Cache coherence in shared-memory architectures

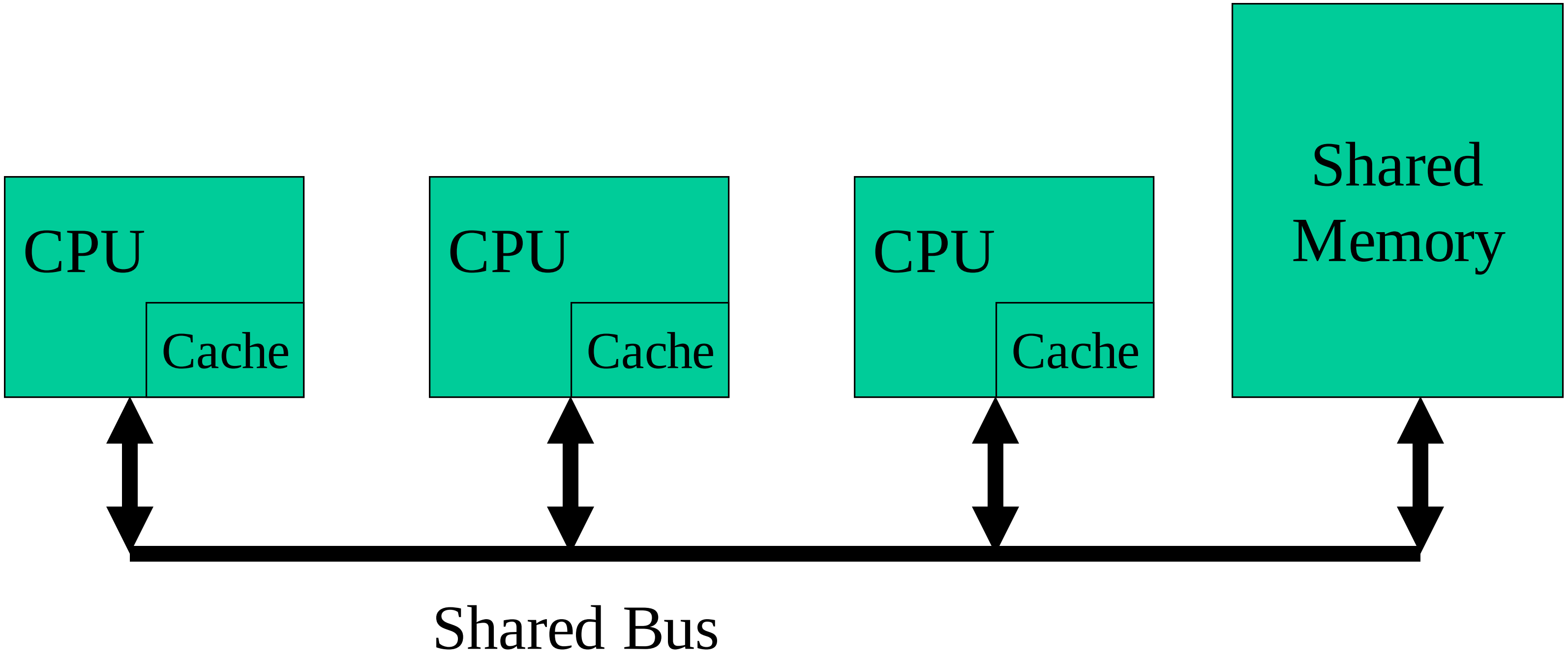
Adapted from a lecture by Ian Watson, University of Machester

Overview

- We have talked about optimizing performance on single cores
  - Locality
  - Vectorization
- Now let us look at optimizing programs for a shared-memory multiprocessor.
- Two architectures:
  - Bus-based shared-memory machines (small-scale)
  - Directory-based shared-memory machines (large-scale)

