Directory-Based Cache Coherence Protocols
Why Directory Protocols?

- Snooping-based protocols may not scale
  - All requests must be broadcast to all processors
  - All processors should monitor all requests on the shared interconnect
  - Shared interconnect utilization can be high, leading to very long wait times

- Directory protocols
  - Coherence state maintained in a directory associated with memory
  - Requests to a memory block do not need broadcasts
    - Served by local nodes if possible
    - Otherwise, sent to owning node

- Note: Some snooping-based protocols do not require broadcast, and therefore are more scalable
Design Issues for Distributed Coherence Protocols

- Correctness
  - Memory consistency model: Performance vs. ease of programming
  - Deadlock avoidance
  - Error handling (fault tolerance)

- Performance
  - Latency
  - Bandwidth

- Distributed Control and Complexity

- Scalability
The Stanford DASH Prototype

- Directory Architecture for SHared memory
- Architecture consists of many clusters
  - Each cluster contains 4 processors
  - Processor caches
    - L1I: 64KB, direct mapped
    - L1D: 64KB, direct-mapped, write-through
    - L2: 256KB, direct-mapped, write-back
    - 4-word write buffer
  - Snooping implemented within a cluster (Illinois protocol, similar to MSI)
- General architecture of DASH: paper figure 1
- Sample 2x2 DASH system: paper figure 2
DASH Directories

- Directory controller (DC)
  - Directory memory corresponding to cluster’s main memory portion
  - Initiates out-bound network requests and replies
- Pseudo-CPU (PCPU)
  - Buffers incoming requests and issues them on cluster bus
  - Mimics a CPU on behalf of remote processors (except for bus replies sent by DC)
- Reply Controller (RC)
  - Remote Access Cache (RAC) tracks outstanding requests by local processors
  - Receives and buffers corresponding replies from remote clusters
  - RAC snoops on bus
- Requests and replies sent on two different networks using wormhole routing (discussed later in this course)
- Directory block diagram: paper figure 3
DASH Coherence Protocol

- **Terminology**
  - Local cluster: cluster containing the processor originating a request
  - Home cluster: cluster containing the main memory and directory for a given memory address
  - Remote cluster: Any cluster other than local and home clusters
  - Local memory: main memory associated with the local cluster
  - Remote memory: Any memory whose home is not the local cluster

- **Invalidation-based protocol**
  - Cache states: invalid, shared, and dirty

- **Directory state (for all local memory blocks)**
  - Uncached-remote: not cached by any remote cluster
  - Shared-remote: Cached, unmodified, by one or more remote clusters
  - Dirty-remote: Cached, modified, by one remote cluster

- **Owning cluster for a block** is the home cluster except if *dirty-remote*

- **Owning cluster responds to requests and updates directory state**
Read Requests

- Initiated by CPU load instruction
- If address is in L1 cache, L1 supplies data – otherwise, fill request sent to L2
- If address is in L2, L2 supplies data – otherwise, read request sent on bus
- If address is in the cache of another processor in the cluster or in the RAC, that cache responds
  - Shared: data transferred over the bus to requester
  - Dirty: data transferred over bus to requester, RAC takes ownership of cache line
- If address not in local cluster, processor retries bus operation, and request is sent to home cluster, RAC entry is allocated
- Requests to remote nodes explained in figure 4
Read-Exclusive Requests

- Initiated by CPU store instruction
- Data written through L1 and buffered in a write buffer
- If L2 has ownership permission, write is retired – otherwise, read-exclusive request sent on local bus
  - Write buffer is stalled
- If address is in “dirty” in one of the caches in the cluster or in the RAC
  - Owning cache sends data and ownership to requester
  - Owning cache invalidates its copy
- If address not in local cluster
  - Processor retries bus operation
  - Request is sent to home cluster
  - RAC entry is allocated
- Requests to remote nodes explained in figure 5
Other Implementation Details

- Writeback requests: When a dirty block is replaced
  - Home is local cluster: Write data to main memory
  - Home is a remote cluster: Send data to home which updates memory and state as “uncached-remote”
- Latency for memory operations: paper figure 6
- Exception conditions
  - Request to a dirty block of a remote cluster after it gave up ownership
  - Ownership bouncing back and forth between two remote clusters while a third cluster requests block
  - Multiple paths in the system lead to requests being received out of order
- Amount of information stored in directory affects scalability
  - For each memory block, DASH stores state and bit vector for other processors
  - For a more scalable system, overhead needs to be lower
The SGI Origin

- Cache coherent non-uniform memory access
- Up to 512 nodes
- Scalable Cray link network (hypercube)
- 1 or 2 R10000 MIPS processors per node
- Up to 4G bytes per node
- Node connects to a portion of the IO subsystem
- No snooping within node
Key Goals

- Scale to large number of processors
- Provide higher performance per processor
- Maintain cache-coherent globally addressable memory model
  - For ease of programming
- Entry level and incremental cost of the system lower than a high performance SMP
Origin Architecture

- Distributed shared memory (DSM)
- Directory based cache coherence
- Designed to minimize latency difference between local and remote memory
- Hardware and software provided to insure most memory references are local
- Origin block diagram: paper figure 1
- Cache coherence does not require in-order message delivery
- I/O subsystem is also distributed and globally addressable
- I/O can DMA to and from all memory in the system
- Cluster bus is multiplexed but is not a snoopy bus
  - Reduce local and remote memory latency
    - Fewer processors on the bus
    - Remote request does not need to wait for snoop response
Origin Architecture (Cont.)

- Non-snoopy node bus tradeoff
  - Disadvantage: remote bandwidth needs to match local bandwidth, unlike in SMP node systems
  - Advantage: easier migration path for existing SMP software

- Page migration and replication insures most references are local
  - Memory reference hardware counters
  - Copy engine to copy at near peak memory bandwidth

- Rich synchronization primitives

- Fetch and op primitives are not cached and performed at memory
  - Useful in highly contended locks

- HUB implements 4-way full crossbar between processors, memory and I/O-network

- RAS features
  - ECC in external cache and memory
  - Faulty packets automatic retries
  - Modular design provides highly available hardware
Network

- Six ported router chip
- Fat-hypercube (paper figures 3 and 4)
- Low latency wormhole routing
- Four virtual channels per physical channel
- Congestion control to allow messages to adaptively switch between two virtual channels
- Support for 256 levels of message priority
- Increased priority via packet aging
- Automatic packet retries
- Software programmable routing tables
Cache Coherence Protocol

- Similar to DASH protocol but with significant improvements
  - MESI protocol is fully supported
    - Single fetch from memory for read-modify-writes
    - Permits processor to replace E block in cache without informing directory
    - Requests from processors that had replaced E blocks can be immediately satisfied from memory
  - Support of upgrade requests from S to E without data transfer
- Cache coherence requests (see paper)
Configuration and Performance

- CPU Configuration
  - MIPS R10000
  - 195 MHz
  - 4-way out-of-order
  - 4 M byte L2 cache
  - Bus connected to the HUB chip

- Latency variation (paper table 4)
- High memory bandwidth (paper figures 11 & 12)
- Synchronization (paper figure 13)
Reading Assignment

- Wednesday

- Monday
  - Babak Falsafi and David Wood, "Reactive NUMA: A Design for Unifying S-COMA and CC-NUMA," ISCA 1997 (Skim)

- Homework 3 due Wednesday
  - Submission instructions same as HW2. Text and C files should be submitted in D2L