Fat Trees

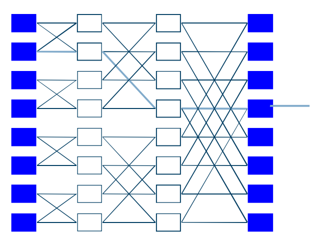
- **Problem with trees: too much contention at or near root**
- **Fat tree: same as tree, but with more bandwidth near the root (by adding multiple roots and high order switches)**



CM-5 "Thinned" Fat Tree

Indirect Topologies: Butterflies

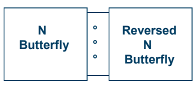
- **Multistage: nodes at ends, switches in middle**
- **Exactly one path between each pair of nodes**
- **Each node sees a tree rooted at itself**



Indirect Topologies: More Butterflies

- **In general, called k-ary, n-flies**
  - **n stages of radix-k switches**
- **Have many nice features, esp. $\log_n$ distances**
- **But conflicts cause tree saturation**
  - **How can we spread the traffic more evenly?**

Benes (pronounced "BEN-ish") Network



- **Routes all permutations w/o conflict**
- **Notice similarity to fat tree (fold in half)**
- **Randomization is major breakthrough**

Indirect Networks in Real World (ancient)

- Thinking Machines CM-5 (really old machine)
  - Fat tree
- Sun UltraEnterprise E10000 (old machine)
  - 4 trees (interleaved by address)
- And lots and lots of buses!

Multiprocessor Microarchitecture

- Many design issues unique to multiprocessors
  - Interconnection network
  - Communication between cores
  - Memory system design
  - Others?

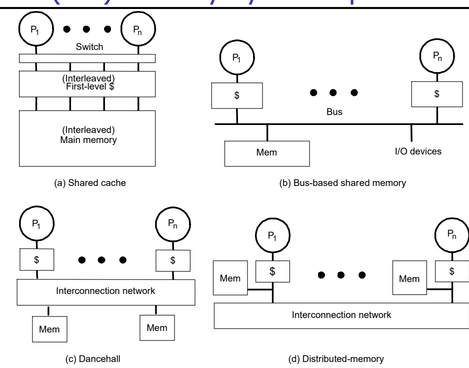
Communication Between Cores (Threads)

- How should threads communicate with each other?
- Two popular options
- Shared memory
  - Perform loads and stores to shared addresses
  - Requires synchronization (can't read before write)
- Message passing
  - Send messages between threads (cores)
  - No shared address space

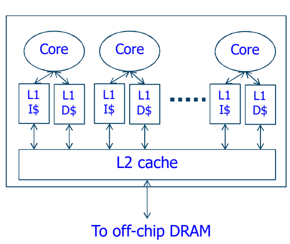
What is (Hardware) Shared Memory?

- Take multiple microprocessors
- Implement a memory system with a single global physical address space (usually)
  - Special HW does the "magic" of cache coherence

Some (Old) Memory System Options



A (Newer) Memory System Option

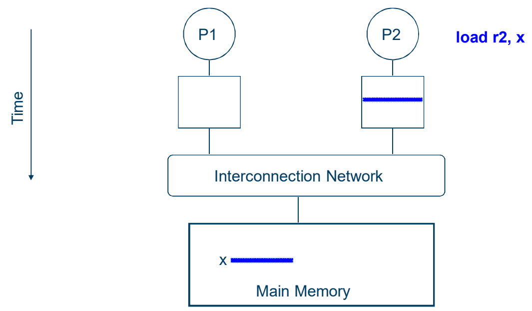


Cache Coherence

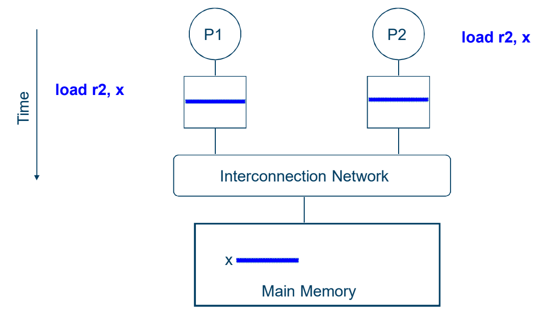
- According to Webster's dictionary …
  - Cache: a secure place of storage
  - Coherent: logically consistent
- Cache Coherence: keep storage logically consistent
  - Coherence requires enforcement of 2 properties per block

1) At any time, only one writer or >=0 readers of block
   - Can't have writer at same time as other reader or writer
2) Data propagates correctly
   - A request for a block gets the most recent value

