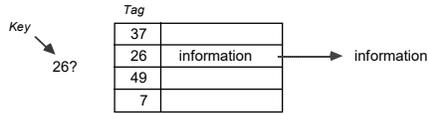


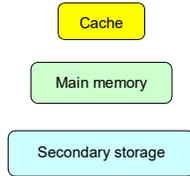
Cache memories

[§6.1] A *cache* is a small, fast memory which is *transparent* to the processor.

- The cache duplicates information that is in main memory.
- With each data block in the cache, there is associated an *identifier* or *tag*. This allows the cache to be *content addressable*.



- Caches are smaller and faster than main memory.
- *Secondary storage*, on the other hand, is larger and slower.
- A *cache miss* is the term analogous to a page fault. It occurs when a referenced word is not in the cache.
 - Cache misses must be handled much more quickly than page faults. Thus, they are handled in hardware.
- Caches can be *organized* according to four different strategies:
 - Direct
 - Fully associative
 - Set associative
 - Sectored



- *Miss*—referenced information is not in cache, must be read in from main memory.

$$\text{Hit ratio} = \frac{\text{Number of hits}}{\text{Total number of references}}$$

We will study caches that have three different placement policies (direct, fully associative, set associative).

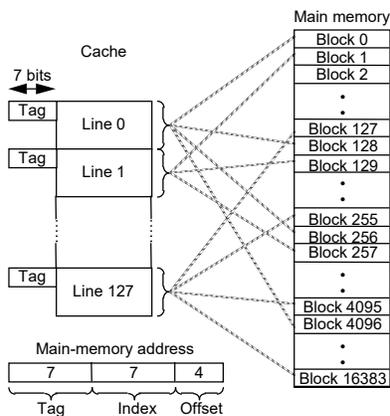
Direct

Only 1 choice of where to place a block.

$$\text{block } i \rightarrow \text{line } i \bmod 128$$

Each line has its own tag associated with it.

When the line is in use, the tag contains the high-order seven bits of the main-memory address of the block.



- A cache implements several different *policies* for retrieving and storing information, one in each of the following categories:

- *Placement policy*—determines where a block is placed when it is brought into the cache.
- *Replacement policy*—determines what information is purged when space is needed for a new entry.
- *Write policy*—determines how soon information in the cache is written to lower levels in the memory hierarchy.

Cache memory organization

[§6.2] Information is moved into and out of the cache in *blocks*. When a block is in the cache, it occupies a cache *line*. Blocks are usually larger than one byte,

- to take advantage of locality in programs, and
- because memory may be organized so that it can overlap transfers of several bytes at a time.

The block size is the same as the line size of the cache.

A *placement policy* determines where a particular block can be placed when it goes into the cache. E.g., is a block of memory eligible to be placed in any line in the cache, or is it restricted to a single line?

In our examples, we assume—

- The cache contains 2048 bytes, with 16 bytes per line. Thus it has 128 lines.
- Main memory is made up of 256K bytes, or 16384 blocks. Thus an address consists of 18 bits.

We want to structure the cache to achieve a high *hit ratio*.

- *Hit*—the referenced information is in the cache.

To search for a word in the cache,

1. Determine what line to look in (easy; just select bits 10–4 of the address).
2. Compare the leading seven bits (bits 17–11) of the address with the tag of the line. If it matches, the block is in the cache.
3. Select the desired bytes from the line.

Advantages:

Fast lookup (only one comparison needed).

Cheap hardware (only one tag needs to be checked).

Easy to decide where to place a block

Disadvantage: Contention for cache lines.

Exercise: What would the size of the tag, index, and offset fields be if—

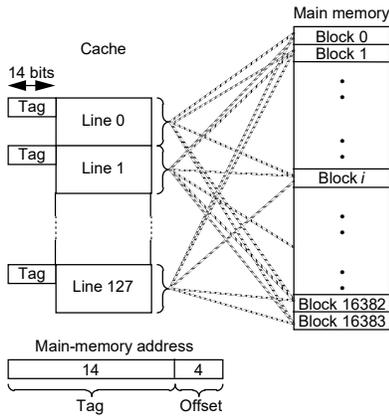
- the line size from our example were doubled, without changing the size of the cache? 7, 6, 5
- the cache size from our example were doubled, without changing the size of the line? 6, 8, 4
- an address were 32 bits long, but the cache size and line size were the same as in the example? 21, 7, 4

Fully associative

Any block can be placed in *any* line in the cache.

This means that we have 128 choices of where to place a block.

block $i \rightarrow$ any free (or purgeable) cache location



Each line has its own tag associated with it.

When the line is in use, the tag contains the high-order *fourteen* bits of the main-memory address of the block.

To search for a word in the cache,

1. Simultaneously compare the leading 14 bits (bits 17–4) of the address with the tag of all lines. If it matches any one, the block is in the cache.
2. Select the desired bytes from the line.

Advantages:

- Minimal contention for lines.
- Wide variety of replacement algorithms feasible.

Exercise: What would the size of the tag and offset fields be if—

- the line size from our example were doubled, without changing the size of the cache?

Which steps would be different if the cache were directly mapped?

Set associative

$1 < n < 128$ choices of where to place a block.

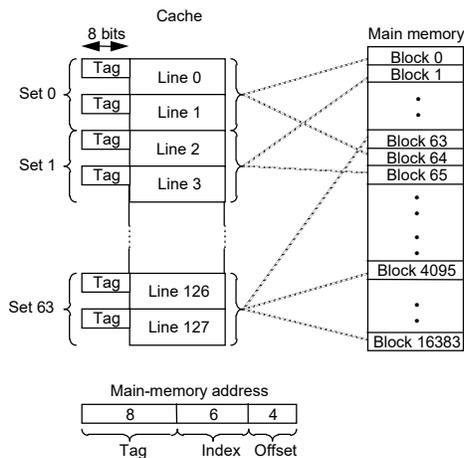
A compromise between direct and fully associative strategies.

The cache is divided into s sets, where s is a power of 2.

$$\text{block } i \rightarrow \text{any line in set } i \text{ mod } s$$

Each line has its own tag associated with it.

When the line is in use, the tag contains the high-order *eight* bits of the main-memory address of the block. (The next six bits can be derived from the set number.)

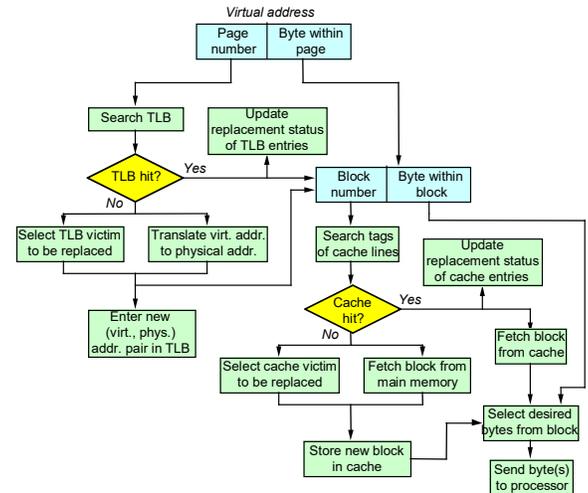


- the cache size from our example were doubled, without changing the size of the line?
- an address were 32 bits long, but the cache size and line size were the same as in the example?

Disadvantage:

The most expensive of all organizations, due to the high cost of associative-comparison hardware.

A flowchart of cache operation: The process of searching a fully associative cache is very similar to using a directly mapped cache. Let us consider them in detail.



Note that this diagram assumes a *separate* TLB.

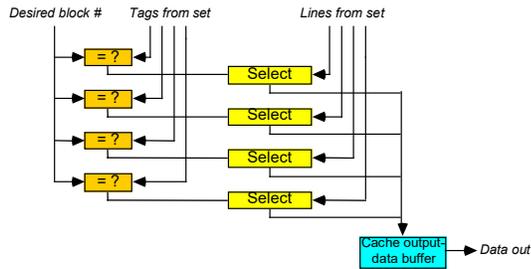
Exercise: What would the size of the tag, index, and offset fields be if—

- the line size from our example were doubled, without changing the size of the cache?
- the set size from our example were doubled, without changing the size of a line or the cache?
- the cache size from our example were doubled, without changing the size of the line or a set?
- an address were 32 bits long, but the cache size and line size was the same as in the example?

To search for a word in the cache,

1. Select the proper set ($i \text{ mod } s$).
2. Simultaneously compare the leading 8 bits (bits 17–10) of the address with the tag of all lines in the set. If it matches any one, the block is in the cache.

At the same time, the (first bytes of) the lines are also being read out so they will be accessible at the end of the cycle.
3. If a match is found, gate the data from the proper block to the cache-output buffer.
4. Select the desired bytes from the line.



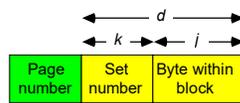
- All reads from the cache occur as early as possible, to allow maximum time for the comparison to take place.
- Which line to use is decided late, after the data have reached high-speed registers, so the processor can receive the data fast.

[§6.2.6] To attain maximum speed in accessing data, we would like to start searching the cache *at the same time* we are looking up the page number in the TLB.

When the bit-selection method is used, both can be done at once if the page number *is disjoint from* the set number.

This means that

- the number of bits k in the set number
- + the number of bits j which determine the byte within a line
- must be \leq the number of bits d in the displacement field.



We want $k + j \leq d$.

(If the page size is 2^d , then there will be d bits in the displacement field.)

Factors influencing line lengths:

- Long lines \Rightarrow higher hit ratios.
- Long lines \Rightarrow less memory devoted to tags.
- Long lines \Rightarrow longer memory transactions (undesirable in a multiprocessor).
- Long lines \Rightarrow more write-backs (explained below).

For most machines, line sizes between 32 and 128 bytes perform best.

If there are b lines per set, the cache is said to be b -way set associative. How many way associative was the example above?

The logic to compare 2, 4, or 8 tags simultaneously can be made quite fast.

But as b increases beyond that, cycle time starts to climb, and the higher cycle time begins to offset the increased associativity.

Almost all L1 caches are less than 8-way set-associative. L2 caches often have higher associativity.

Two-level caches

Write policy

[§6.2.3] Answer [these questions](#), based on the text.

What are the two write policies mentioned in the text?

Which one is typically used when a block is to be written to main memory, and why?

Which one can be used when a block is to be written to a lower level of the cache, and why?

Can you explain what error correction has to do with the choice of write policy?

Explain what a parity bit has to do with this.

Principle of inclusion

[§6.2.4] To analyze a second-level cache, we use the *principle of inclusion*—a large second-level cache includes everything in the first-level cache.

