EC 440 – Introduction to Operating Systems

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Slides from Christopher Kruegel, UCSB

Coding discussion

- How many of you have started?
- You have learned to use your tools, test driven development...
  - Please use and beat this up
- Nobody has yet posted tests for extra grades.
- We are building a repo for tests that we will be available soon...
  - You should be able to submit pull requests with new tests
  - You should be able to review each other's tests, and comment on them
  - We will select the best ones and incorporate them

Expectations HW

- You must only and exclusively submit code you wrote yourself.
- After the HW1 was submitted, we ran all solutions through software similarity detection.
  - It is clear that the majority of the class did the work themselves. Thank you!
  - There are a few situations where there are strong similarities to existing projects.
  - We are now collecting corpus of all previous years, and public shells, and running through similarity detection
- Why do we care?
  - You don't learn by doing this
  - Getting a good grade in this course is something to be proud of
  - You don't learn by doing this; you will be quizzed by future employers on what you did here...
  - In the long run it never works out.
- The end of this week I will be talking to anyone that the TFs were not confident fully understood their code and/or who's program was similar to other current or previous ones.
- Post a private note to Piazza if you want to talk to me first.

Review

- Bit about OS structure, history of OS and core services
- System calls, processes, threads, stacks and calling code conventions
- Scheduling policies, and a start to synchronization.
- Next:
  - go through example of how we expect you to be able to reason about synchronization
  - finish up synchronization
  - Discuss deadlock

Worksheet

```
monitor M
  condition cond1, cond2;
  function sub1();
  begin
    ...
    wait(cond1);
  end;
  function sub2();
  begin
    ...
    signal(cond1);
    ...
    wait(cond2);
  end;
  function sub3();
  begin
    ...
    signal(cond2);
    signal(cond2);
  end;
end;
```

- Process A is waiting on cond1 (in end of sub1)
- Process B is waiting on cond2 (in end of sub2)
- At time t0 process C calls M.sub2()
- At time t1 > t0 process D calls M.sub2()
- At time t2 > t1 process E calls M.sub3()

Problem:

- Assume all waiting queues are FIFO
- If Q has been waiting for condition "x" and P performs "signal(x)", consider two possible policies:
  - Policy 1: P waits until Q either leaves the monitor, or waits for another condition; or
  - Policy 2: Q waits until P either leaves the monitor, or waits for another condition
- Determine the order of execution of the processes

Policy 1 - Signalee runs

```
monitor M
  condition cond1, cond2;
  function sub1();
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    ...
    wait(cond1);
  end;
  function sub2();
  begin
    ...
    signal(cond1);
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    wait(cond2);
  end;
  function sub3();
  begin
    ...
    signal(cond2);
    signal(cond2);
  end;
end;
```

- P-A is on cond1 (in sub1)
- P-B is on cond2 (in sub2)
- At t0 P-C calls M.sub2()
- At t1 P-D calls M.sub2()
- At t2 P-E calls M.sub3()

C1

C2

M

Policy 1 - Signalee runs

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end;
```

- P-A is on cond1 (in sub1)
- P-B is on cond2 (in sub2)
- At t0 P-C calls M.sub2()
- At t1 P-D calls M.sub2()
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C1	P-A
C2	P-B
M	

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C1	P-A
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M	

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- P-A is on cond1 (in sub1)
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- At t0 P-C calls M.sub2()
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Policy 1 - Signalee runs

time t0

- C executes signal(cond1) and wakes up A

C1	P-A
C2	P-B
M	

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Policy 1 - Signalee runs

time t0

- C executes signal(cond1) and wakes up A
- C suspends and A starts executing sub1()

C1

C2 P-B

M P-C

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Policy 1 - Signalee runs

time t0

- C executes signal(cond1) and wakes up A
- C suspends and A starts executing sub1()
- A exits the monitor
- C restarts
- C waits on cond2 (after B)

C1

C2 P-B P-C

M

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time t0

- C executes signal(cond1) and wakes up A
- C suspends and A starts executing sub1()
- A exits the monitor
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- C waits on cond2 (after B)

time t1

- D enters the monitor with sub2()
- D executes signal(cond1) and nothing happens
- D waits on cond2 after (B and C)

- P-A is on cond1 (in sub1)
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- At t0 P-C calls M.sub2()
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C1

C2 P-B P-C P-D

M

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time t2

- E enters the monitor with sub3()
- E executes the first signal on cond2 and wakes B
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C1		
C2	P-C	P-D
M	P-E	

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time t0

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C2 P-D

M P-E

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time t1

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time t2

- E enters the monitor with sub3()
- E executes the first signal on cond2 and wakes B
- E suspends and B starts
- B exits the monitor and E restarts
- E executes the second signal and wakes C
- E suspends and C starts

```
monitor M
  condition cond1, cond2;
  function sub1();
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    wait(cond1);
  end;
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C1

C2 P-D

M

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- E exits the monitor

Worksheet

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Policy 2 - Signaler runs first

- C executes signal(cond1) and wakes up A
- C continues until it waits on cond2 (after B)
- C suspends and A starts executing sub1()
- A exits the monitor
- D enters the monitor with sub2()
- D executes signal(cond1) and nothing happens
- D waits on cond2 after (B and C)
- E enters the monitor with sub3()
- E executes the first signal on cond2 and wakes B
- E executes the second signal on cond2 and wakes C
- E exits the monitor
- B starts
- B exits the monitor and C starts
- C exits the monitor

Solution

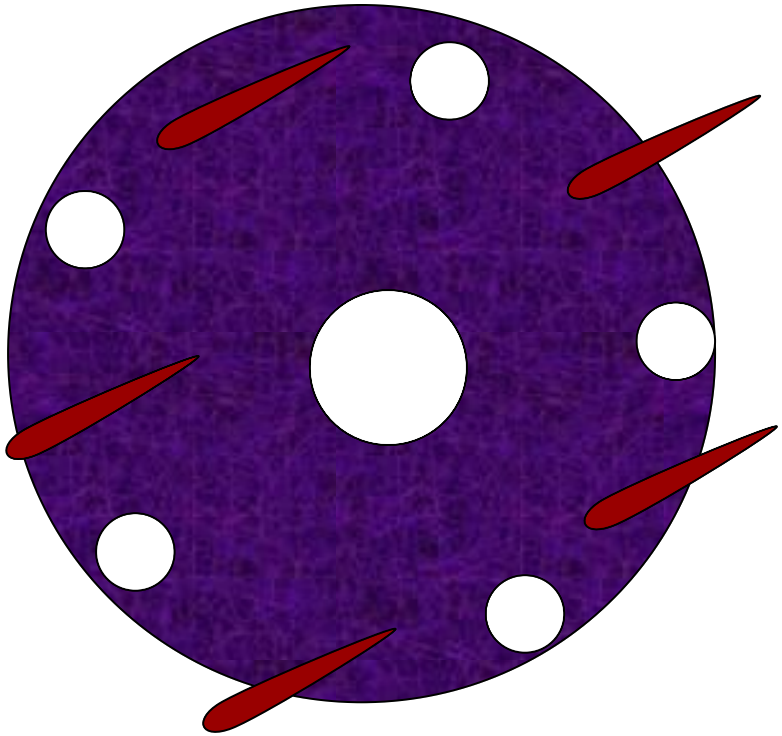
Policy 1- Signalee runs first

- C executes signal(cond1) and wakes up A
- C suspends and A starts executing sub1()
- A exits the monitor
- C restarts
- C waits on cond2 (after B)
- D enters the monitor with sub2()
- D executes signal(cond1) and nothing happens
- D waits on cond2 after (B and C)
- E enters the monitor with sub3()
- E executes the first signal on cond2 and wakes B
- E suspends and B starts
- B exits the monitor and E restarts
- E executes the second signal and wakes C
- E suspends and C starts
- C exits the monitor and E restarts
- E exits the monitor

Policy 2- Signaler runs first

- C executes signal(cond1) and wakes up A
- C continues until it waits on cond2 (after B)
- C suspends and A starts executing sub1()
- A exits the monitor
- D enters the monitor with sub2()
- D executes signal(cond1) and nothing happens
- D waits on cond2 after (B and C)
- E enters the monitor with sub3()
- E executes the first signal on cond2 and wakes B
- E executes the second signal on cond2 and wakes C
- E exits the monitor
- B starts
- B exits the monitor and C starts
- C exits the monitor

Dining Philosophers Problem



First Solution

```
philosopher(int i) {
 while (1) {
    think();
    take_chopstick(i);
    take_chopstick((i + 1) % N);
    eat();
    put_chopstick(i);
    put_chopstick((i + 1) % N);
  }
}
```

If all the philosopher take their left chopsticks they get stuck

Second Solution

```
philosopher(int i) {
 while (1) {
     think();
     take_chopstick(i);
     if (!available((i + 1) % N))
   {
        put_chopstick(i);
        continue();
    }
     take_chopstick((i + 1) % N);
     eat();
     put_chopstick(i);
     put_chopstick((i + 1) % N);
  }
}
```

It is possible that all the philosophers put down and pick up their chopsticks at the same time, leading to starvation

`think()` should be randomized

Third Solution

Use one mutex

- Do a `down()` when acquiring chopsticks
- Do an `up()` when releasing chopsticks

Problem:

Only one philosopher can eat at once

Fourth Solution

- Maintain state of philosophers
  - Switch to `HUNGRY` when ready to eat
  - Sleep if no chopsticks available
  - When finished wake up your neighbors
- Use one semaphore for each philosopher, to be used to suspend in case no chopsticks are available
- Use one mutex for critical regions
- Use `take_chopsticks/put_chopsticks` to acquire both chopsticks