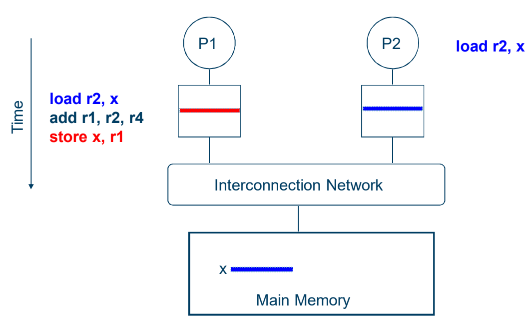
Cache Coherence Problem (Step 1)



Cache Coherence Problem (Step 2)



Cache Coherence Problem (Step 3)



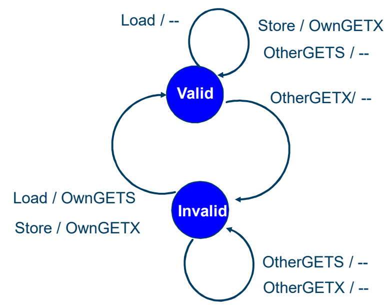
Snooping Cache-Coherence Protocols

- Each cache controller “snoops” all bus transactions
  - Transaction is relevant if it is for a block this cache contains
  - Take action to ensure coherence
    - Invalidate
    - Update
    - Supply value to requestor if Owner
  - Actions depend on the state of the block and the protocol
- Main memory controller also snoops on bus
  - If no cache is owner, then memory is owner
- Simultaneous operation of independent controllers

Processor and Bus Actions

- Processor:
  - Load
  - Store
  - Writeback on replacement of modified block
- Bus
  - GetShared (GETS): Get without intent to modify, data could come from memory or another cache
  - GetExclusive (GETX): Get with intent to modify, must invalidate all other caches' copies
  - PutExclusive (PUTX): cache controller puts contents on bus and memory is updated
  - Definition: cache-to-cache transfer occurs when another cache satisfies GETS or GETX request
- Let's draw it!

Simple 2-State Invalidate Snooping Protocol



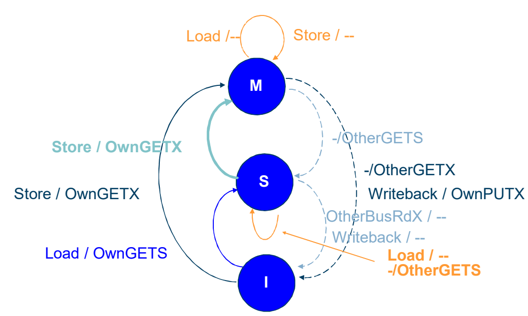
- Write-through, no-write-allocate cache
- Proc actions: Load, Store
- Bus actions: GETS, GETX

Notation: *observed event / action taken*

A 3-State Write-Back Invalidation Protocol

- 2-State Protocol
  - \+ Simple hardware and protocol
  - Uses lots of bandwidth (every write goes on bus!)
- 3-State Protocol (MSI)
  - Modified
    - One cache exclusively has valid (modified) copy ➔ Owner
    - Memory is stale
  - Shared
    - >= 1 cache and memory have valid copy (memory = owner)
  - Invalid (only memory has valid copy and memory is owner)
- Must invalidate all other copies before entering Modified state
- Requires bus transaction (order and invalidate)

MSI State Diagram



Note: we never take any action on an OtherPUTX

An MSI Protocol Example

Proc Action	P1 State	P2 state	P3 state	Bus Act	Data from
initially	I	I	I		
1. P1 load u	I→S	I	I	GETS	Memory
2. P3 load u	S	I	I→S	GETS	Memory
3. P3 store u	S→I	I	S→M	GETX	Memory or P1 (?)
4. P1 load u	I→S	I	M→S	GETS	P3's cache
5. P2 load u	S	I→S	S	GETS	Memory

- **Single writer, multiple reader protocol**
- **Why Modified to Shared in line 4?**
- **What if not in any cache? Memory responds**
- **Read then Write produces 2 bus transactions**
  - **Slow and wasteful of bandwidth for a common sequence of actions**

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Some Real-World Multicores

- Intel/AMD 2/4/8-core chips
  - Pretty standard
- Sun's Niagara (UltraSPARC T1-T3)
  - 4-16 simple, in-order, multithreaded cores
- Sun's Rock processor: 16 cores
- Cell Broadband Engine: in PlayStation 3
- Intel's MIC/Larrabee chip: 80 simple x86 cores in a ring
- Cisco CRS-1 Processor: 188 in-order cores
- Graphics processing units (GPUs): hundreds of "cores"