Bus-based Shared Memory Organization

Basic picture is simple :-



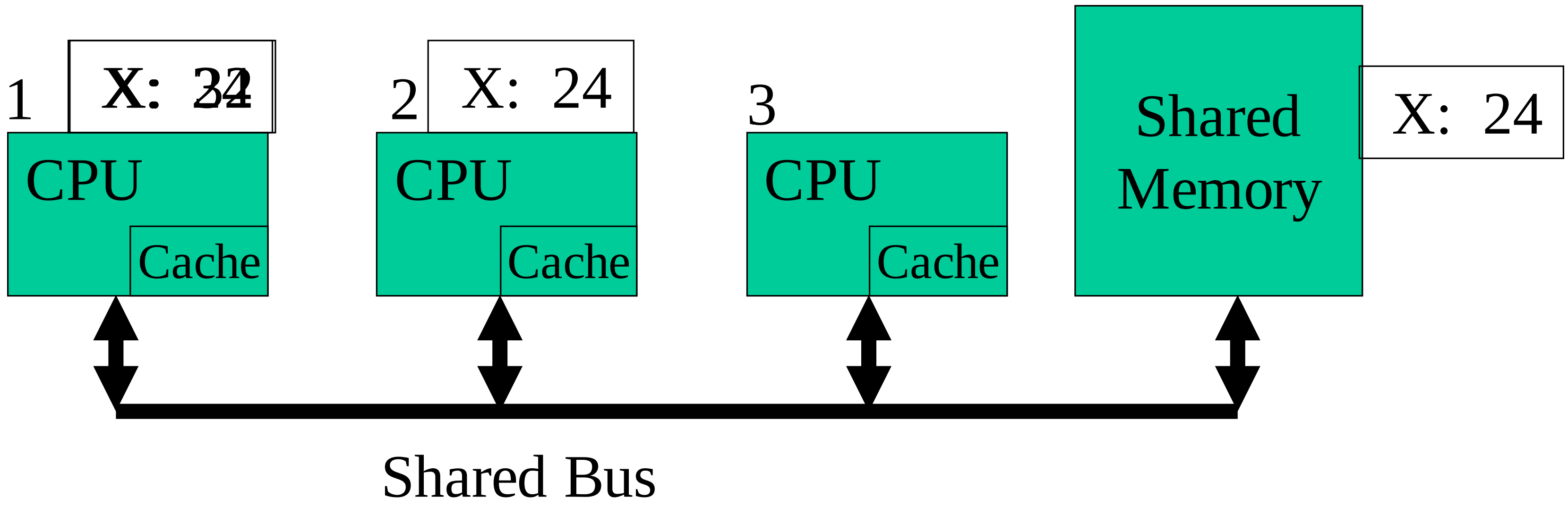
Organization

- Bus is usually simple physical connection (wires)
- Bus bandwidth limits no. of CPUs
- Could be multiple memory elements
- For now, assume that each CPU has only a single level of cache

Problem of Memory Coherence

- Assume just single level caches and main memory
- Processor writes to location in its cache
- Other caches may hold shared copies - these will be out of date
- Updating main memory alone is not enough

Example



Processor 1 reads X: obtains 24 from memory and caches it
Processor 2 reads X: obtains 24 from memory and caches it
Processor 1 writes 32 to X: its locally cached copy is updated
Processor 3 reads X: what value should it get?
Memory and processor 2 think it is 24
Processor 1 thinks it is 32

Notice that having write-through caches is not good enough

Bus Snooping

- Each CPU (cache system) ‘snoops’ (i.e. watches continually) for write activity concerned with data addresses which it has cached.
- This assumes a bus structure which is ‘global’, i.e all communication can be seen by all.
- More scalable solution: ‘directory based’ coherence schemes

Snooping Protocols

- Write Invalidate
  - CPU wanting to write to an address, grabs a bus cycle and sends a 'write invalidate' message
  - All snooping caches invalidate their copy of appropriate cache line
  - CPU writes to its cached copy (assume for now that it also writes through to memory)
  - Any shared read in other CPUs will now miss in cache and re-fetch new data.