Fourth Solution

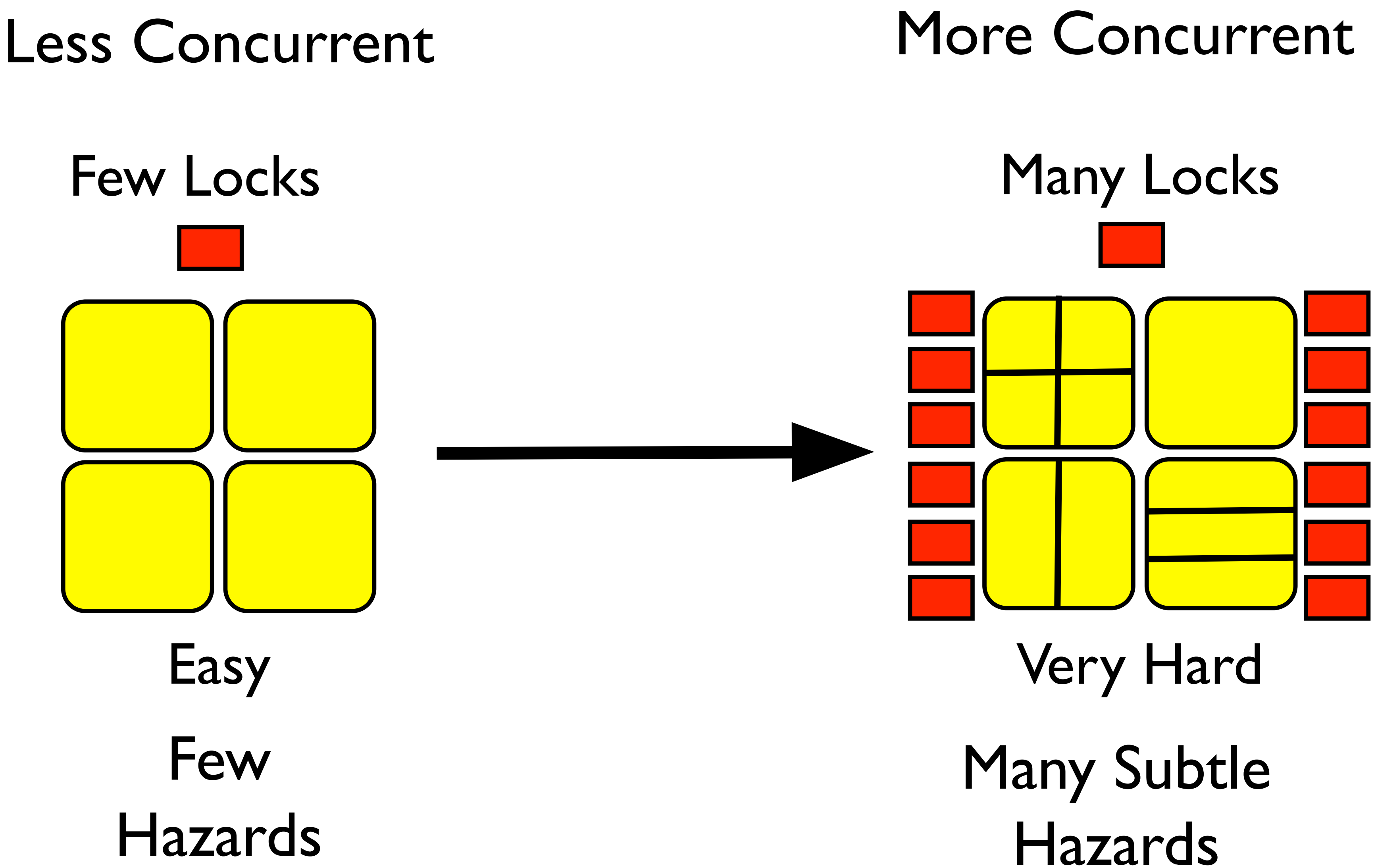
```
philosopher(i) {
  think();
  take_chopsticks(i);
  eat();
  put_chopsticks(i);
}
```

```
take_chopsticks(i) {
  mutex.down();
  state[i] = HUNGRY;
  test(i);
  mutex.up();
  philosopher[i].down();
}
```

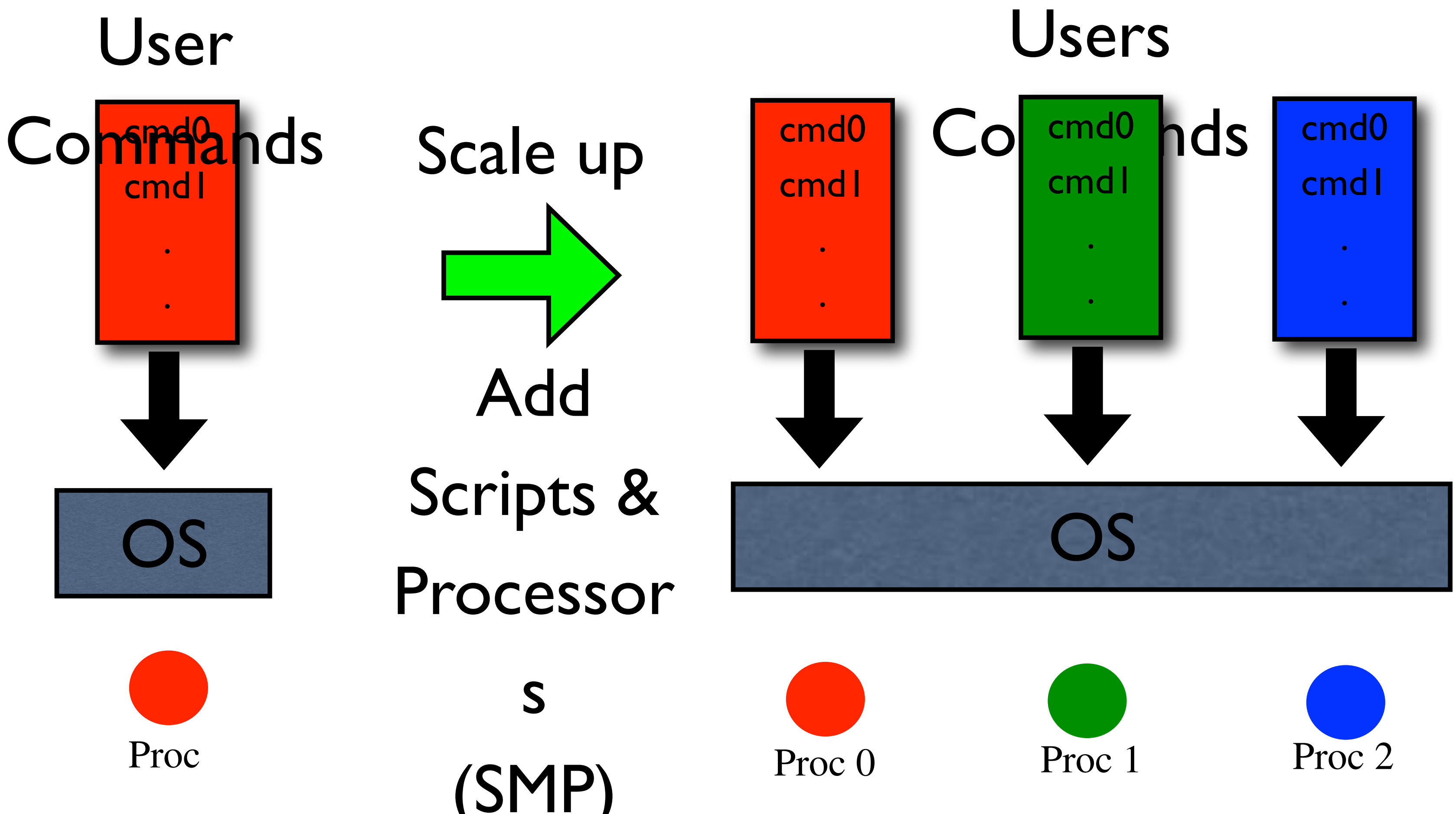
```
put_chopsticks(i) {
  mutex.down();
  state[i] = THINKING;
  test((i + 1) % N);
  test((i + N - 1) % N);
  mutex.up();
}
```

```
test(i) {
  if (state[i] == HUNGRY && state[(i + 1) % N] != EATING &&
                      state[(i + N - 1) % N] != EATING) {
        state[i] = EATING;
        philosopher[i].up();
  }
}
```

Lets discuss real world...

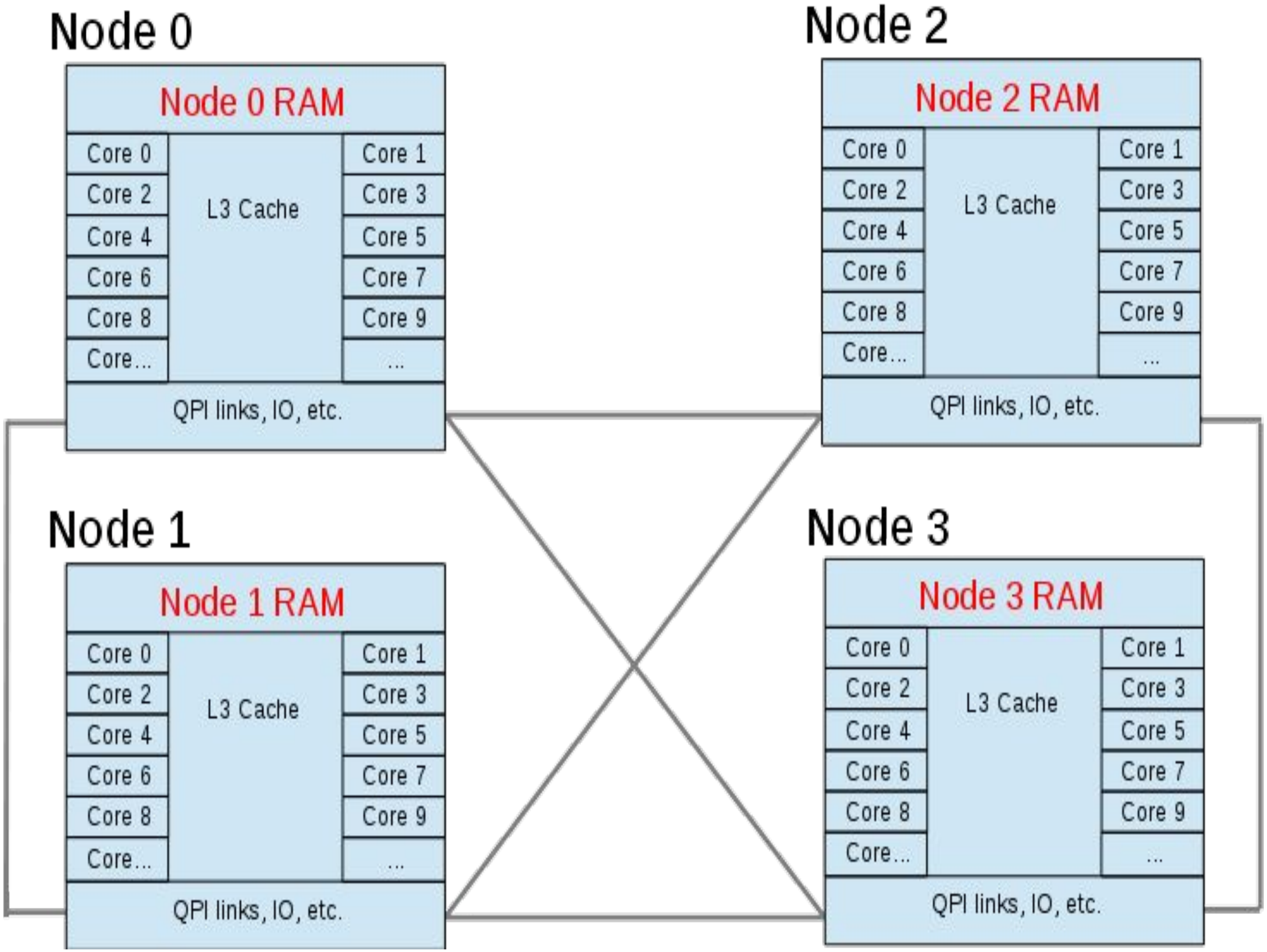

Less Concurrent
More Concurrent
Few Locks
Many Locks
Easy
Very Hard
Few
Hazards
Many Subtle
Hazards

Systems view of Scalability



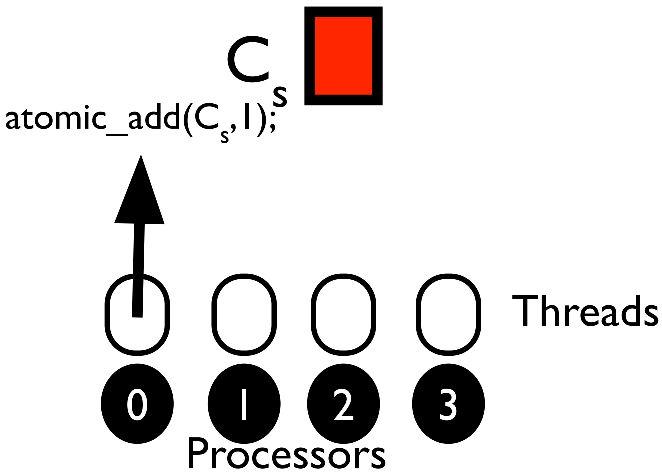
Measure throughput -- Does it scale?