We can then do the analysis by assuming the first-level cache did not exist, and measuring the hit ratio of the second-level cache alone.

How should the line length in the second-level cache relate to the line length in the first-level cache?

When we measure a two-level cache system, two miss ratios are of interest:

- The *local miss rate* for a cache is the
$$\frac{\# \text{ misses experienced by the cache}}{\text{number of incoming references}}$$

To compute this ratio for the L2 cache, we need to know the number of misses in

- The *global miss rate* of the cache is

$$\frac{\# \text{ L2 misses}}{\# \text{ of references made by processor}}$$

This is the primary measure of the L2 cache.

What conditions need to be satisfied in order for inclusion to hold?

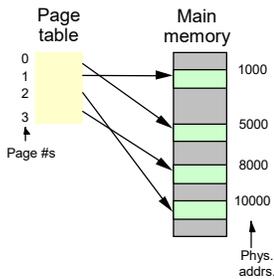
- L2 associativity must be \geq L1 associativity, irrespective of the number of sets.
Otherwise, more entries in a particular set could fit into the L1 cache than the L2 cache, which means the L2 cache couldn't hold everything in the L1 cache.
- The number of L2 sets has to be \geq the number of L1 sets, irrespective of L2 associativity.
(Assume that the L2 line size is \geq L1 line size.)
If this were not true, multiple L1 sets would depend on a single L2 set for backing store. So references to one L1 set could affect the backing store for another L1 set.
- All reference information from L1 is passed to L2 so that it can update its replacement bits.

Even if all of these conditions hold, we still won't have logical inclusion if L1 is write-back. (However, we will still have *statistical inclusion*—L2 *usually* contains L1 data.)

Translation Lookaside Buffers

The CPU generates *virtual* addresses, which correspond to locations in virtual memory.

In principle, the virtual addresses are translated to physical addresses using a page table.

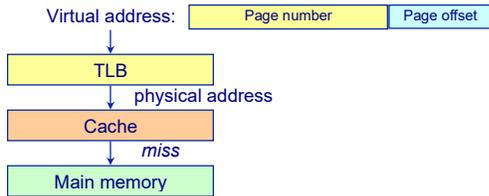


But this is too slow, so in practice, a *translation lookaside buffer* (TLB) is used.

It is like a special cache that is indexed by page number.

If there is a hit on a page number, then the address of the page in memory (called the *page-frame address*) is immediately obtained.

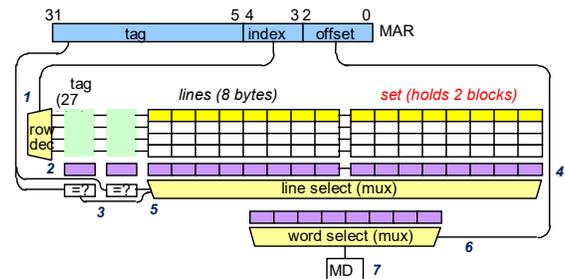
Therefore, the TLB and the cache must be accessed sequentially.



This adds an extra cycle in case of a hit.

How can we avoid wasting this time?

Let's look at what happens when a memory address is accessed.



What are the [steps in cache access](#)?

1. Access the set that could contain the sought-after address.
2. Pull down the tags into the sense amplifiers (purple).
3. Compare the tags with the tag of the sought-after address.
4. Read all lines in the set into the sense amplifiers (purple).
5. Select the line that actually contains the sought-after address.
6. Select the sought-after byte(s) or word(s) to return.
7. Return the sought-after byte(s) or word(s) to the processor.

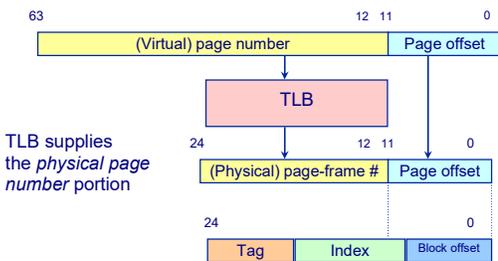
We always need to read lines into the sense amplifiers and then select the word (cf. the direct-mapped cache diagram in Lecture 10).

Now, if we know the index *before* address translation takes place, [we can perform steps 1, 2, and 4](#) while address translation is occurring.

There is a tradeoff between speed and power efficiency.

- For power efficiency, which order should steps 1 through 4 be performed in? **sequentially: 1, 2, 3, 4**
- For maximum speed, which of steps 1 through 4 can be performed in parallel? **2 and 4.**

Let's take a look at address translation.

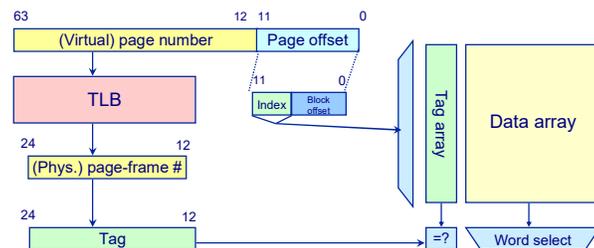


In this example, what is the page size? 2^{12}

How much physical memory is there? 2^{25}

Our goal is to allow the cache to be indexed before address translation completes.

In order to do that, we need to have the index field be *entirely contained* within the page offset.



Cache hit time reduces from two cycles to one!

... because the cache can now be *indexed* in parallel with TLB (although the tag match uses output from the TLB).

But there are some constraints...

- Suppose our cache is direct mapped. Then the index field just contains the line number. So, (line number || block offset) must fit inside the page offset. What is the largest the cache can be? $2^{12} = \text{one page}$
- If we want to increase the size of the cache, what can we do? **Increase associativity**

Options:

- For new machines, select page size such that—

$$\text{page size} \geq \frac{\text{cache size}}{\text{associativity}}$$
- If page size is fixed, select associativity so that—

$$\text{associativity} \geq \frac{\text{cache size}}{\text{page size}}$$

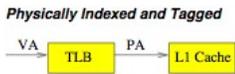
Example: MC88110

- Page size = 4KB
- I-cache, D-cache are both: 8KB, 2-way set-associative (4KB = 8KB / 2)

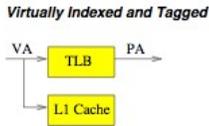
Example: VAX series

- Page size = 512B
- For a 16KB cache, need assoc. = (16KB / 512B) = 32-way set. assoc.!

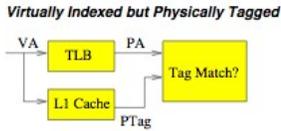
The textbook gives these three alternatives for cache indexing and tagging. [Answer some questions](#) about them.



What's the main disadvantage of physically indexed and tagged?



What is the organization we have just been discussing (in the last diagram)?



What is the main disadvantage of virtually indexed and tagged?

Multilevel cache design

What are distinguishing [features of the different cache levels](#) of the four-level design (from 2013) illustrated on p. 135 of the textbook?

	Distinguishing feature	Size	Access time	Implement'n technology
L1 cache				
L2 cache				
L3 cache				
L4 cache				
Main mem.				

What are some advantages of a centralized cache?

What are some advantages of a banked structure?

Inclusion in multilevel caches

Answer [these questions](#) about inclusion policies.

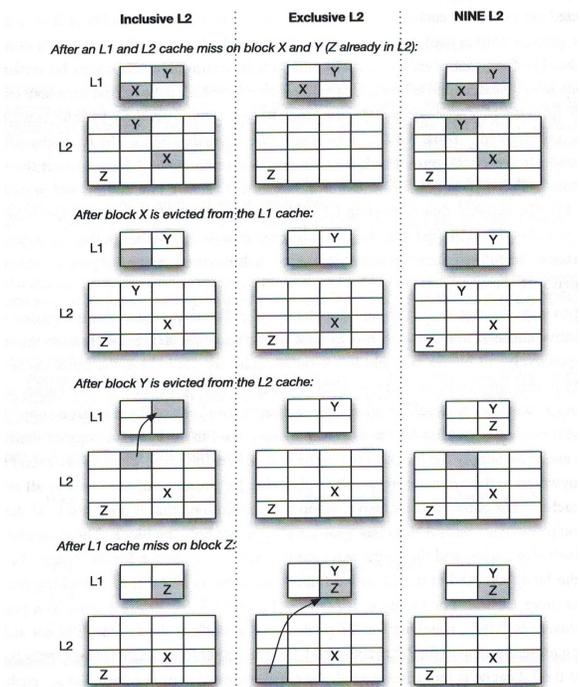
Which kind(s) of caches move a block from one level to the other?

Which kind(s) of caches propagate up an eviction from the L2 to the L1?

Which kind(s) of caches have to inform the L2 about a write to the L1?

In an inclusive cache, can L2 associativity be greater than L1 associativity?

Find and describe the typo in this diagram.



In a set-associative cache, LRU is reasonably cheap to implement. Why? **Because you can only afford to look in a few places, since you have to do the replacement in hardware. Finding the LRU line in a set is easy enough to do in hardware because not many lines need to be examined.**

With the LRU algorithm, the lines can be arranged in an *LRU stack*, in order of recency of reference. Suppose a string of references is—

a b c d a b e a b c d e

and there are 4 lines. Then the LRU stacks after each reference are—

```

a b c d a b e a b c d e
a b c d a b e a b c d
a b c d a b e a b c
a b c d d d e a b
* * * * *

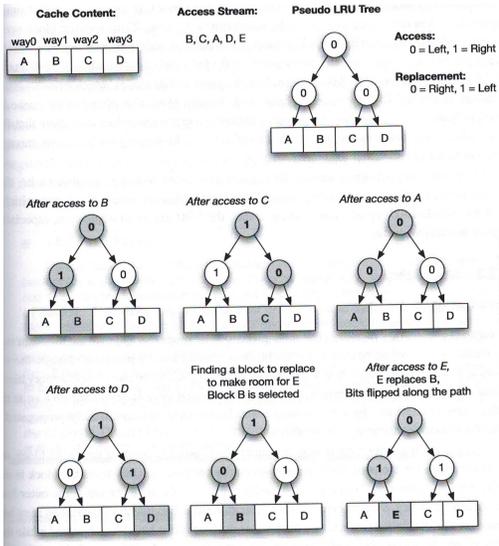
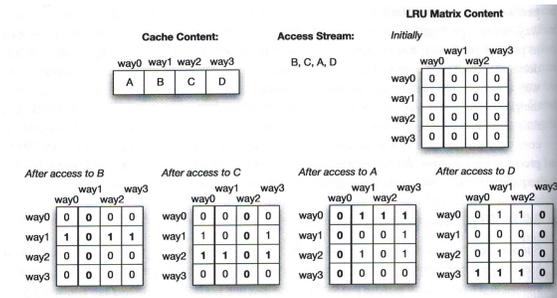
```

Notice that at each step:

- The line that is referenced moves to the top of the LRU stack.
- All lines below that line keep their same position.
- All lines above that line move down by one position.