Snooping Protocols

- Write Update
  - CPU wanting to write grabs bus cycle and broadcasts new data as it updates its own copy
  - All snooping caches update their copy
- Note that in both schemes, problem of simultaneous writes is taken care of by bus arbitration - only one CPU can use the bus at any one time.

Update or Invalidate?

- Update looks the simplest, most obvious and fastest, but:-
  - Multiple writes to same word (no intervening read) need only one invalidate message but would require an update for each
  - Writes to same block in (usual) multi-word cache block require only one invalidate but would require multiple updates.

Update or Invalidate?

- Due to both spatial and temporal locality, previous cases occur often.
- Bus bandwidth is a precious commodity in shared memory multi-processors
- Experience has shown that invalidate protocols use significantly less bandwidth.
- Will consider implementation details only of invalidate.

Implementation Issues

- In both schemes, knowing if a cached value is not shared (copy in another cache) can avoid sending any messages.
- Invalidate description assumed that a cache value update was written through to memory. If we used a ‘copy back’ scheme other processors could re-fetch old value on a cache miss.
- We need a protocol to handle all this.

MESI Protocol (1)

- A practical multiprocessor invalidate protocol which attempts to minimize bus usage.
- Allows usage of a ‘write back’ scheme - i.e. main memory not updated until ‘dirty’ cache line is displaced
- Extension of usual cache tags, i.e. invalid tag and ‘dirty’ tag in normal write back cache.

MESI Protocol (2)

Any cache line can be in one of 4 states (2 bits)

- **Modified** - cache line has been modified, is different from main memory - is the only cached copy. (multiprocessor 'dirty')
- **Exclusive** - cache line is the same as main memory and is the only cached copy
- **Shared** - Same as main memory but copies may exist in other caches.
- **Invalid** - Line data is not valid (as in simple cache)

MESI Protocol (3)

- Cache line changes state as a function of memory access events.
- Event may be either
  - Due to local processor activity (i.e. cache access)
  - Due to bus activity - as a result of snooping
- Cache line has its own state affected only if address matches

MESI Protocol (4)

- Operation can be described informally by looking at action in local processor
  - Read Hit
  - Read Miss
  - Write Hit
  - Write Miss
- More formally by state transition diagram

MESI Local Read Hit

- Line must be in one of MES
- This must be correct local value (if M it must have been modified locally)
- Simply return value
- No state change

MESI Local Read Miss (1)

- No other copy in caches
  - Processor makes bus request to memory
  - Value read to local cache, marked E
- One cache has E copy
  - Processor makes bus request to memory
  - Snooping cache puts copy value on the bus
  - Memory access is abandoned
  - Local processor caches value
  - Both lines set to S

MESI Local Read Miss (2)

- Several caches have S copy
  - Processor makes bus request to memory
  - One cache puts copy value on the bus (arbitrated)
  - Memory access is abandoned
  - Local processor caches value
  - Local copy set to S
  - Other copies remain S

MESI Local Read Miss (3)

- One cache has M copy
  - Processor makes bus request to memory
  - Snooping cache puts copy value on the bus
  - Memory access is abandoned
  - Local processor caches value
  - Local copy tagged S
  - **Source (M) value copied back to memory**
  - Source value M -> S

MESI Local Write Hit (1)

Line must be one of MES

- M
  - line is exclusive and already ‘dirty’
  - Update local cache value
  - no state change
- E
  - Update local cache value
  - State E -> M

MESI Local Write Hit (2)

- S
  - Processor broadcasts an invalidate on bus
  - Snooping processors with S copy change S->I
  - Local cache value is updated
  - Local state change S->M

MESI Local Write Miss (1)

Detailed action depends on copies in other processors

- No other copies
  - Value read from memory to local cache (?)
  - Value updated
  - Local copy state set to M

MESI Local Write Miss (2)

- Other copies, either one in state E or more in state S
  - Value read from memory to local cache - bus transaction marked RWITM (read with intent to modify)
  - Snooping processors see this and set their copy state to I
  - Local copy updated & state set to M