Typical Four-Node NUMA System



Concurrent SW != Scalability

Shared Counter



Uni-Processor atomic inc: 0.1 % of path

Concurrent SW != Scalability

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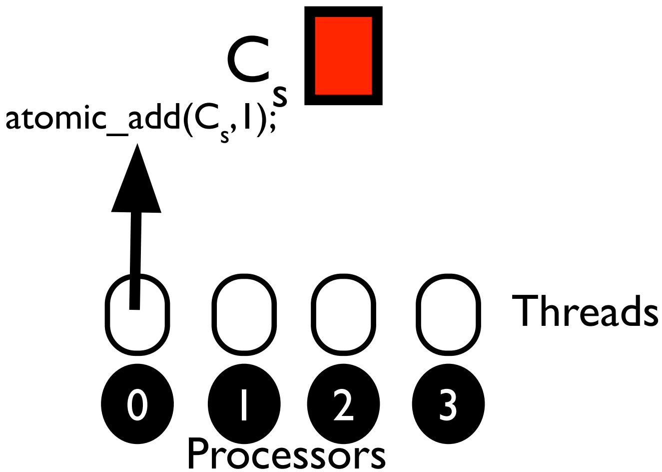

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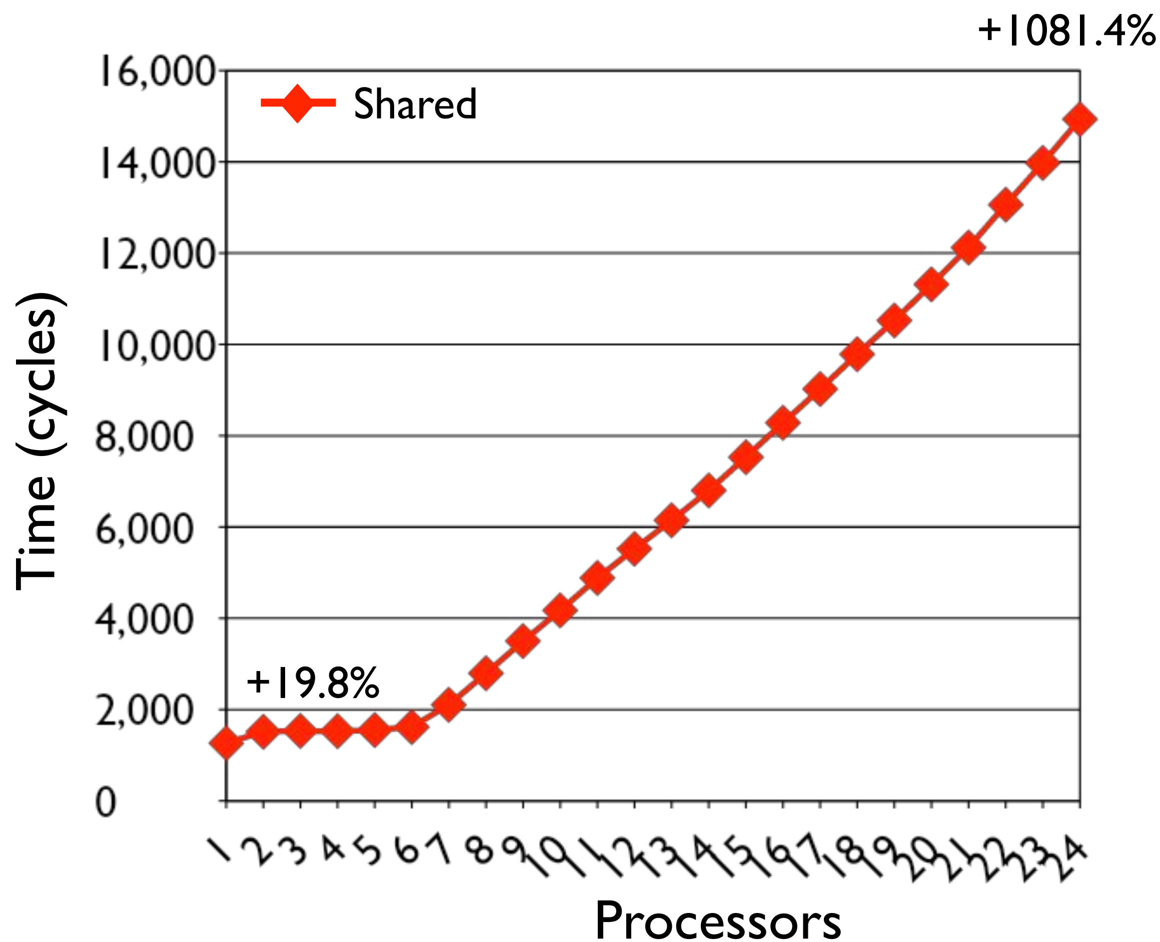

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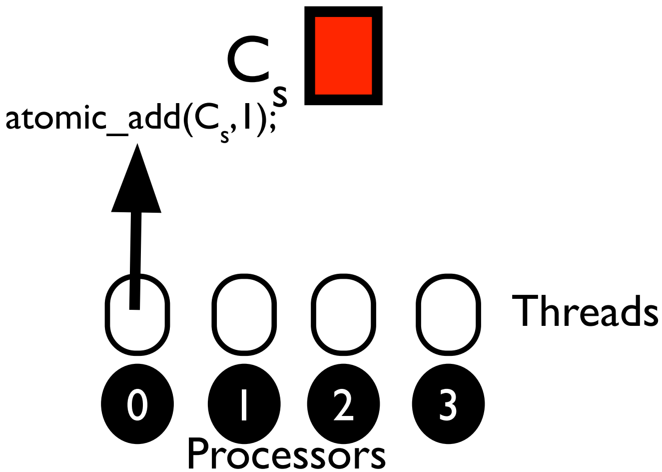
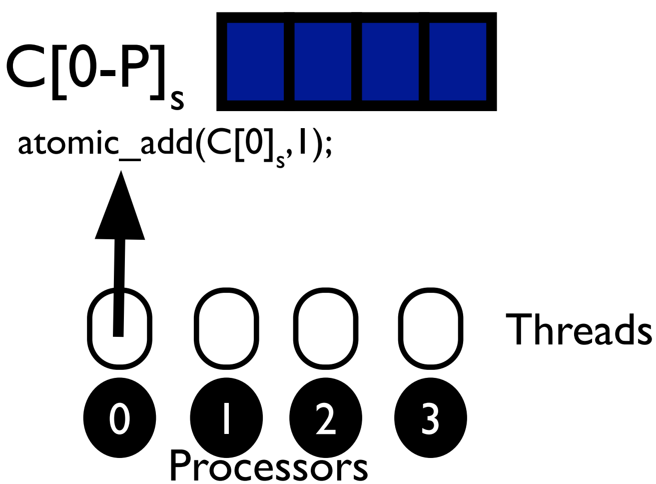


Array of Counters



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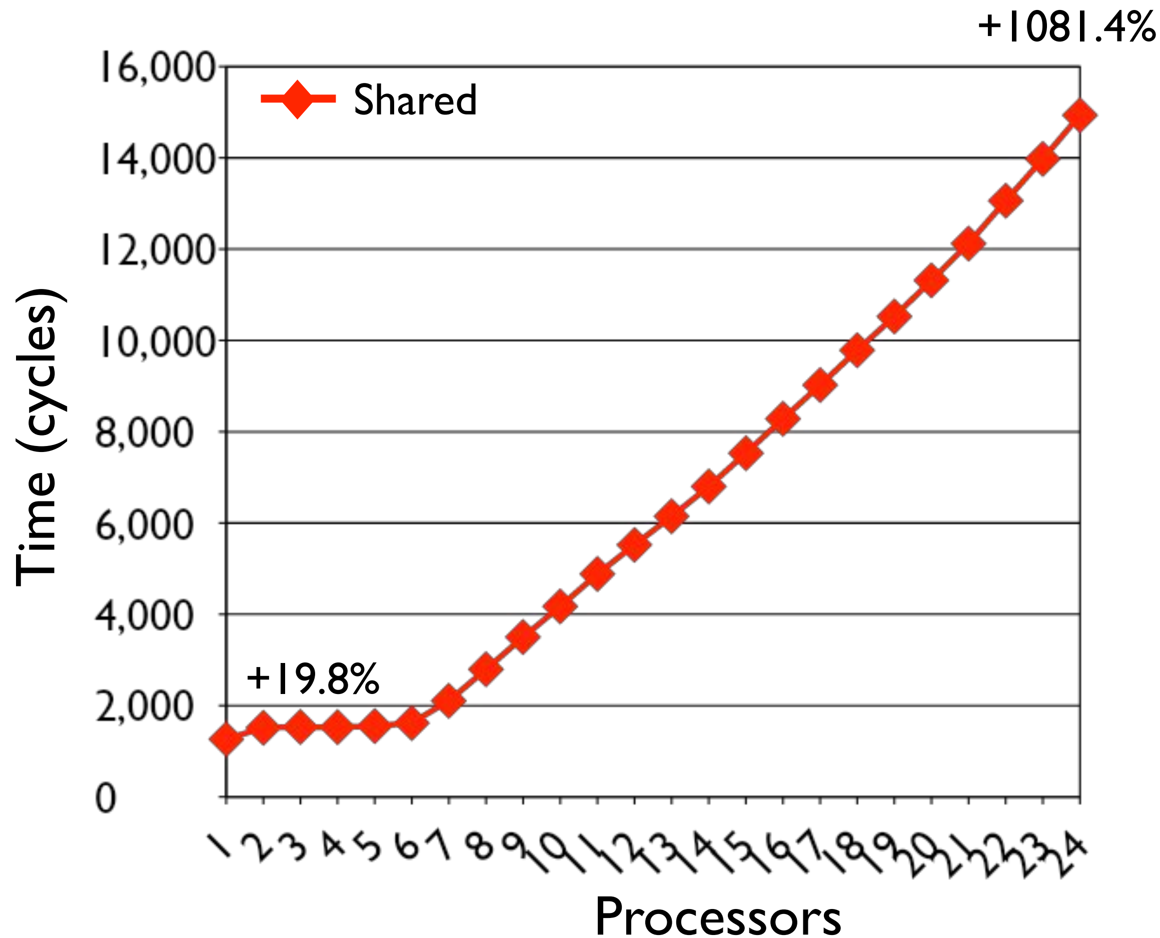