How many bits per set are required to keep track of LRU status in both of the implementations described in the text?

- Matrix N^2
- Pseudo-LRU $N-1$



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The Cache-Coherence Problem

Lecture 12
(Chapter 6)

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1

Small to Large Multiprocessors

- **Small scale** (2–30 processors): shared memory
 - Often on-chip: shared memory (+ perhaps shared cache)
 - Most processors have MP support out of the box
 - Most of these systems are bus-based
 - Popular in commercial as well as HPC markets
- **Medium scale** (64–256): shared memory and clusters
 - Clusters are cheaper
 - Often, clusters of SMPs
- **Large scale** (> 256): few shared memory and many clusters
 - SGI [Altix 3300](#): 512-processor shared memory (NUMA)
 - Large variety of custom/off-the-shelf components such as interconnection networks.
 - Beowulf clusters: fast Ethernet
 - Myrinet: fiber optics
 - IBM SP2: custom

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1

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Outline

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- **Bus-based multiprocessors**
- The cache-coherence problem
- Peterson's algorithm
- Coherence vs. consistency

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2

Shared Memory vs. No Shared Memory

- Advantages of shared-memory machines (vs. distributed memory w/same total memory size)
 - Support shared-memory programming
 - Clusters can also support it via *software shared virtual memory*, but with much coarser granularity and higher overheads
 - Allow fine-grained sharing
 - You can't do this with messages—there's too much overhead to share small items
 - Single OS image
- Disadvantage of shared-memory machines
 - Cost of providing shared-memory abstraction

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5

Shared vs. Distributed Memory

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- What is the difference between ...
 - SMP
 - NUMA
 - Cluster ?

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3

A Bus-Based Multiprocessor

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3

6

Outline

- Bus-based multiprocessors
- **The cache-coherence problem**
- Peterson's algorithm
- Coherence vs. consistency

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Cache-Coherence Problem Illustration

Start state. All caches empty and main memory has $Sum = 0$.

Trace	
P ₁	Read Sum
P ₂	Read Sum
P ₁	Write Sum = 3
P ₂	Write Sum = 7
P ₁	Read Sum

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Will This Parallel Code Work Correctly?

```

sum = 0;
begin parallel
for (i=1; i<=2; i++) {
  lock(id, myLock);
  sum = sum + a[i];
  unlock(id, myLock);
}
end parallel
print sum;

```

Suppose $a[1] = 3$ and $a[2] = 7$

Two issues:

- Will it print $sum = 10$?
- How can it support locking correctly?

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Cache-Coherence Problem Illustration

P₁ reads Sum from memory.

Trace	
P ₁	Read Sum
P ₂	Read Sum
P ₁	Write Sum = 3
P ₂	Write Sum = 7
P ₁	Read Sum

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The Cache-Coherence Problem

```

sum = 0;
begin parallel
for (i=1; i<=2; i++) {
  lock(id, myLock);
  sum = sum + a[i];
  unlock(id, myLock);
}
end parallel
print sum;

```

Suppose $a[1] = 3$ and $a[2] = 7$

• Will it print $sum = 10$?

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Cache-Coherence Problem Illustration

P₂ reads. Let's assume this comes from memory too.

Trace	
P ₁	Read Sum
P ₂	Read Sum
P ₁	Write Sum = 3
P ₂	Write Sum = 7
P ₁	Read Sum

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Cache-Coherence Problem Illustration

P₁ writes. This write goes to the cache.

Cache
Sum=0 V

Cache
Sum=0 V

Cache

Bus

Controller
Sum = 0
Main memory

Trace

P₁ Read Sum

P₂ Read Sum

P₁ Write Sum = 3

P₁ Read Sum

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Cache-Coherence Problem

- Do P₁ and P₂ see the same sum?
- Does it matter if we use a WT cache?
- The code given at the start of the animation does not exhibit the same coherence problem shown in the animation. Explain. Is the result still incoherent?
- What if we do not have caches, or sum is uncacheable. Will it work?

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Cache-Coherence Problem Illustration

P₂ writes.

Cache
Sum=3 D

Cache
Sum=0 V

Cache

Bus

Controller
Sum = 0
Main memory

Trace

P₁ Read Sum

P₂ Read Sum

P₂ Write Sum = 7

P₁ Read Sum

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Write-Through Cache Does Not Work

P₁ reads.

Cache
Sum=3 D

Cache
Sum=7 D

Cache

Bus

Controller
Sum = 7
Main memory

Trace

P₁ Read Sum

P₂ Read Sum

P₁ Write Sum = 3

P₂ Write Sum = 7

P₁ Read Sum

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Cache-Coherence Problem Illustration

P₁ reads.

Cache
Sum=3 D

Cache
Sum=7 D

Cache

Bus

Controller
Sum = 0
Main memory

Trace

P₁ Read Sum

P₂ Read Sum

P₂ Write Sum = 3

P₂ Write Sum = 7

P₁ Read Sum

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Software Lock Using a Flag

- Here's simple code to implement a lock:

```

void lock (int process, int lvar) { // process is 0 or 1
    while (lvar == 1) {} ;
    lvar = 1;
}

void unlock (int process, int lvar) {
    lvar = 0;
}

```

- Will this guarantee mutual exclusion?
- Let's look at an algorithm that will ...

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Outline

- Bus-based multiprocessors
- The cache-coherence problem
- **Peterson's algorithm**
- Coherence vs. consistency

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Race

```

// Proc 0
interested[0] = TRUE;
turn = 1;

while (turn==1 && interested[1]==TRUE)
{};
// since turn = 0,
// Proc 0 enters critical section

// unlock
interested[0] = FALSE;

// Proc 1
interested[1] = TRUE;

turn = 0;

while (turn==0 && interested[0]==TRUE)
{};
// since turn==0 && interested[0]==TRUE
// Proc 1 waits in the loop until Proc 0
// releases the lock

// now Proc 1 can exit the loop and
// acquire the lock
  
```

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Peterson's Algorithm

```

int turn;
int interested[n]; // initialized to false

void lock (int process, int lvar) { // process is 0 or 1
int other = 1 - process;
interested[process] = TRUE;
turn = other;
while (turn == other && interested[other] == TRUE) {} ;
}
// Post: turn != other or interested[other] == FALSE

void unlock (int process, int lvar) {
interested[process] = FALSE;
}
  
```

- Acquisition of lock () occurs only if
 1. interested[other] == FALSE: either the other process has not competed for the lock, or it has just called unlock (), or
 2. turn != other: the other process is competing, has set the turn to our process, and will be blocked in the while () loop

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When Does Peterson's Alg. Work?

- Correctness depends on the global order of

A: interested[process] = TRUE;
 B: turn = other;
- Thus, it will not work if—
 - The *compiler* reorders the operations
 - There's no data dependence, so unless the compiler is notified, it may well reorder the operations
 - This prevents compiler from using aggressive optimizations used in serial programs
 - The *architecture* reorders the operations
 - Write buffers, memory controller
 - Network delay for statement A
 - If turn and interested[] are cacheable, A may result in cache miss, but B in cache hit
- This is called the memory-consistency problem.

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No Race

```

// Proc 0
interested[0] = TRUE;
turn = 1;
while (turn==1 && interested[1]==TRUE)
{};
// since interested[1] starts out FALSE,
// Proc 0 enters critical section

// Proc 1
interested[1] = TRUE;
turn = 0;
while (turn==0 && interested[0]==TRUE)
{};
// since turn==0 && interested[0]==TRUE
// Proc 1 waits in the loop until Proc 0
// releases the lock

// unlock
interested[0] = FALSE;

// now Proc 1 can exit the loop and
// acquire the lock
  
```

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Race on a Non-Sequentially Consistent Machine

```

// Proc 0
interested[0] = TRUE;

turn = 1;
while (turn==1 && interested[1]==TRUE)
{};

// Proc 1
interested[1] = TRUE;
turn = 0;

while (turn==0 && interested[0]==TRUE)
{};
  
```

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Race on a Non-Sequentially Consistent Machine

```

// Proc 0
interested[0] = TRUE;

turn = 1;
while (turn==1 && interested[1]==TRUE)
{};
// since interested[1] == FALSE,
// Proc 0 enters critical section

// Proc 1
turn = 0;
interested[1] = TRUE;
while (turn==0 && interested[0]==TRUE)
{};
// since turn==1,
// Proc 1 enters critical section

```

Can you explain what has gone wrong here?

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Coherence vs. Consistency

Cache coherence	Memory consistency
Deals with the ordering of operations to a <i>single</i> memory location.	Deals with the ordering of operations to <i>different</i> memory locations.
Tackled by hardware <ul style="list-style-type: none"> using coherence protocols. Hw. alone guarantees correctness but with varying performance 	Tackled by consistency models <ul style="list-style-type: none"> supported by hardware, but software must conform to the model.
All protocols realize same abstraction <ul style="list-style-type: none"> A program written for 1 protocol can run w/o change on any other. 	Models provide diff. abstractions <ul style="list-style-type: none"> Compilers must be aware of the model (no reordering certain operations ...). Programs must "be careful" in using shared variables.

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Coherence vs. Consistency

Cache coherence	Memory consistency
Deals with the ordering of operations to a <i>single</i> memory location.	Deals with the ordering of operations to <i>different</i> memory locations.

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Two Approaches to Consistency

- Sequential consistency
 - Multi-threaded codes for uniprocessors automatically run correctly
 - How? Every shared R/W completes globally in program order
 - Most intuitive but worst performance
- Relaxed consistency models
 - Multi-threaded codes for uniprocessor need to be ported to run correctly
 - Additional instruction (memory fence) to ensure global order between 2 operations

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Coherence vs. Consistency

Cache coherence	Memory consistency
Deals with the ordering of operations to a <i>single</i> memory location.	Deals with the ordering of operations to <i>different</i> memory locations.
Tackled by hardware <ul style="list-style-type: none"> using coherence protocols. Hw. alone guarantees correctness but with varying performance 	Tackled by consistency models <ul style="list-style-type: none"> supported by hardware, but software must conform to the model.

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Cache Coherence

- Do we need caches?
 - Yes, to reduce average data access time.
 - Yes, to reduce bandwidth needed for bus/interconnect.
- Sufficient conditions for coherence:
 - Notation: Request_{proc}(data)
 - Write propagation:**
 - Rd_i(X) must return the "latest" Wr_j(X)
 - Write serialization:**
 - Wr_i(X) and Wr_j(X) are seen in the same order by everybody
 - e.g., if I see w2 after w1, you shouldn't see w2 before w1
 - There must be a **global ordering** of memory operations to a *single* location
 - Is there a need for *read serialization*?