MESI Local Write Miss (3)

Another copy in state M

- Processor issues bus transaction marked RWITM
- Snooping processor sees this
  - Blocks RWITM request
  - Takes control of bus
  - Writes back its copy to memory
  - Sets its copy state to I

MESI Local Write Miss (4)

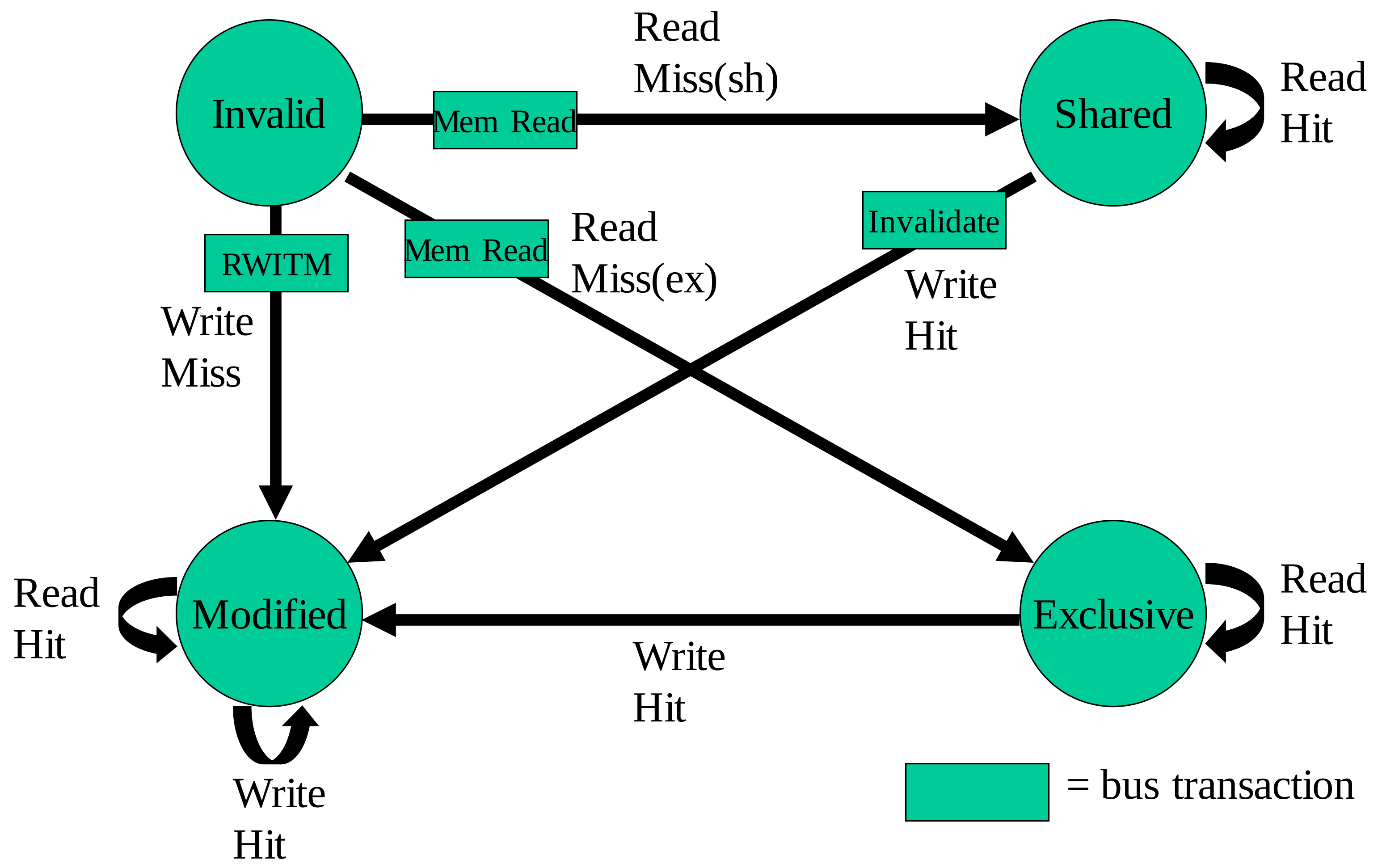
Another copy in state M (continued)