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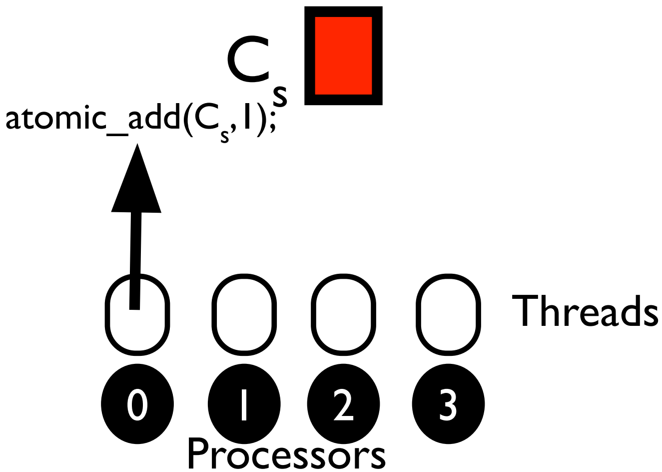

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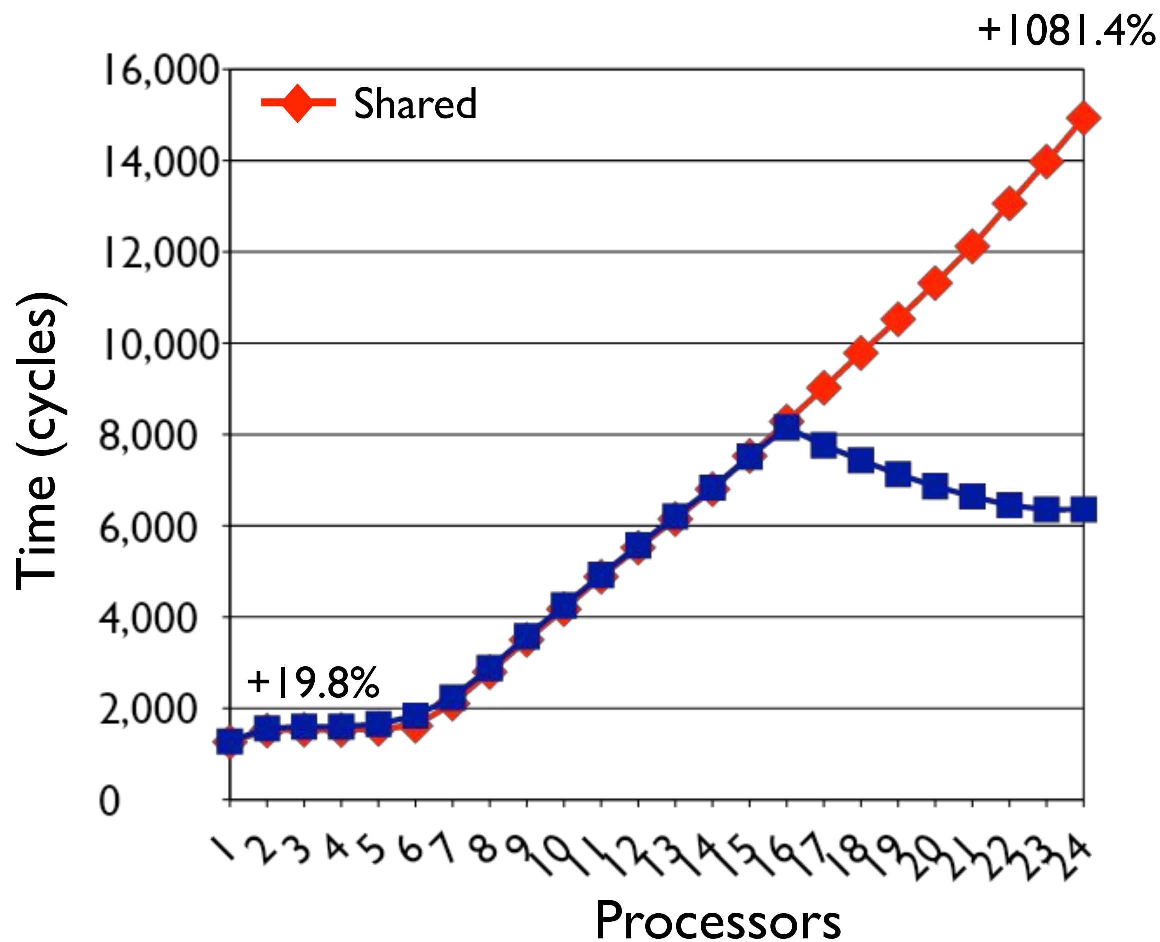

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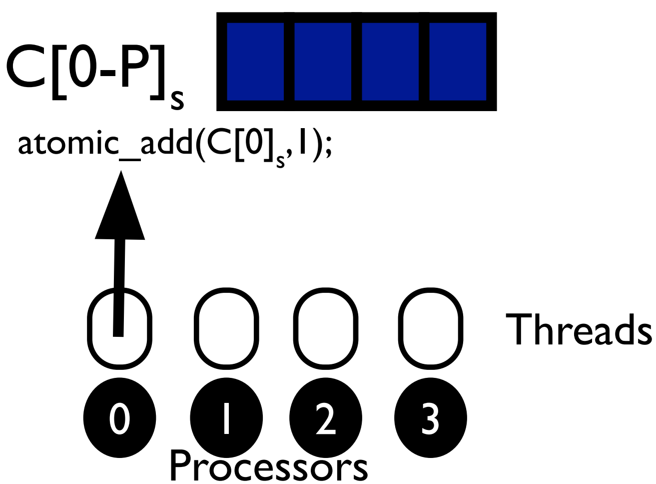

So what's the problem?

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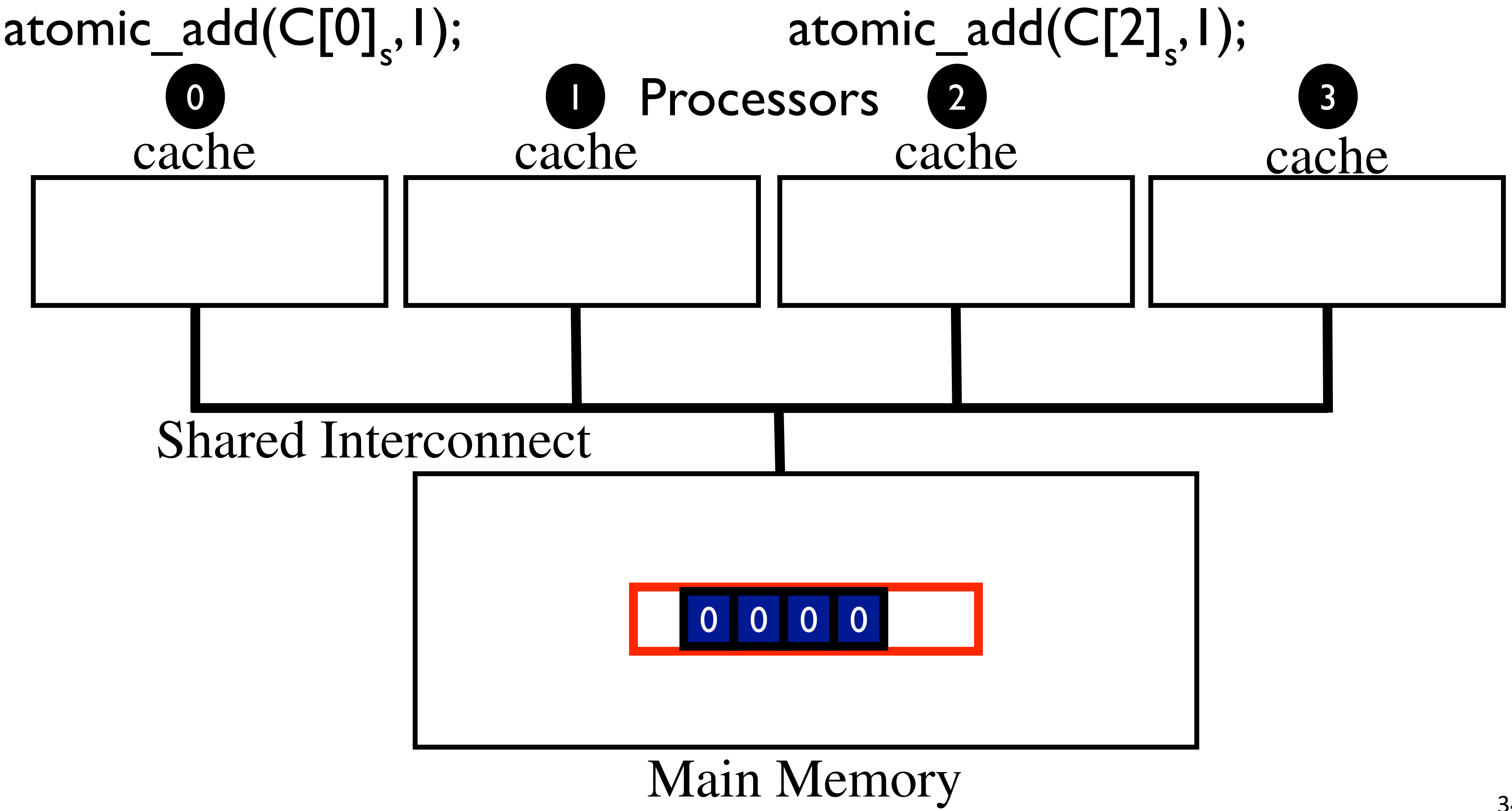