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A Coherent Memory System: Intuition

- Uniprocessors
 - Coherence between I/O devices and processors
 - Infrequent, so software solutions work
 - uncacheable memory, uncacheable operations, flush pages, pass I/O data through caches
- But coherence problem much more critical in multiprocessors
 - Pervasive
 - Performance-critical
 - Necessitates a hardware solution
- * Note that “latest write” is ambiguous.
 - Ultimately, what we care about is that any write is propagated everywhere in the same order.
 - Synchronization defines what “latest” means.

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Summary

- Shared memory with caches raises the problem of cache coherence.
 - Writes to the same location must be seen in the same order everywhere.
- But this is not the only problem
 - Writes to *different* locations must also be kept in order if they are being depended upon for synchronizing tasks.
 - This is called the memory-consistency problem

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Coherence and Consistency

Lecture 13 (Chapter 7)

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Assume a Bus-Based SMP

- Built on top of two fundamentals of uniprocessor system
 - Bus transactions
 - Cache-line finite-state machine
- Uniprocessor bus transaction:
 - Three phases: arbitration, command/address, data transfer
 - All devices observe addresses, one is responsible
- Uniprocessor cache states:
 - Every cache line has a finite-state machine
 - In WT+write no-allocate: Valid, Invalid states
 - WB: Valid, Invalid, Modified ("Dirty")
- Multiprocessors extend both these somewhat to implement coherence

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Outline

- Bus-based coherence
- Invalidation vs. update coherence protocols
- Memory consistency
 - Sequential consistency

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Snoop-Based Coherence on a Bus

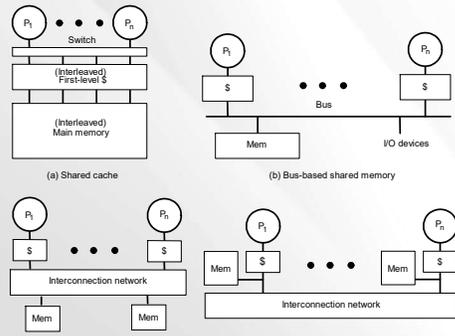
- Basic Idea**
 - Assign a snoopers to each processor so that all bus transactions are visible to all processors ("snooping").
 - Processors (via cache controllers) change line states on relevant events.



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Several Configurations for a Memory System



(a) Shared cache

(b) Bus-based shared memory

(c) Dancehall

(d) Distributed-memory

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Snoop-Based Coherence on a Bus

- Basic Idea**
 - Assign a snoopers to each processor so that all bus transactions are visible to all processors ("snooping").
 - Processors (via cache controllers) change line states on relevant events.
- Implementing a Protocol**
 - Each **cache controller** reacts to processor and bus events:
 - Takes actions when necessary
 - Updates state, responds with data, generates new bus transactions
 - The **memory controller** also snoops bus transactions and returns data only when needed
 - Granularity of coherence is typically cache line/block
 - Same granularity as in transfer to/from cache

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Coherence with Write-Through Caches

```

sum = 0;
begin parallel
for (i=0; i<2; i++) {
  lock(id, myLock);
  sum = sum + a[i];
  unlock(id, myLock);
}
end parallel
Print sum;

```

Suppose $a[0] = 3$ and $a[1] = 7$

● = Snooper

- What happens when we snoop a write?
 - Write-update protocol: write is immediately propagated **or**
 - Write-invalidation protocol: causes miss on later access, and memory up-to-date via write-through

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Write-Through State-Transition Diagram

**write-through
no-write-allocate
write invalidate**

How does this protocol guarantee write propagation?

How does it guarantee write serialization?

- Key: A write invalidates all other caches
- Therefore, we have:
 - Modified line: exists as V in only 1 cache
 - Clean line: exists as V in at least 1 cache
 - Invalid state represents invalidated line or not present in the cache

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Snooper Assumptions

- Atomic bus
- Writes occur in program order

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Is It Coherent?

- Write propagation:
 - through invalidation
 - then a cache miss, loading a new value
- Write serialization: Assume—
 - atomic bus
 - invalidation happens instantaneously
 - writes serialized by order in which they appear on bus (*bus order*)
 - So are invalidations
- Do reads see the latest writes?
 - Read misses generate bus transactions, so will get the last write
 - Read hits: do not appear on bus, but are preceded by
 - most recent write by this processor (self), or
 - most recent read miss by this processor
 - Thus, reads hits see latest written values (according to bus order)

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Transactions

- To show what's going on, we will use diagrams involving—
 - Processor transactions
 - PrRd
 - PrWr
 - Snooped bus transactions
 - BusRd
 - BusWr

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Determining Orders More Generally

A memory operation M2 follows a memory operation M1 if the operations are issued by the same processor and M2 follows M1 in program order.

1. Read follows write W if read generates bus transaction that follows W's action.

- Writes establish a partial order
- Doesn't constrain ordering of reads, though bus will order read misses too
 - any order among reads between writes is fine, as long as in program order ¹²

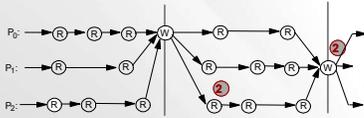
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Determining Orders More Generally

A memory operation M2 follows a memory operation M1 if the operations are issued by the same processor and M2 follows M1 in program order.

1. Read follows write W if read generates bus transaction that follows W's action.
2. Write follows read or write M if M generates bus transaction and the transaction for the write follows that for M.



- Writes establish a partial order
- Doesn't constrain ordering of reads, though bus will order read misses too
—any order among reads between writes is fine, as long as in program order

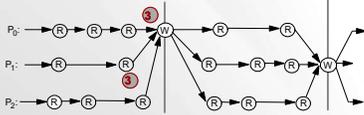
Lecture 13 Outline

- Bus-based coherence
- **Invalidation vs. update coherence protocols**
- Memory consistency
 - Sequential consistency

Determining Orders More Generally

A memory operation M2 follows a memory operation M1 if the operations are issued by the same processor and M2 follows M1 in program order.

1. Read follows write W if read generates bus transaction that follows W's action.
2. Write follows read or write M if M generates bus transaction and the transaction for the write follows that for M.
3. Write follows read if read does not generate a bus transaction and is not already separated from the write by another bus transaction.



- Writes establish a partial order
- Doesn't constrain ordering of reads, though bus will order read misses too
—any order among reads between writes is fine, as long as in program order

Dealing with "Dirty" Lines

- What does it mean to say a cache line is "dirty"?
 - That at least one of its words has been changed since it was brought in from main memory.
- Dirty in a uniprocessor vs. a multiprocessor
 - Uniprocessor:
 - Only need to keep track of *whether* a line has been modified.
 - Multiprocessor:
 - Keep track of *whether* line is modified.
 - Keep track of which cache *owns* the line.
- Thus, a cache line must know whether it is—
 - **Exclusive:** "I'm the only one that has it, other than possibly main memory."
 - The **Owner:** "I'm responsible for supplying the block upon a request for it."



Problem with Write-Through

- Write-through can guarantee coherence, but needs a lot of bandwidth.
 - Every write goes to the shared bus and memory
 - Example:
 - 200MHz, 1-CPI processor, and 15% instrs. are 8-byte stores
 - Each processor generates 30M stores, or 240MB data, per second
 - How many processors could a 1GB/s bus support without saturating?
 - Thus, unpopular for SMPs
- Write-back caches
 - Write hits do not go to the bus \Rightarrow reduce most write bus transactions
 - But now how do we ensure write propagation and serialization?

Invalidation vs. Update Protocols

- Question: What happens to a line if *another* processor changes one of its words?

– It can be *invalidated*.



– It can be *updated*.



Invalidation-Based Protocols

- Idea: When I write the block, invalidate everybody else
⇒ I get exclusive state.
- “Exclusive” means ...
 - Can modify without notifying anyone else (i.e., without a bus transaction)
- But, before writing to it,
 - Must first get block in exclusive state
 - Even if block is already in state V, a bus transaction (Read Exclusive = RdX) is needed to invalidate others.
- What happens when a block is ejected from the cache?
 - if the block is not dirty?
 - if the block *is* dirty?

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Lecture 13 Outline

- Bus-based coherence
- Invalidation vs. update coherence protocols
- Memory consistency**
 - Sequential consistency

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-Based Protocols

- Idea: If this block is written, send the new word to all other caches.
 - New bus transaction: Update
- Compared to invalidate, what are advs. and disads.?
- Advantages
 - Other processors don't miss on next access
 - Saves refetch: In invalidation protocols, they would miss & bus transaction.
 - Saves bandwidth: A single bus transaction updates several caches
- Disadvantages
 - Multiple writes by same processor cause multiple update transactions
 - In invalidation, first write gets exclusive ownership, other writes local

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Let's Switch Gears to Memory Consistency

Coherence: Writes to a single location are visible to all in the same order
Consistency: Writes to multiple locations are visible to all in the same order

- Recall Peterson's algorithm (`turn= ...; interested[process]=...`)
- When "multiple" means "all", we have sequential consistency (SC)

P_1	P_2
/*Assume initial values of A and flag are 0*/	
<pre>A = 1; flag = 1;</pre>	<pre>while (flag == 0); /*spin idly*/ print A;</pre>

- Sequential consistency (SC) corresponds to our intuition.
- Other memory consistency models do not obey our intuition!
- Coherence doesn't help; it pertains only to a single location

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Invalidate versus Update

- Is a block written by one processor read by other processors before it is rewritten?
- Invalidation:
 - Yes → Readers will take a miss.
 - No → Multiple writes can occur without additional traffic.
 - Copies that won't be used again get cleared out.
- Update:
 - Yes → Readers will not miss if they had a copy previously
 - A single bus transaction will update all copies
 - No → Multiple useless updates, even to dead copies
- Invalidation protocols are much more popular.
 - Some systems provide both, or even hybrid

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Another Example of Ordering

P_1	P_2
/*Assume initial values of A and B are 0*/	
<pre>(1a) A = 1; (1b) B = 2;</pre>	<pre>(2a) print B; (2b) print A;</pre>

- What do you think the results should be? You may think:
 - 1a, 1b, 2a, 2b ⇒ {A=1, B=2}
 - 1a, 2a, 2b, 1b ⇒ {A=1, B=0}
 - 2a, 2b, 1a, 1b ⇒ {A=0, B=0}
 } programmers' intuition: sequential consistency
- Is {A=0, B=2} possible? Yes, suppose P2 sees: 1b, 2a, 2b, 1a e.g. evil compiler, evil interconnection.
- Whatever our intuition is, we need
 - an **ordering model** for clear semantics across different locations
 - as well as **cache coherence!**

so programmers can reason about what results are possible.