- Original local processor re-issues RWITM request
- Is now simple no-copy case
  - Value read from memory to local cache
  - Local copy value updated
  - Local copy state set to M

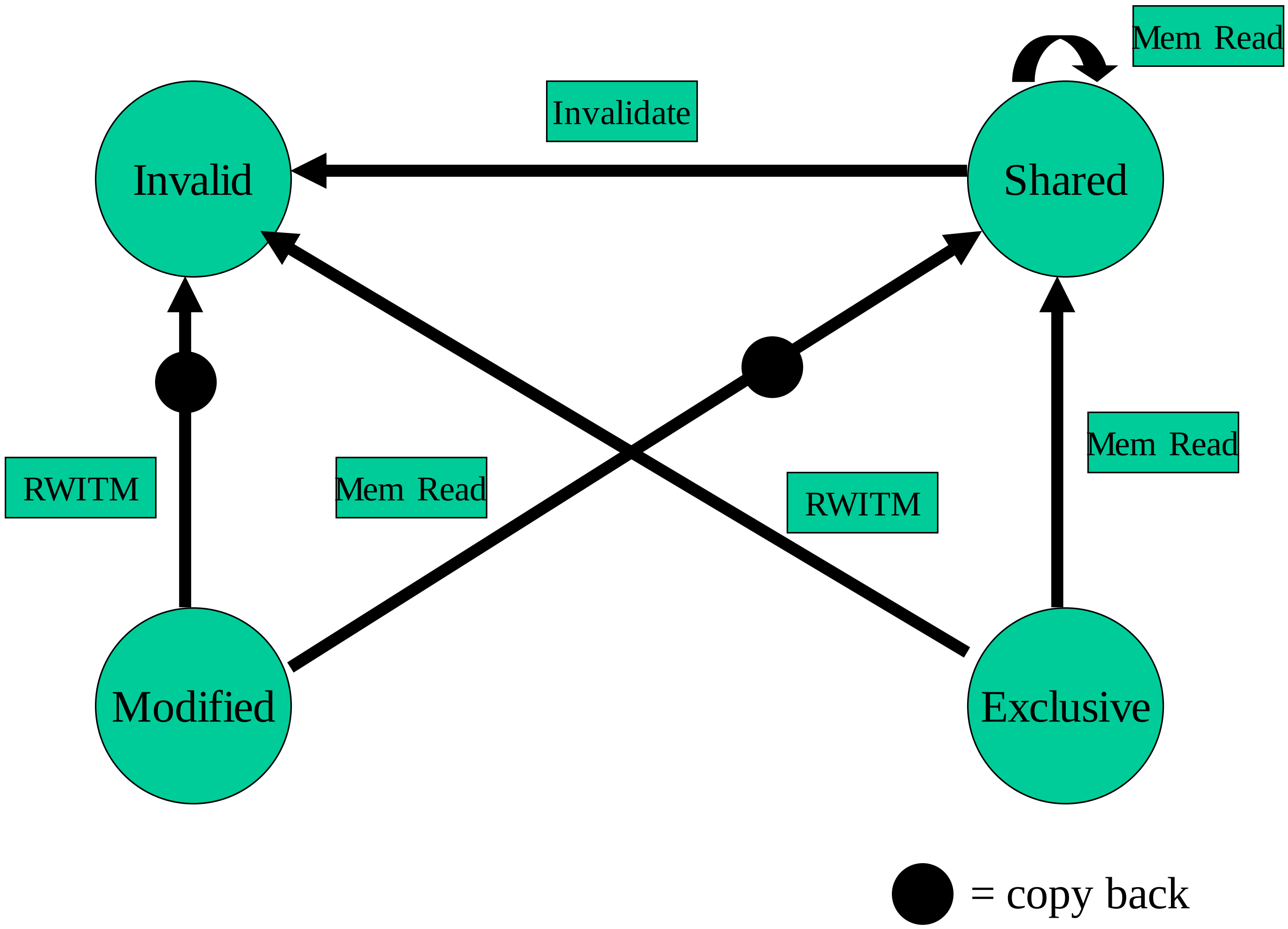
Putting it all together

- All of this information can be described compactly using a state transition diagram
- Diagram shows what happens to a cache line in a processor as a result of
  - memory accesses made by that processor (read hit/miss, write hit/miss)
  - memory accesses made by other processors that result in bus transactions observed by this snoopy cache (Mem read, RWITM,Invalidate)

MESI – locally initiated accesses



MESI – remotely initiated accesses



MESI notes

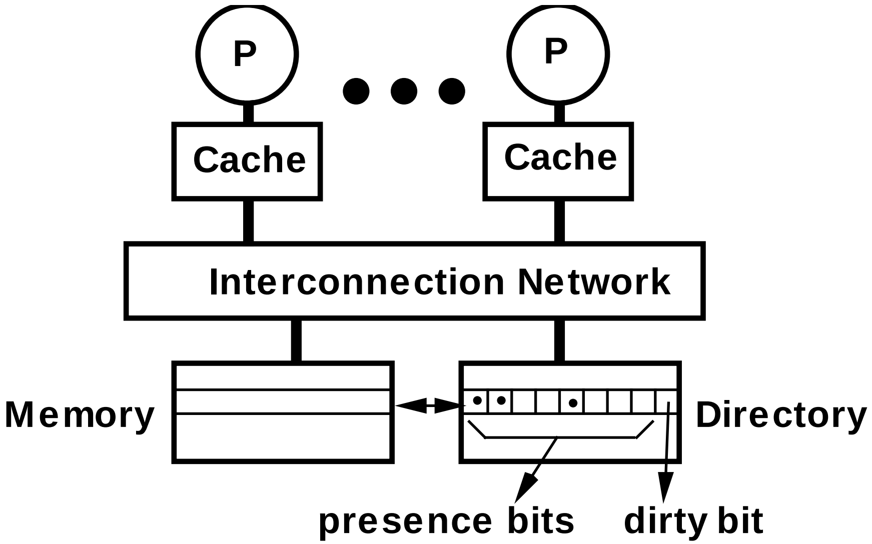
- There are minor variations (particularly to do with write miss)
- Normal ‘write back’ when cache line is evicted is done if line state is M
- Multi-level caches
  - If caches are inclusive, only the lowest level cache needs to snoop on the bus

Directory Schemes

- Snoopy schemes do not scale because they rely on broadcast

- Directory-based schemes allow scaling.
  - avoid broadcasts by keeping track of all PEs caching a memory block, and then using point-to-point messages to maintain coherence
  - they allow the flexibility to use any scalable point-to-point network

Basic Scheme (Censier & Feautrier)



- **Assume "k" processors.**
- **With each cache-block in memory: k presence-bits, and 1 dirty-bit**
- **With each cache-block in cache: 1valid bit, and 1 dirty (owner) bit**

– Read from main memory by PE-i:

- If dirty-bit is OFF then { read from main memory; turn p[i] ON; }
- if dirty-bit is ON then { recall line from dirty PE (cache state to shared); update memory; turn dirty-bit OFF; turn p[i] ON; supply recalled data to PE-i; }

– Write to main memory:

- If dirty-bit OFF then { send invalidations to all PEs caching that block; turn dirty-bit ON; turn P[i] ON; ... }
- ...

Key Issues

- Scaling of memory and directory bandwidth
  - Can not have main memory or directory memory centralized
  - Need a distributed memory and directory structure
- Directory memory requirements do not scale well
  - Number of presence bits grows with number of PEs
  - Many ways to get around this problem
    - limited pointer schemes of many flavors
- Industry standard
  - SCI: Scalable Coherent Interface