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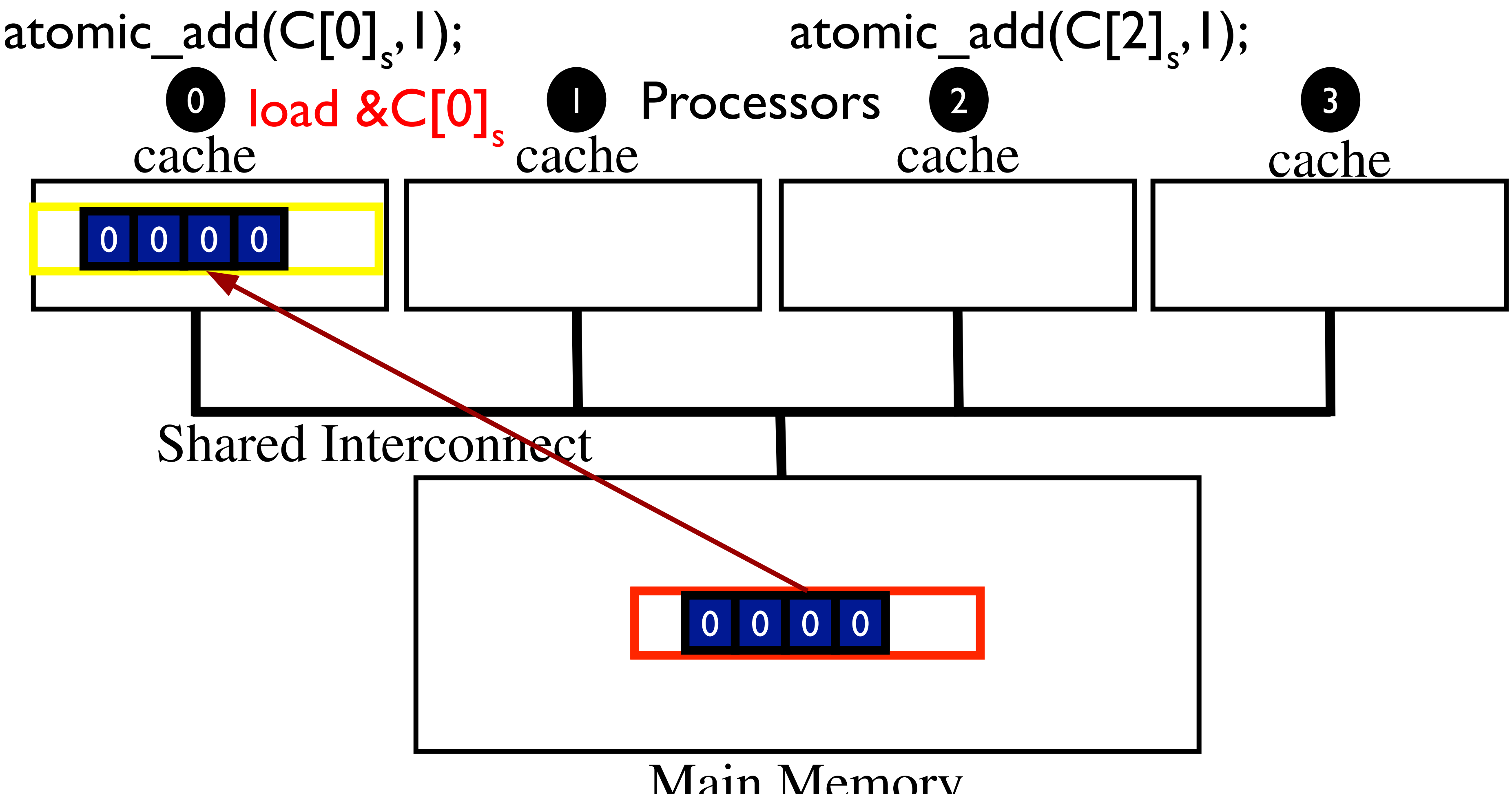

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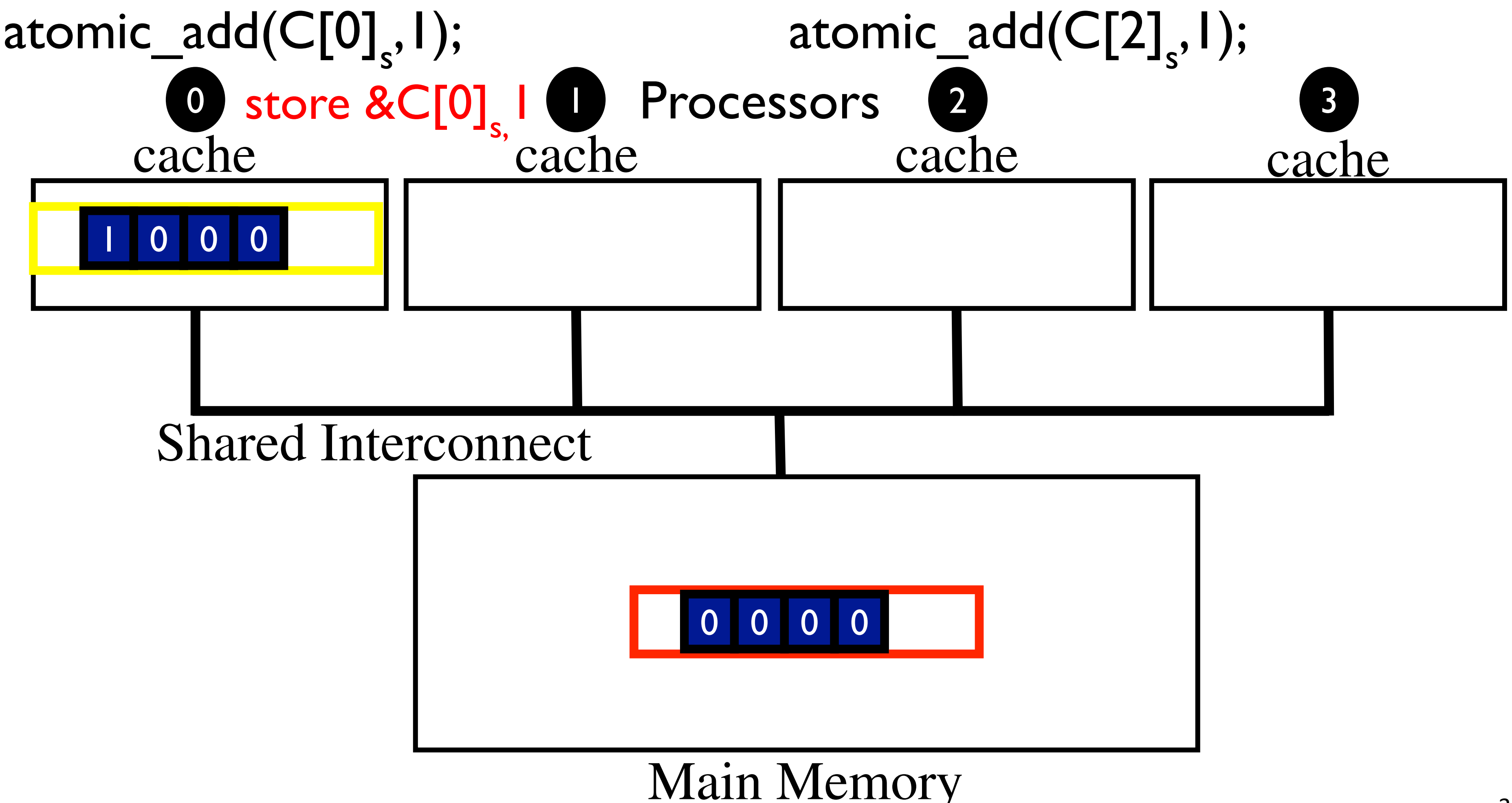

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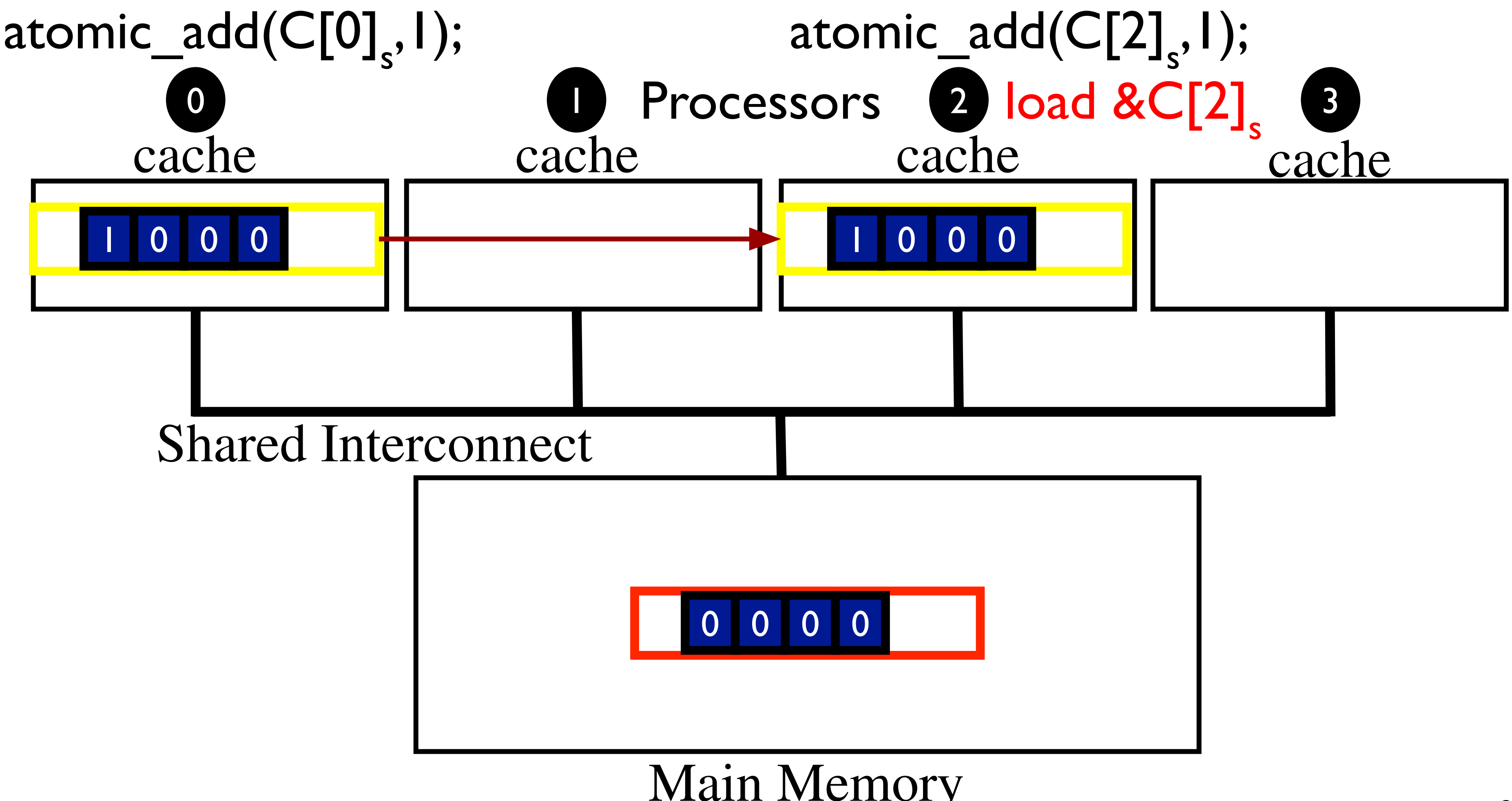