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A Memory-Consistency Model ...

- Is a contract between programmer and system
 - Necessary to reason about correctness of shared-memory programs
- Specifies constraints on the order in which memory operations (from any process) can *appear to execute* with respect to one another
 - Given a load, constrains the possible values returned by it
- Implications for programmers
 - Restricts algorithms that can be used
 - e.g., Peterson's algorithm, home-brew synchronization will be incorrect in machines that do not guarantee SC
- Implications for compiler writers and computer architects
 - Determines how much accesses can be reordered.



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What Really Is Program Order?

- Intuitively, the order in which operations appear in source code
- Thus, we assume order as seen by programmer,
 - the compiler is prohibited from reordering memory accesses to shared variables.
- Note that this is one reason parallel programs are less efficient than serial programs.



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Lecture 13 Outline

- Bus-based coherence
- Memory consistency
 - Sequential consistency
- Invalidation vs. update coherence protocols

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What Reordering Is Safe in SC?

What matters is the order in which code *appears to execute*, not the order in which it actually *executes*.

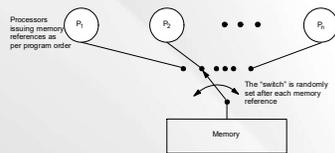
P ₁	P ₂
<i>/*Assume initial values of A and B are 0 */</i>	
(1a) A = 1;	(2a) print B;
(1b) B = 2;	(2b) print A;

- Possible outcomes for (A,B): (0,0), (1,0), (1,2); impossible under SC: (0,2)
- Proof: By program order we know 1a → 1b and 2a → 2b
 - A = 0 implies 2b → 1a, which implies 2a → 1b
 - B = 2 implies 1b → 2a, which leads to a contradiction
- BUT, actual execution 1b → 1a → 2b → 2a is SC, despite not being in program order
 - It produces the same result as 1a → 1b → 2a → 2b.
 - Actual execution 1b → 2a → 2b → 1a is not SC, as shown above
 - Thus, some reordering is possible, but difficult to reason that it ensures SC

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Sequential Consistency



"A multiprocessor is sequentially consistent if the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program." [Lamport, 1979]

- (as if there were no caches, and a single memory)
- Total order achieved by *interleaving* accesses from different processes
- Maintains *program order*, and memory operations, from all processes, appear to [issue, execute, complete] atomically w.r.t. others

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Conditions for SC

- Two kinds of requirements
 - **Program order**
 - Memory operations issued by a process must appear to become visible (to others and itself) in program order.
 - **Global order**
 - Atomicity: One memory operation should appear to complete with respect to all processes before the next one is issued.
 - Global order: The same order of operations is seen by all processes.
- Tricky part: how to make writes atomic?
 - → Necessary to detect write completion
 - Read completion is easy: a read completes when the data returns
- Who should enforce SC?
 - Compiler should not change program order
 - Hardware should ensure program order and atomicity



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Performance of coherence protocols

Cache misses have traditionally been classified into four categories:

- *Cold misses* (or “compulsory misses”) occur the first time that a block is referenced.
- *Conflict misses* are misses that would not occur if the cache were fully associative with LRU replacement.
- *Capacity misses* occur when the cache size is not sufficient to hold data between references.
- *Coherence misses* are misses caused by the coherence protocol.

The first three types occur in uniprocessors. The last is specific to multiprocessors.

To these, Solihin adds *context-switch* (or “system-related”) misses, which are related to task switches.

Let’s take a look at a uniprocessor example, a very small cache that has only four lines.

Let’s look first at a fully associative cache, because which kind(s) of misses can’t it have?

Here’s an example of a reference trace of 0, 2, 4, 0, 2, 4, 6, 8, 0.

Fully associative									
	0	2	4	0	2	4	6	8	0
0	0			0				8	
1		2			2				0
2			4			4			
3							6		
	cold	cold	cold	hit	hit	hit	cold	cold	capacity

In a fully associative cache, there are 5 cold misses, because 5 different blocks are referenced.

2-way set-associative									
	0	2	4	0	2	4	6	8	0
0	0		4	0		4		8	0
1									
2		2			2		6		
3									
	cold	Cold	Cold	conflict	Hit	Conflict	cold	cold	capacity

Classify each of these references as a hit or a particular kind of miss.

Of the three conflict misses in the set-associative cache, one is a hit here. Block 2 is still in the cache the second time it is referenced. The other two are conflict misses in this cache.

Now, let’s talk about coherence misses.

Coherence misses can be divided into those caused by *true sharing* and those caused by *false sharing* (see p. 236 of the Solihin text).

- False-sharing misses are those caused by having a line size larger than one word. [Can you explain?](#)
- True-sharing misses, on the other hand, occur when
 - a processor writes into a cache line, invalidating a copy of the same block in another processors’ cache,
 - after which

How can we [attack each](#) of the four kinds of misses?

- To reduce capacity misses, we can **increase cache size**
- To reduce conflict misses, we can **increase associativity**
- To reduce cold misses, we can **increase line size**
- To reduce coherence misses, we can **use an update-based protocol**.

Similarly, context-switch misses can be divided into categories.

There are 3 hits.

The remaining reference (the third one to block 0) is not a cold miss.

It must be a capacity miss, because the cache doesn’t have room to hold all five blocks.

We’ll assume that replacement is LRU; in this case, block 0 replaces the LRU line, which at that point is line 1.

Now let’s suppose the cache is 2-way set associative. This means there are two sets, one (set 0) that will hold the even-numbered blocks, and one (set 1) that will hold the odd-numbered blocks.

2-way set-associative									
	0	2	4	0	2	4	6	8	0
0	0		4		2		6		0
1		2		0		4		8	
2									
3									
	cold	cold	cold	conflict	conflict	conflict	cold	cold	capacity

Since only even-numbered blocks are referenced in this trace, they will all map to set 0.

This time, though, there won’t be any hits.

[Classify each of these references](#) as a hit or a particular kind of miss.

References that would have been hits in a fully associative cache, but are misses in a less-associative cache, are conflict misses.

Finally, let’s look at a direct-mapped cache. Blocks with numbers congruent to 0 mod 4 map to line 0; blocks with numbers congruent to 1 mod 4 map to line 1, etc.

Direct mapped									
---------------	--	--	--	--	--	--	--	--	--

- *Replaced* misses are blocks that were replaced while the other process(es) were active.
- *Reordered* misses are blocks that were shoved so far down the LRU stack by the other process(es) that they are replaced soon afterwards (when they otherwise would’ve stayed in the cache).

Which protocol is best? What cache line size performs best? What kind of misses predominate?

Simulations

Questions like these can be answered by simulation. Getting the answer right is part art and part science.

Parameters need to be chosen for the simulator. Culler & Singh (1998) selected a single-level 4-way set-associative 1 MB cache with 64-byte lines.

The simulation assumes an idealized memory model, which assumes that references take constant time. Why is this not realistic?

The simulated workload consists of

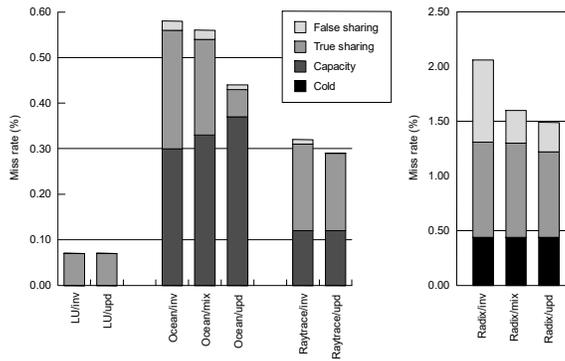
- six parallel programs (Barnes, LU, Ocean, Radix, Radiosity, Raytrace) from the SPLASH-2 suite and
- one multiprogrammed workload, consisting of mainly serial programs.

Invalidate vs. update

with respect to miss rate

Which is better, an update or an invalidation protocol?

Let’s look at real programs.



Where there are many coherence misses, **update performs better.**

If there were many capacity misses, **invalidate would be better, because update would keep updating dead blocks, and they would occupy space in the cache.**

with respect to bus traffic

Compare the
 • upgrades in inv. protocol
 with the
 • updates in upd. protocol

Each of these operations produces bus traffic.
 Which are more frequent?

Updates in an update protocol are more prevalent than upgrades in an invalidation protocol.

Which protocol causes more bus traffic?

The update protocol causes more traffic.

The main problem is that one processor tends to write a block multiple times before another processor reads it.

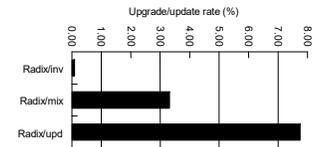
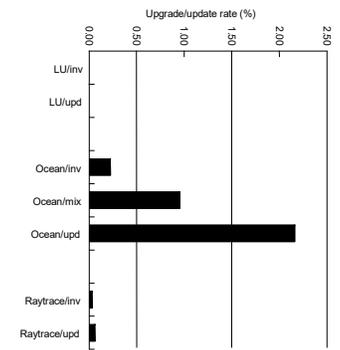
This causes several bus transactions instead of one, as there would be in an invalidation protocol.

Effect of cache line size

on miss rate

If we increase the line size, what happens to each of the following classes of misses?

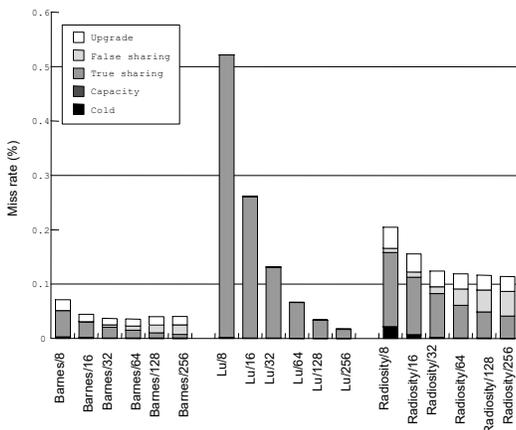
- capacity misses? **down**
- conflict misses? **up**
- true-sharing misses? **down**



- false-sharing misses? **up**

If we increase the line size, what happens to bus traffic?
Increases, because more needs to be brought in for each miss.

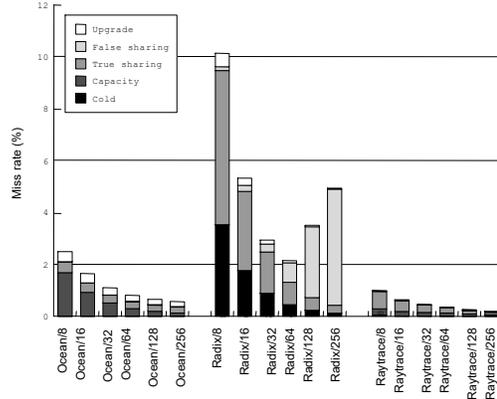
So it is not clear which line size will work best.