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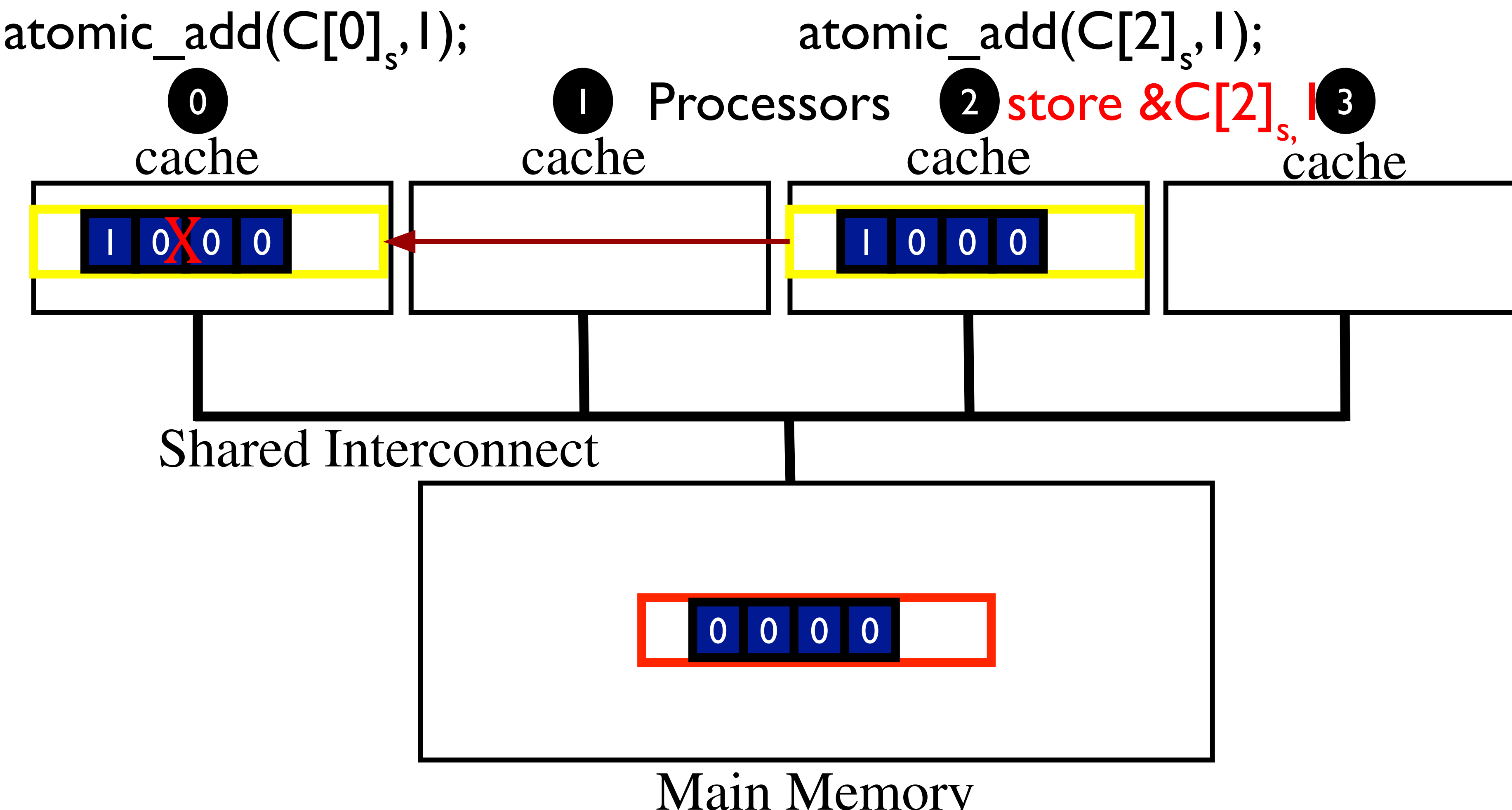

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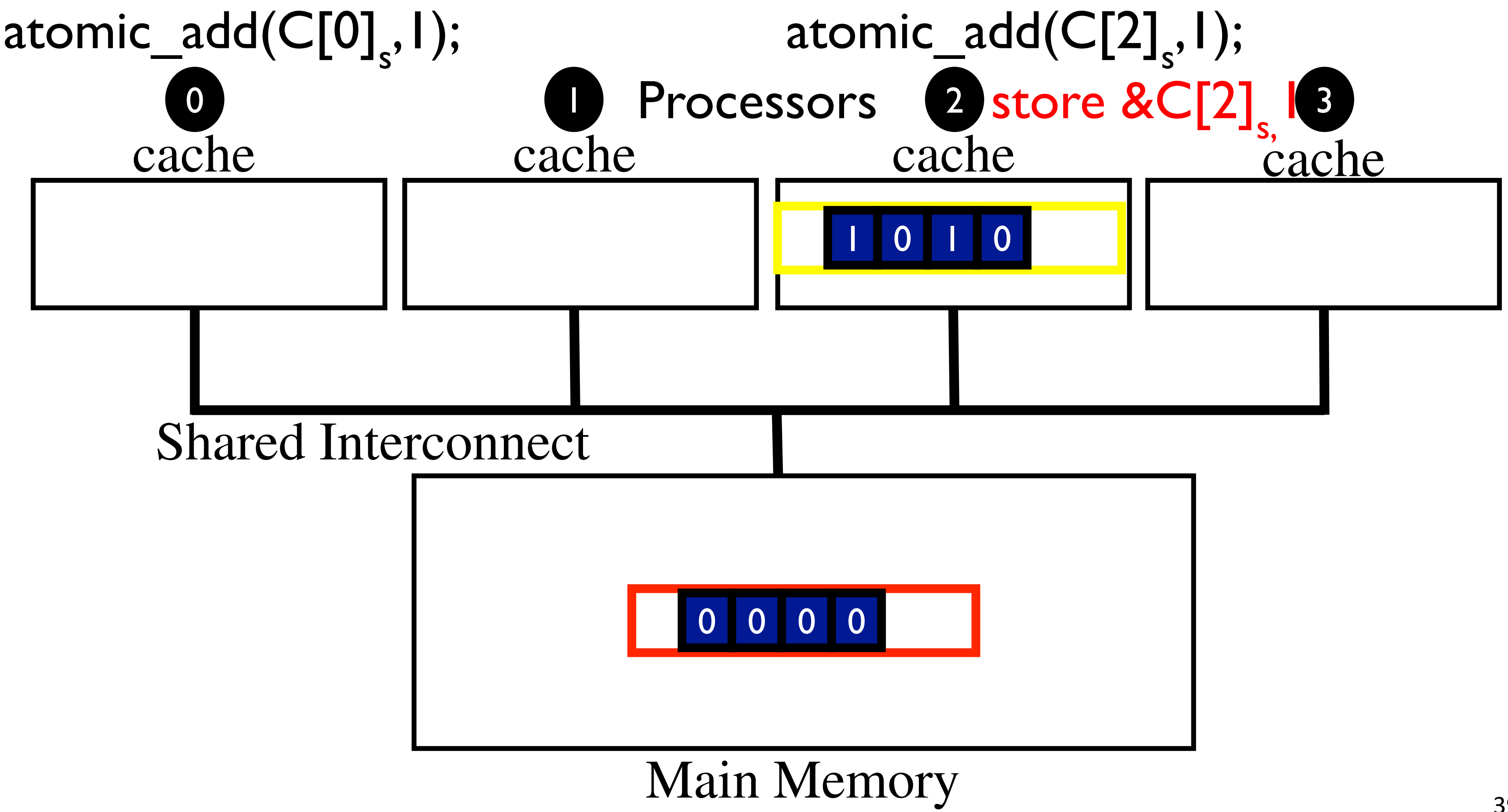
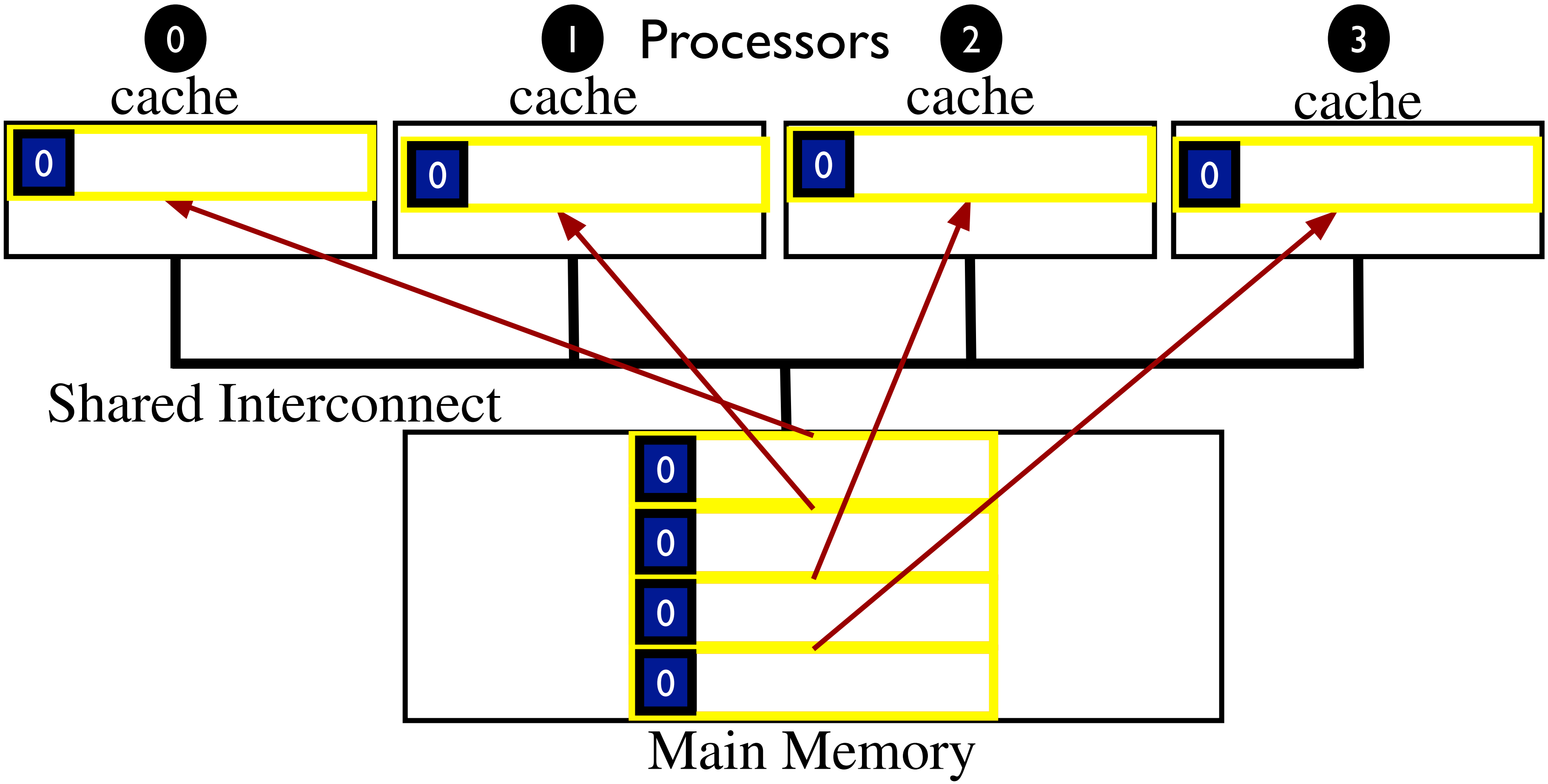


What if we pad to cache line



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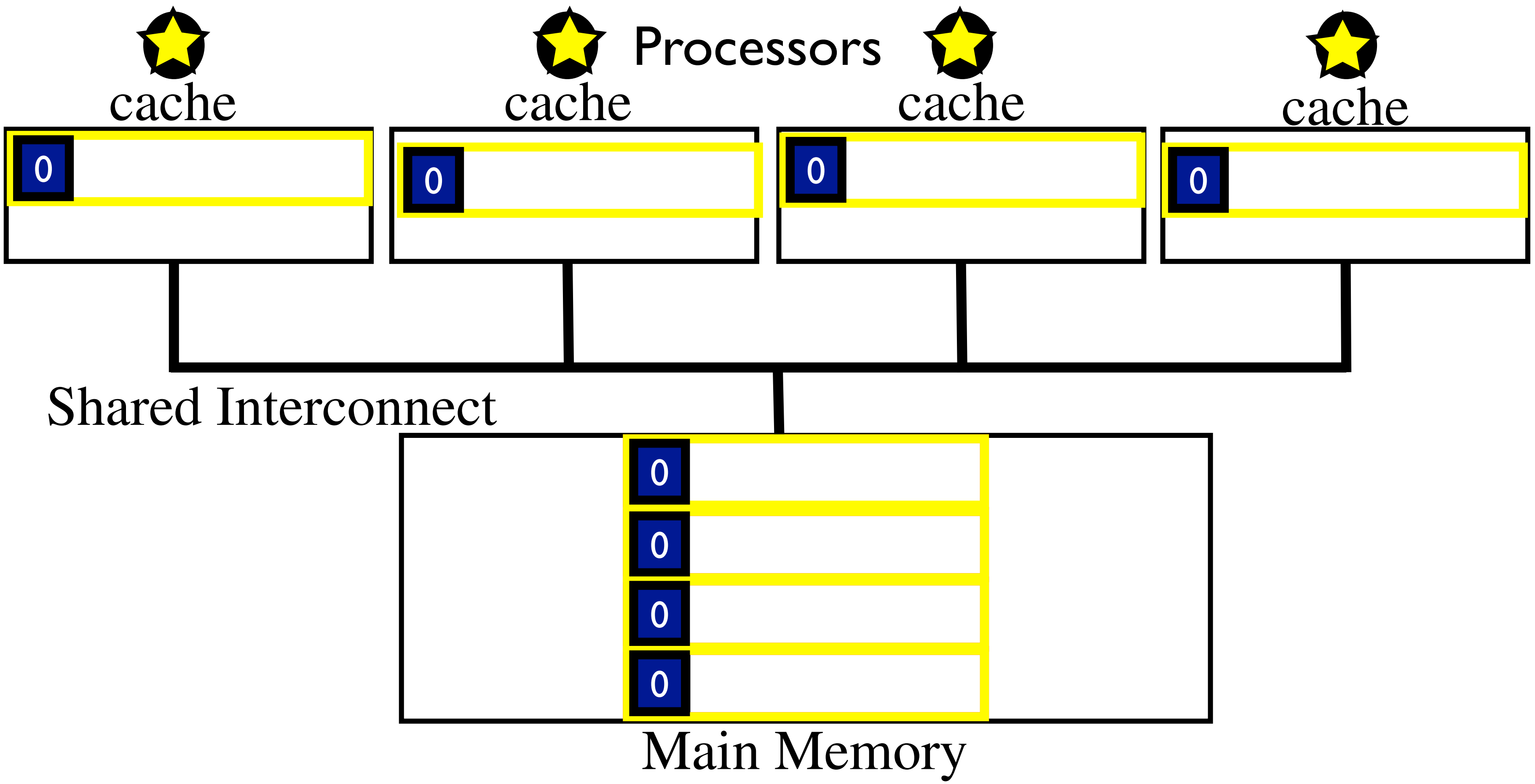
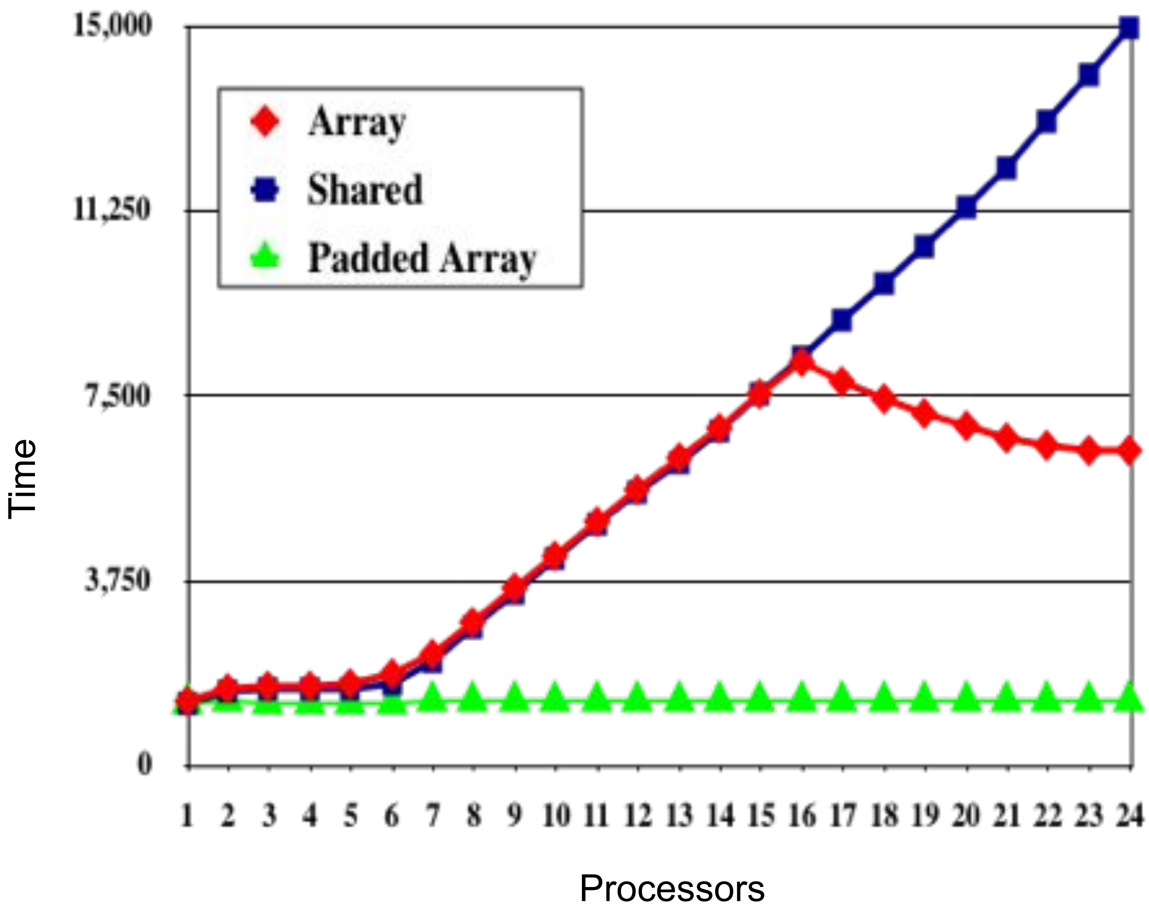


Result, the green line



False Sharing

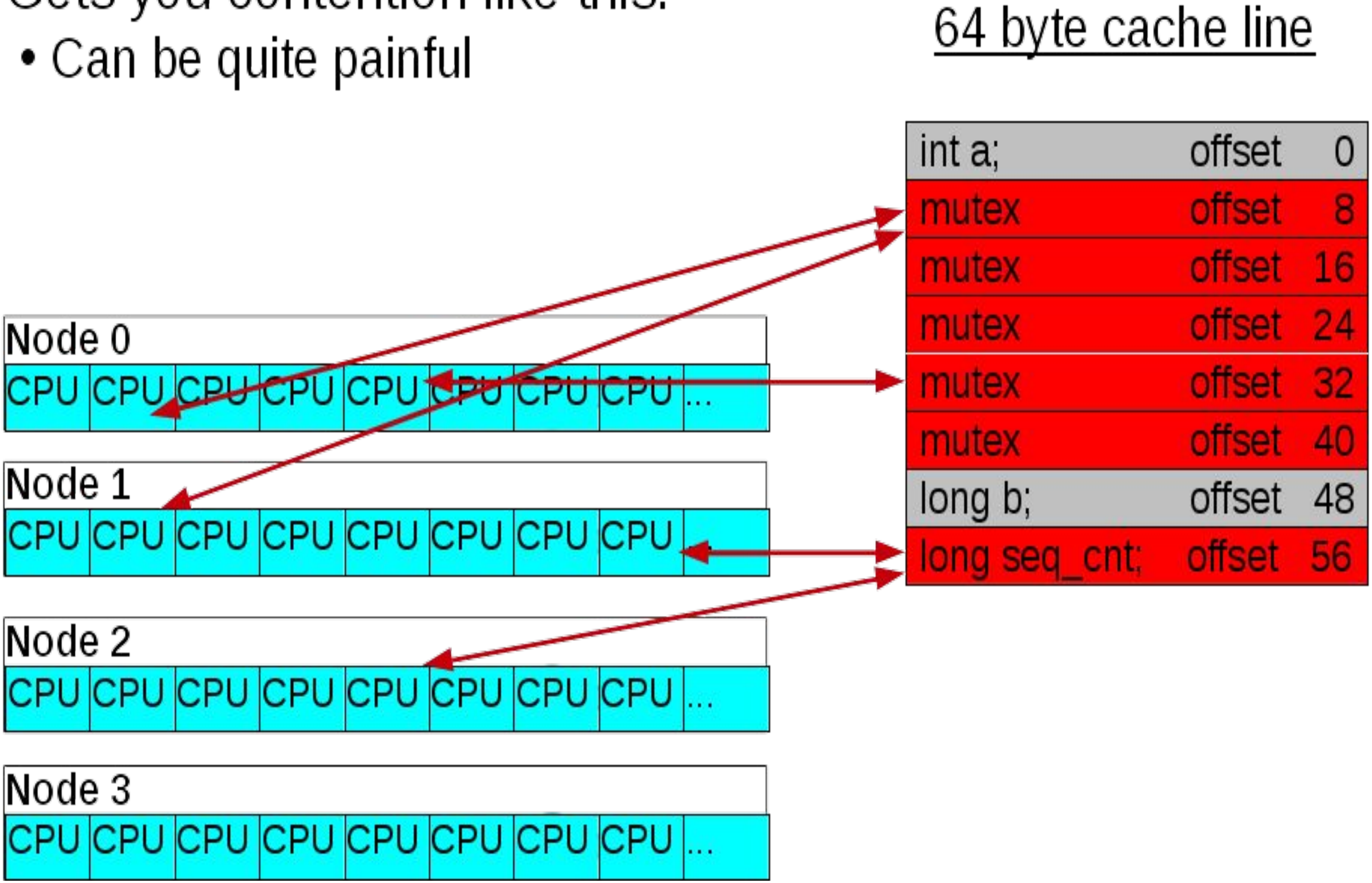
- Different threads sharing common data struct
- Different processes sharing common shared memory.