Results for the first three applications seem to show that which line size is best? **64 to 256 bytes**

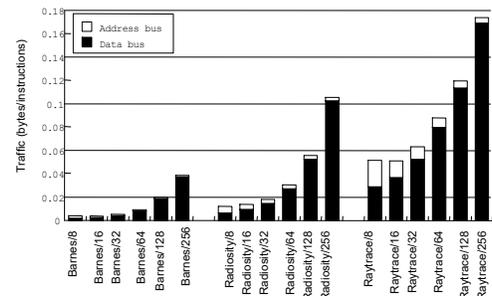
For the second set of applications, which do not fit in cache, Radix shows a greatly increasing number of false-sharing misses with increasing block

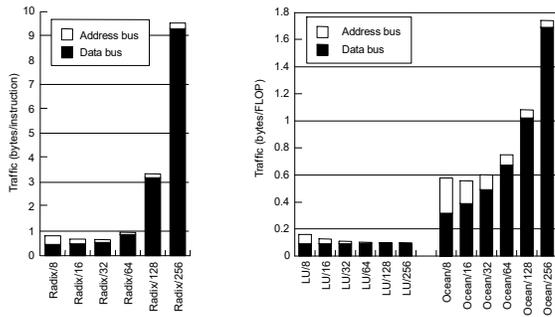
size.



on bus traffic

Larger line sizes generate more bus traffic.





The results are different than for miss rate—traffic almost always increases with increasing line size.

But address-bus traffic moves in the opposite direction from data-bus traffic.

With this in mind, which line size appears to be best? **32 or 64**

Context-switch misses

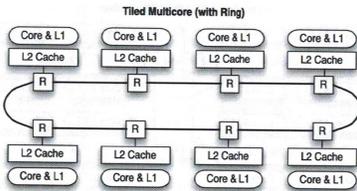
As cache size gets larger, there are fewer uniprocessor (“natural”) cache misses.

But the [number of context-switch misses](#) may go up (mcf, soplex) or down (namd, perlbench).

- Why could it go up?
- Why could it go down?

Reordered misses also decline as the cache becomes large. Why?

Usually, a portion of the L2 is placed near each L1; this is a *tiled* arrangement.



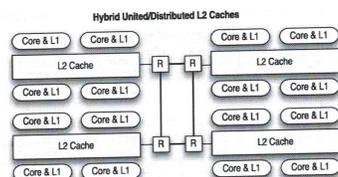
What are some advantages of a distributed structure?

- In replication: **tiles can simply be duplicated as many times as you have cores on a chip**
- In layout: **wires are shorter, heat is not centralized.**

Hybrid centralized + distributed structure: There’s a tradeoff between centralized and distributed.

- A large cache is uniformly slow, especially if it needs to handle coherence.
- A distributed cache requires a lot of interconnections, and routing latency is high if the cache is in too many places.

A compromise is to have an L2 cache that is distributed, but not as distributed as the L1 caches.



Logical cache organization

[Solihin §5.7] Regardless of whether a cache is centralized or distributed, there are several options in mapping addresses to tiles.

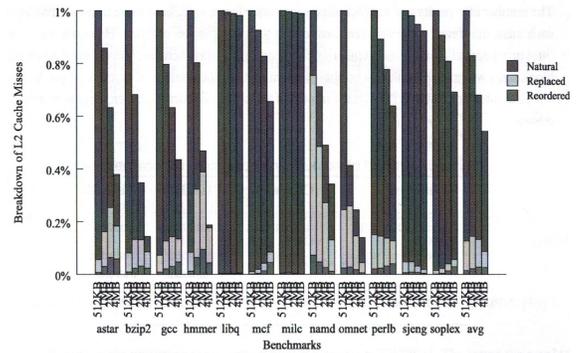


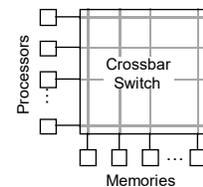
Figure 5.13: Breakdown of the types of L2 cache misses suffered by SPEC2006 applications with various cache sizes. Source: [39].

Physical cache organization

[Solihin §5.6] An cache is *centralized* (“united”) if its banks are adjacent on the chip.

What are some advantages of a centralized structure?

- Uniform **access latency**
- Interconnect between the cache and the next level (e.g., on-chip memory controller) **is simpler, because it can be in one place.**



A centralized cache usually uses a crossbar (see also p. 167 of the text).

A cache is *distributed* if its banks are scattered around the chip.

- A processor can be limited to accessing a single tile, the one closest to it (private cache configuration).
 - A block in the local cache may also exist in other caches; the copies must be kept coherent by a coherence protocol.
- All of the tiles can form a large logical cache. The address of a block completely determines what tile it is found in (shared 1-tile associative).
 - It may require a lot of hops to get from a processor to the cache.
- A block can be mapped to two tiles (shared 2-tile associative).
 - Block numbers are arranged to improve distance locality.
- Or, a block can be allowed to map to any tile (full tile associativity).
 - [What is the upside?](#)
 - What is the downside?

Another option is a partitioned shared cache organization.

- [Can you tell](#) how many tiles each block can map to?
- Can you tell how many *lines* each block can map to?
- How does coherence play a role?

Lock Implementations

[§8.1] Recall the three kinds of synchronization from Lecture 6:

- Point-to-point **send() and receive(); wait() and post()**
- Lock

- **Barrier**

Performance metrics for lock implementations

- Uncontended latency
 - Time to acquire a lock when there is no contention
- Traffic
 - Lock acquisition when lock is already locked
 - Lock acquisition when lock is free
 - Lock release
- Fairness
 - Degree in which a thread can acquire a lock with respect to others
- Storage
 - As a function of # of threads/processors

The need for atomicity

This code sequence illustrates the need for atomicity. Explain.

```
void lock (int *lockvar) {
    while (*lockvar == 1) {} ; // wait until released
    *lockvar = 1;           // acquire lock
}

void unlock (int *lockvar) {
    *lockvar = 0;
}
```

In assembly language, the sequence looks like this:

```
lock: ld R1, &lockvar    // R1 = lockvar
      bnz R1, lock       // jump to lock if R1 != 0
      sti &lockvar, #1   // lockvar = 1
      ret                // return to caller
unlock: sti &lockvar, #0 // lockvar = 0
      ret                // return to caller
```

The ld-to-sti sequence must be executed atomically:

- The sequence appears to execute in its entirety
- Multiple sequences are serialized

Examples of atomic instructions

- **test-and-set Rx, M**
 - read the value stored in memory location **M**, test the value against a constant (e.g. 0), and if they match, write the value in register **Rx** to the memory location **M**.
- **fetch-and-op M**
 - read the value stored in memory location **M**, perform op to it (e.g., increment, decrement, addition, subtraction), then store the new value to the memory location **M**.
- **exchange Rx, M**
 - atomically exchange (or swap) the value in memory location **M** with the value in register **Rx**.
- **compare-and-swap Rx, Ry, M**
 - compare the value in memory location **M** with the value in register **Rx**. If they match, write the value in register **Ry** to **M**, and copy the value in **Rx** to **Ry**.

How to ensure one atomic instruction is executed at a time:

1. Reserve the bus until done
 - Other atomic instructions cannot get to the bus
2. Reserve the cache block involved until done
 - Obtain exclusive permission (e.g. "M" in MESI)
 - Reject or delay any invalidation or intervention requests until done
3. Provide "illusion" of atomicity instead

- Using load-link/store-conditional (to be discussed later)

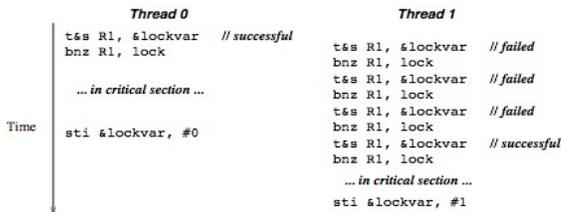
Test and set

test-and-set can be used like this to implement a lock:

```
lock:  t&s R1, &lockvar // R1 = MEM[&lockvar];
      // if (R1==0) MEM[&lockvar]=1
      bnz R1, lock;    // jump to lock if R1 != 0
      ret              // return to caller
unlock: sti &lockvar, #0 // MEM[&lockvar] = 0
      ret              // return to caller
```

What value does **lockvar** have when the lock is acquired? 1 free? 0

Here is an example of **test-and-set** execution. Describe what it shows.



Thread 1 tries repeatedly to get the lock, and succeeds only after thread 0 releases it by setting lockvar to 0.

Let's look at how a sequence of test-and-sets by three processors plays out:

Request	P1	P2	P3	BusRequest
Initially	-	-	-	-
P1: t&s	M	-	-	BusRdX
P2: t&s	I	M	-	BusRdX
P3: t&s	I	I	M	BusRdX
P2: t&s	I	M	I	BusRdX
P1: unlock	M	I	I	BusRdX
P2: t&s	I	M	I	BusRdX
P3: t&s	I	I	M	BusRdX
P3: t&s	I	I	M	-
P2: unlock	I	M	I	BusRdX
P3: t&s	I	I	M	BusRdX
P3: unlock	I	I	M	-

[How does test-and-set perform](#) on the four metrics listed above?

- Uncontended latency
- Fairness
- Traffic
- Storage

Drawbacks of Test&Set Lock (TSL)

What is the main drawback of test&set locks? **Very high traffic**

- Many coherence transactions occur as processors compete for the lock.
- Other processors that are invalidating the lock slow down the process that does have the lock.

Without changing the lock mechanism, how can we diminish this overhead?

- **Back off:** pause for awhile after a failed acquisition. Retry later

- o Back off by too little: still too much contention.
- o Back off by too much: processors are waiting needlessly long.
- Exponential backoff: Increase the backoff interval exponentially with each failure.

Test and Test&Set Lock (TTSL)

- Busy-wait with ordinary read operations, not test&set.
 - o Cached lock variable will be invalidated when release occurs
- When value changes (to 0), try to obtain lock with test&set
 - o Only one attempter will succeed; others will fail and start testing again.

Let's compare the code for TSL with TTSL.

TSL:

```
lock:  t&s R1, &lockvar // R1 = MEM[&lockvar];
      // if (R1==0) MEM[&lockvar]=1
      bnz R1, lock;    // jump to lock if R1 != 0
      ret              // return to caller
unlock: sti &lockvar, #0 // MEM[&lockvar] = 0
      ret              // return to caller
```

TTSL:

```
lock:  ld R1, &lockvar // R1 = MEM[&lockvar]
      bnz R1, lock;    // jump to lock if R1 != 0
      t&s R1, &lockvar // R1 = MEM[&lockvar];
      // if (R1==0)MEM[&lockvar]=1
      bnz R1, lock;    // jump to lock if R1 != 0
      ret              // return to caller
```

```
unlock: sti &lockvar, #0 // MEM[&lockvar] = 0
      ret                // return to caller
```

The lock method now contains two loops. What would happen if we removed the first loop? **Reduces to TSL**
 What happens if we remove the second loop? **You get the code that we started with, that does enforce synchronization.**

Here's a trace of a TSL, and then TTSL, execution. Let's compare them line by line.

Fill out this table:

	TSL	TTSL
# BusReads	0	6
# BusReadXs	9	0
# BusUpgrs	0	4
# invalidations	8	5

(What's the proper way to count invalidations?)

TSL: Request	P1	P2	P3	BusRequest
Initially	-	-	-	-
P1: t&s	M	-	-	BusRdX
P2: t&s	I	M	-	BusRdX
P3: t&s	I	I	M	BusRdX
P2: t&s	I	M	I	BusRdX
P1: unlock	M	I	I	BusRdX
P2: t&s	I	M	I	BusRdX
P3: t&s	I	I	M	BusRdX
P3: t&s	I	I	M	-
P2: unlock	I	M	I	BusRdX
P3: t&s	I	I	M	BusRdX
P3: unlock	I	I	M	-

P2: t&s	I	M	I	BusUpgr
P3: ld	I	S	S	BusRd
P3: ld	I	S	S	-
P2: unlock	I	M	I	BusUpgr
P3: ld	I	S	S	BusRd
P3: t&s	I	I	M	BusUpgr
P3: unlock	I	I	M	-

TTSL: Request	P1	P2	P3	Bus Request
Initially	-	-	-	-
P1: ld	E	-	-	BusRd
P1: t&s	M	-	-	-
P2: ld	S	S	-	BusRd
P3: ld	S	S	S	BusRd
P2: ld	S	S	S	-
P1: unlock	M	I	I	BusUpgr
P2: ld	S	S	I	BusRd

TSL vs. TTSL summary

- Successful lock acquisition:
 - o 2 bus transactions in TTSL
 - 1 BusRd to intervene with a remotely cached block
 - 1 BusUpgr to invalidate all remote copies
 - o vs. only 1 in TSL
 - 1 BusRdX to invalidate all remote copies
- Failed lock acquisition:
 - o 1 bus transaction in TTSL
 - 1 BusRd to read a copy
 - then, loop until lock becomes free
 - o vs. unlimited with TSL
 - Each attempt generates a BusRdX

LL/SC

- TTSL is an improvement over TSL.
- But bus-based locking

- o has a limited applicability (explain)
 - o is not scalable with fine-grain locks (explain)
 - using *any* lock ties up the bus, so fine-grain locks have a high overhead (when they were used to increase concurrency)
 - Suppose we could lock a *cache block* instead of a bus ...
 - o Expensive, must rely on buffering or NACK
 - Instead of providing atomicity, can we provide an illusion of atomicity instead?
 - o This would involve detecting a violation of atomicity.
 - o If something "happens to" the value loaded, cancel the store (because we must not allow newly stored value to become visible to other processors)
 - o Go back and repeat all other instructions (load, branch, etc.).
- This can be done with two new instructions:

- Load Linked/Locked (LL)
 - o reads a word from memory, and
 - o stores the address in a special LL register
 - o The LL register is cleared if anything happens that may break atomicity, e.g.,
 - A context switch occurs
 - The block containing the address in the LL register is invalidated.
- Store Conditional (SC)
 - o tests whether the address in the LL register matches the store address
 - o if so, store succeeds: store goes to cache/memory;
 - o else, store fails: the store is canceled, 0 is returned.

Here is the code.

```
lock: LL R1, &lockvar // R1 = lockvar;
      // LINKREG = &lockvar
```

P2: SC	I	M	I	BusUpgr
P3: LL	I	S	S	BusRd
P3: LL	I	S	S	-
P2: unlock	I	M	I	BusUpgr
P3: LL	I	S	S	BusRd
P3: SC	I	I	M	BusUpgr
P3: unlock	I	I	M	-

- Similar bus traffic
 - o Spinning using loads \Rightarrow no bus transactions when the lock is not free
 - o Successful lock acquisition involves two bus transactions. What are they? **BusRd, BusUpgr**
- But a failed SC does not generate a bus transaction (in TTSL, all test&sets generate bus transactions).
 - o Why don't SCs fail often?
 - The first loop only falls through if the lock is available, so some unusual condition has to occur to cause the SC to fail.

Limitations of LL/SC

- Suppose a lock is highly contended by p threads
 - o There are $O(p)$ attempts to acquire and release a lock
 - o A single release invalidates $O(p)$ caches, causing $O(p)$ subsequent cache misses
 - o Hence, each critical section causes $O(p^2)$ bus traffic
- Fairness: There is no guarantee that a thread that contends for a lock will eventually acquire it.

```
bnz R1, lock // jump to lock if R1 != 0
add R1, R1, #1 // R1 = 1
SC R1, &lockvar // lockvar = R1;
beqz R1, lock // jump to lock if SC fails
ret // return to caller
```

```
unlock: sti &lockvar, #0 // lockvar = 0
ret // return to caller
```

Note that this code, like the TTSL code, consists of two loops. Compare each loop with its TTSL counterpart.

- The first loop
- The second loop

Here is a trace of execution. [Compare it](#) with TTSL.

Request	P1	P2	P3	BusRequest
Initially	-	-	-	-
P1: LL	E	-	-	BusRd
P1: SC	M	-	-	-
P2: LL	S	S	-	BusRd
P3: LL	S	S	S	BusRd
P2: LL	S	S	S	-
P1: unlock	M	I	I	BusUpgr
P2: LL	S	S	I	BusRd

These issues can be addressed by two different kinds of locks.

Ticket Lock

- Ensures fairness, but still incurs $O(p^2)$ traffic
- Uses the concept of a "bakery" queue
- A thread attempting to acquire a lock is given a ticket number representing its position in the queue.
- Lock acquisition order follows the queue order.

Implementation:

```
ticketLock_init(int *next_ticket, int *now_serving) {
    *now_serving = *next_ticket = 0;
}

ticketLock_acquire(int *next_ticket, int *now_serving) {
    my_ticket = fetch_and_inc(next_ticket);
    while (*now_serving != my_ticket) {};
}

ticketLock_release(int *next_ticket, int *now_serving) {
    *now_serving++;
}
```

Trace:

Steps	next_ticket	now_serving	my_ticket		
			P1	P2	P3
Initially	0	0	-	-	-
P1: fetch&inc	1	0	0	-	-
P2: fetch&inc	2	0	0	1	-
P3: fetch&inc	3	0	0	1	2
P1:now_serving++	3	1	0	1	2
P2:now_serving++	3	2	0	1	2
P3:now_serving++	3	3	0	1	2

Note that fetch&inc can be implemented with LL/SC.

Array-Based Queueing Locks

With a ticket lock, a release still invalidates $O(p)$ caches.

Idea: Avoid this by letting each thread wait for a unique variable. Waiting processes poll on different locations in an array of size p .

Just change `now_serving` to an array! (renamed "`can_serve`").

A thread attempting to acquire a lock is given a ticket number in the queue.

Lock acquisition order follows the queue order

- Acquire
 - fetch&inc obtains the address on which to spin (the next array element).
 - We must ensure that these addresses are in different cache lines or memories
- Release
 - Set next location in array to 1, thus waking up process spinning on it.

Advantages and disadvantages:

- $O(1)$ traffic per acquire with coherent caches
 - And each release invalidates only one cache.

Let's compare array-based queueing locks with ticket locks.

Fill out this table, assuming that 10 threads are competing:

	Ticket locks	Array-based queueing locks
#of invalidations	$9+8+\dots+1 = 45$	9
# of subsequent cache misses	9	9

Comparison of lock implementations

Criterion	TSL	TTSL	LL/SC	Ticket	ABQL
Uncontested latency	Lowest	Lower	Lower	Higher	Higher
1 release max traffic	$O(p)$	$O(p)$	$O(p)$	$O(p)$	$O(1)$
Wait traffic	High	Low	-	-	-
Storage	$O(1)$	$O(1)$	$O(1)$	$O(1)$	$O(p)$
Fairness guaranteed?	No	No	No	Yes	Yes

Discussion:

- Design must balance latency vs. scalability
 - ABQL is not necessarily best.
 - Often LL/SC locks perform very well.
 - Scalable programs rarely use highly-contended locks.
- Fairness sounds good in theory, but

- FIFO ordering, as in ticket lock, ensuring fairness
- But, $O(p)$ space per lock
- Good scalability for bus-based machines

Implementation:

```

ABQL_init(int *next_ticket, int *can_serve) {
    *next_ticket = 0;
    for (i=1; i<MAXSIZE; i++)
        can_serve[i] = 0;
    can_serve[0] = 1;
}

ABQL_acquire(int *next_ticket, int *can_serve) {
    *my_ticket = fetch_and_inc(next_ticket) % MAXSIZE;
    while (can_serve[*my_ticket] != 1) {}
}

ABQL_release(int *next_ticket, int *can_serve) {
    can_serve[*my_ticket + 1] = 1;
    can_serve[*my_ticket] = 0; // prepare for next time
}

```

Trace:

Steps	next_ticket	can_serve[]	my_ticket		
			P1	P2	P3
Initially	0	[1, 0, 0, 0]	-	-	-
P1: f&i	1	[1, 0, 0, 0]	0	-	-
P2: f&i	2	[1, 0, 0, 0]	0	1	-
P3: f&i	3	[1, 0, 0, 0]	0	1	2
P1: can_serve[1]=1	3	[0, 1, 0, 0]	0	1	2
P2: can_serve[2]=1	3	[0, 0, 1, 0]	0	1	2
P3: can_serve[3]=1	3	[0, 0, 0, 1]	0	1	2

- Must ensure that the current/next lock holder does not suffer from context switches or any long delay events

Barriers

[§8.2] Like locks, barriers can be implemented in different ways, depending upon how important efficiency is.

- Performance criteria
 - Latency: time spent from reaching the barrier to leaving it
 - Traffic: number of bytes communicated as a function of number of processors
- In current systems, barriers are typically implemented in software using locks, flags, counters.
 - Adequate for small systems
 - Not scalable for large systems

A thread might have this general organization:

```

..
parallel region
BARRIER
parallel region
BARRIER
..

```

Note that barriers are usually constructed using locks, and thus can use any of the lock implementations in the previous lecture.

A barrier can be implemented like this (first attempt):

```

// shared variables used in barrier & their initial values
int numArrived = 0;
lock_type barLock = 0;
int canGo = 0;

// barrier implementation
void barrier () {

```

```

lock(&barLock);
if (numArrived == 0) // first thread sets flag
    canGo = 0;
numArrived++;
int myCount = numArrived;
unlock(&barLock);

if (myCount < NUM_THREADS) {
    while (canGo == 0) {}; // wait for last thread
}
else { // this is the last thread to arrive
    numArrived = 0; // reset for next barrier
    canGo = 1; // release all threads
}
}

```

What's wrong with this?

Sense-reversal centralized barrier

[§8.2.1] The simplest solution to the correctness problem above just toggles the barrier ...

- the first time, the threads wait for `canGo` to become 1;
- the next time they wait for it to become 0;
- and then they alternate waiting for it to become 1 and 0 at successive barriers.

Here is the code:

```

// variables used in a barrier and their initial values
int numArrived = 0;
lock_type barLock = 0;
int canGo = 0;

// thread-private variable
int valueToAwait = 0;

```

```

// barrier implementation
void barrier () {
    valueToAwait = 1 - valueToAwait; // toggle it
    lock(&barLock);
    numArrived++;
    int myCount = numArrived;
    unlock(&barLock);

    if (myCount < NUM_THREADS) {
        while (canGo != valueToAwait) {}; // await last thread
    }
    else { // this is the last thread to arrive
        numArrived = 0; // reset for next barrier
        canGo = valueToAwait; // release all threads
    }
}

```

How does the [traffic at this barrier scale?](#)

Combining-tree barrier

[§8.2.2] A tree-based strategy can be used to reduce contention, similarly to the way we used partial sums in Lecture 5.

- Threads represent the leaf nodes of a tree.
- The non-leaf nodes are the variables that the threads spin on.
- Each thread spins on the variable of its immediate parent, which constitutes an intermediate barrier.

- Once all threads have arrived at the intermediate barrier, one of these threads goes on and spins on the variable immediately above.
- This is repeated until the root is reached. At this point, the root releases all threads by setting a flag.

How does this [improve performance?](#)

But there is an offsetting cost to a combining tree. What is it?

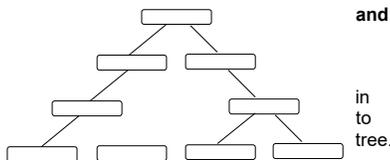
[§8.2.3] In very large supercomputers, however, this technique does not suffice.

The BlueGene/L system has a special *barrier network* for implementing barriers and broadcasting notifications to processors.

The network contains four independent channels.

Each level does a global of the signals from the levels below it.

The signals are combined hardware and propagate the top of a combining



The tree can also be used to do a global interrupt when the entire machine or partition must be stopped as soon as possible "for diagnostic purposes."

In this case, each level does a global or of the signals from beneath.

Once the signal propagates to the top of the tree, the resultant notification is broadcast down the tree.

The round-trip latency is only 1.5 μs for a system of 64K nodes.

Cache Coherence vs. Memory Consistency

- Cache coherence
 - deals with ordering of writes to a **single** memory location
 - only needed for systems with caches
- Memory consistency
 - deals with ordering of reads/writes to *all* memory locations
 - needed in systems with or without caches

Why is a memory consistency model needed?

[§9.1] Programmer's intuition:

P0: S1: datum = 5; S2: datumIsReady = 1;	P1: S3: while (!datumIsReady); S4: ... = datum
--	--

Programmers expect S4 to read the new value of datum (i.e., 5).

This expectation is violated if—

- S2 appears to be executed before S1
- S4 appears to be executed before S3

Thus, *Hypothesis 1: Program-order expectation*

Programmers expect memory accesses in a thread to be executed in the same order in which they occur in the source code.

Not only the executing thread, but *all* threads, are expected to see them in this order.

P0: S1: x = 5; S2: xReady = 1;	P1: S3: while (!xReady) {}; S4: y = x + 4; S5: xyReady = 1;	P2: S6: while (!xyReady) {}; S7: z = x * y;
--------------------------------------	--	---

Let's say, initially, $x = y = z = xReady = xyReady = 0$

As a programmer, what would you expect to be the value of z at $S7$?

This implies that if the new value of x has been propagated to $P2$, it has also been propagated to

Thus, *Hypothesis 2: Atomicity expectation*

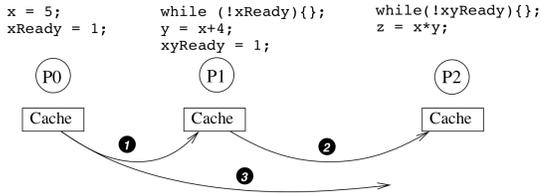
A read or write happens instantaneously with respect to all processors.

How can the atomicity expectation be violated?

Step 1: New values of x and $xReady$ have been propagated to $P1$, but have not reached $P2$.

Step 2: New values of y and $xyReady$ have been propagated to $P2$ before x is propagated to $P2$.

Step 3: When x is propagated to $P2$, $P2$ has already read the old value of x , and z has been set to 0.



Is there any other way that a violation of store atomicity can lead to a wrong value for z ?

What is another "incorrect" value that could be written for z ? Explain how this could happen.

Summary of programmer's expectations:

Memory accesses emanating from a processor should be performed in program order, and each of them should be performed atomically.

These expectations were incorporated in Lamport's 1979 definition of sequential consistency:

A multiprocessor is sequentially consistent if the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor occur in this sequence in the order specified by its program.

Sequentially consistent vs. non-SC outcomes

Consider these code sequences, with a and b initialized to 0.

P0: S1: a = 1; S2: b = 1;	P1: S3: print b; S4: print a;
--	--

Note that this program is *non-deterministic* due to a lack of synchronization.

Under SC, $S1 \rightarrow S2$ and $S3 \rightarrow S4$ are guaranteed

Assuming SC, what values might possibly be printed for a and b ?

- S1, S2, S3, S4 \rightarrow 1, 1
- S1, S3, S4, S2 \rightarrow 1, 0
- S3, S4, S1, S2 \rightarrow 0, 0

What values for a, b are impossible? **0, 1**

Prove it.

For a to print as **0**, it must be that $S4 \rightarrow S1$: e.g.,

For b to print as **1**, it must be that $S2 \rightarrow S3$: e.g.,

Both of these conditions cannot hold. **Prove it. $S1 \rightarrow S2, S3 \rightarrow S4$ So if $S2 \rightarrow S3$, then $S1 \rightarrow S4$**

On a non-SC machine, the outcome of $a, b = 0, 1$ is possible. What statement ordering can produce it? **S2, S3, S4, S1**

In this case, which of the two SC precedence guarantees (above) is violated? **Program-order the order between two writes**

What's a way to get the same result that violates the other precedence guarantee? **S4, S1, S2, S3 the order between 2 reads**

Let's take another example.

P0: S1: a = 1; S2: print b;	P1: S3: b = 1; S4: print a;
--	--

Exercise: Assuming that a and b are initialized to 0,

- what values can be printed under SC?
- what values are impossible to print under SC?
- prove that the impossible results can only occur if SC is violated.

Answer: Note that the program is non-deterministic due to a lack of synchronization.

With SC, $S1 \rightarrow S2$ and $S3 \rightarrow S4$ are guaranteed

- S1, S2, S3, S4 \rightarrow 1, 0
- S1, S3, S2, S4 \rightarrow 1, 1
- S3, S4, S1, S2 \rightarrow 0, 1

On a nondeterministic machine, the outcome $a, b = 0, 0$ is possible.

- S4, S1, S2, S3
 - In this case, $S3 \rightarrow S4$ is violated
- S2, S3, S4, S1
 - In this case, $S1 \rightarrow S2$ is violated

Both of the previous examples are non-deterministic.

Non-deterministic codes are notoriously hard to debug.

But non-determinism may have legitimate uses. See Code 3.16 (ocean-current simulation) and 3.18 (smoothing filter for grayscale image).

So, does preserving ordering of memory accesses matter?

- Probably not if non-determinism is intentional
- Otherwise, yes, because:
 - Helps keep programmers sane during debugging.
 - Even properly synchronized programs need ordering for the synchronization to work properly.

Building a SC system

[§9.2] Which of the two hypotheses (expectations) can be guaranteed by software? **Program order**

- Ensure that compiler does not reorder memory accesses;
- Declare critical variables as volatile (to avoid register allocation, code elimination, etc.)

What hypothesis needs to be maintained by hardware? **Atomicity**

- Execute one memory access one at a time, in program order. One access needs to be complete before the next can start.
- In the processor pipeline, memory accesses can be overlapped or reordered.

- But they must go to the cache in program order.
- A load is complete when the block has been read from the cache.
- A store is complete when an invalidation has been posted (on a bus) or acknowledged (see details in §9.2.1).

Example of SC Ordering

```

s1: ld R1, A      s1 must complete before s2,
s2: ld R2, B      s2 before s3, etc.
s3: st R3, C
s4: st R4, D
s5: ld R5, D

```

Implications

- If **s1** is a cache miss but **s2** is a cache hit, **s2** still must wait until **s1** is completed. Same with **s3** and **s4**.
- **s4** must wait for **s3** to complete, even though stores are often retired early.
- **s5** must wait for **s4** to complete, even though they are to the same location!

Improving SC performance

Via prefetching

We still have to obey ordering, but we can make each load/store complete faster, e.g. by converting cache misses into cache hits:

- Employ load prefetching
 - As soon as address is known/predictable,
 - fetch before previous loads have completed,
 - issue a prefetch request to fetch the block in Exclusive/Shared state
- Employ store prefetching

- As soon as address is known/predictable, issue a prefetch request to fetch the block in Modified state

But this is not a perfect strategy. [Why not?](#)

- Prefetch too late ⇒
- Prefetch too early ⇒

Via speculation

We can violate ordering, but undo the effect if atomicity is violated.

- The ability to undo execution and re-execute is already present in out-of-order processors (as covered in ECE 563).
 - So, we only need to determine when atomicity has been violated.
- Consider load A, followed by load B
 - In strict SC, load B must wait until load A completes
 - With speculation, load B accesses the cache anyway; the processor just marks load B as speculative
 - If B is invalidated before it "retires," atomicity has been violated.
 - In this case, the architecture cancels B and re-executes it.

Store speculation is harder, because stores cannot be canceled. Hence, only load speculation is employed.