Ex: Two hotly contended data items sharing a 64-byte cacheline.

int a;	0	
pthread_mutex_t mutex1;	8	
	16	
	24	*Hot pthread mutex*
	32	
	40	
long b;	48	
long sequence_cnt;	56	*Hot variable*

Gets you contention like this:

- Can be quite painful



Split it up into two lines, with hot items in their own lines:

Hot mutex

Hot sequence counter

Cacheline 1	pthread_mutex_t mutex1;	0
		8
		16
		24
		32
	long a;	40
	long b;	48
	long cold_var;	56
Cacheline 2	long sequence_cnt;	0
With padding or cold variables	long pad1;	8
	long pad2;	16
	long pad3;	24
	long pad4;	32
	long pad5;	40
	long pad6;	48
	long pad7;	56

Future Red Hat update to perf: “c2c data sharing” tool

```
=============================================================================================
Cache                                                                                      CPU
 #   Refs    Stores    Data Address        Pid    Tid    Inst Address          Symbol     Object  Participants
=============================================================================================
0   118789  273709    0x602380            37878
     17734  136078    0x602380            37878  37878  0x401520              read_wrt_thread  a.out  0{0}
     13452  137631    0x602388            37878  37883  0x4015a0              read_wrt_thread  a.out  0{1}
     15134       0    0x6023a8            37878  37882  0x4011d7              reader_thread    a.out  1{5}
     14684       0    0x6023b0            37878  37880  0x4011d7              reader_thread    a.out  1{6}
     13864       0    0x6023b8            37878  37881  0x4011d7              reader_thread    a.out  1{7}

1       31      69    0xffff88023960df40  37878
        13      69    0xffff88023960df70  37878  ***    0xffffffff8109f8e5  update_cfs_rq_blocked_load      vmlinux  0{0,1,2};1{14,16}
        17       0    0xffff88023960df60  37878  ***    0xffffffff8109fc2e  __update_entity_load_avg_contrib  vmlinux  0{0,1,2};1{14,16}
         1       0    0xffff88023960df78  37878  37882  0xffffffff8109fc4e  __update_entity_load_avg_contrib  vmlinux  0{2}
```

<u>This shows who is contributing to the false sharing:</u>

- The hottest contended cachelines
- The process names, data addr, ip, pids, tids
- The node and CPU numbers they ran on,
- And how the cacheline is being accessed (read or write)
- Disassemble the binary to find the ip, and track back to the sources.

Techniques we use today

- Atomic operations, e.g., increment/decrement
- Per-core/per-socket locks/replication - data on different cache lines
- multiple reader and single writer locks
- Fine grained locks embedded in data/objects: cache-miss gets you the data and lock
  - Different data structures on allocated on different cache lines
- Scalable locks:
  - Ticketed spinlocks
  - MCS locks
    - enqueue blocked threads on list
    - each spins on a local variable
    - communication one-to-one
- Read Copy Update (RCU) synchronization
- lockless code implementation(if possible)
  - Example: Linux Kernel memory allocator

Ticketed spinlocks

- Problem:
  - starvation caused by locks allocated in preferred cache/memory.

    CPUs close to the memory the lock resides in will always get spinlock first.
- Solution: round-robin lock acquisition based on CPU ID.
  - spinlock():
    - if bitmask is clear

      acquire spinlock

      set CPUID bit in per-lock bitmask and spin
  - spinunlock()
    - clear CPUID bit in per-lock bitmask

      if bitmask is not clear

      grant lock to next CPU set in bitmask.

      else release spinlock

*Simple and stops starvation but is not fair.

MCS/queued spinlocks

- Problem:
  - ticketed spinlocks are unfair, round-robin rather than first-come-first-serve.
- Solution: build FIFO queue of CPUs trying to acquire lock.
  - spinlock():
    - if queue-is-empty

      acquire spinlock

      else

      insert CPU in per-lock queue and just spin
  - spinunlock()
    - if !queue-is-empty

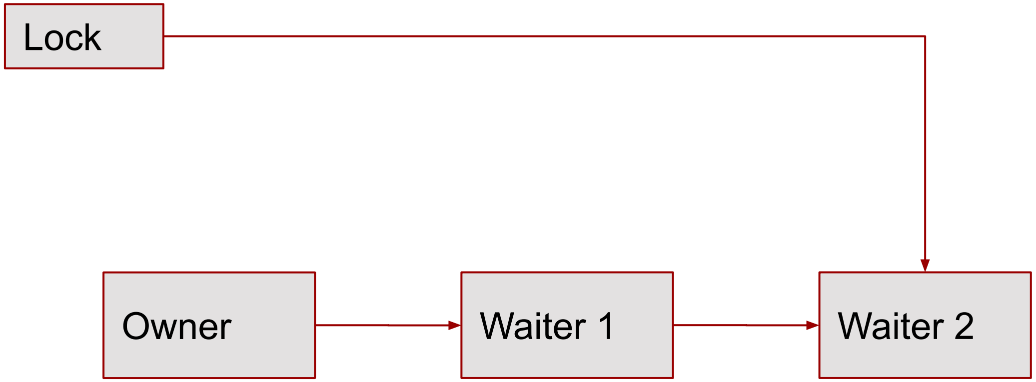
      pass spinlock to first CPU in queue

      else

      release spinlock

*Complex but stops starvation with fairness.

MCS spinlock



Key idea RCU

- Let multiple readers access data concurrently with one writer
- Writer copies data, modifies, atomically inserts modification
- Readers see consistent version,
  - either before writer or after writer
- Data not deleted until guaranteed all readers done

Avoiding Locks: Read-Copy-Update (1)

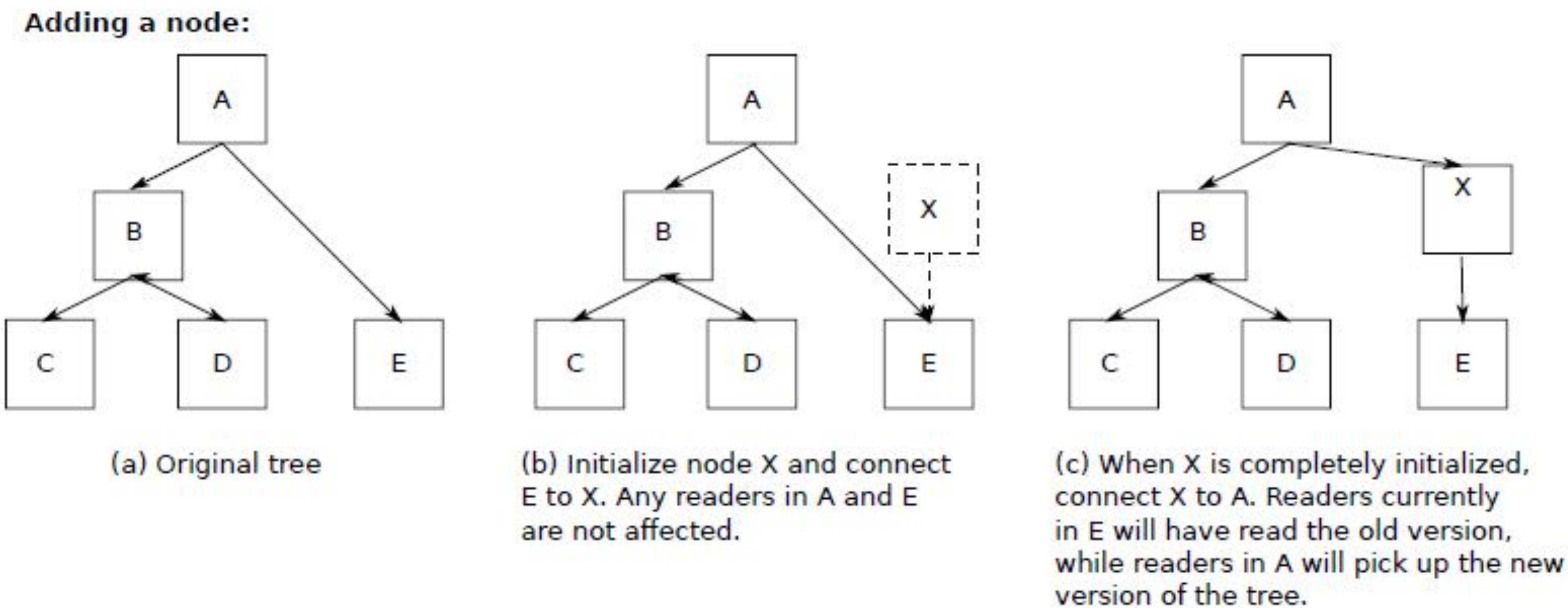
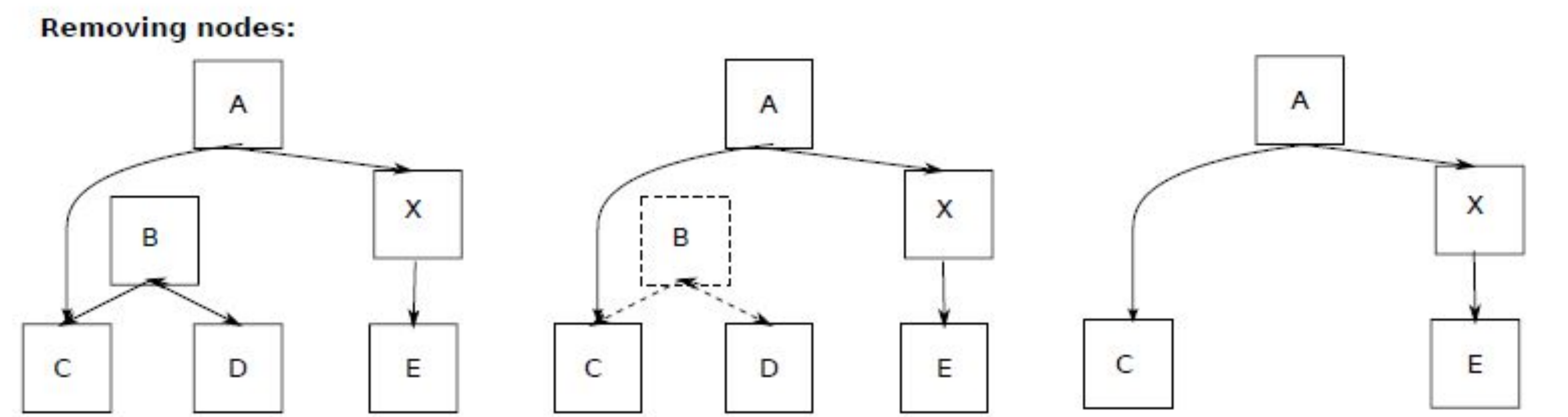


Figure 2-38. Read-Copy-Update: inserting a node in the tree and then removing a branch—all without locks

Avoiding Locks: Read-Copy-Update (2)



(d) Decouple B from A. Note that there may still be readers in B. All readers in B will see the old version of the tree, while all readers currently in A will see the new version.

(e) Wait until we are sure that all readers have left B and C. These nodes cannot be accessed by anymore.

(f) Now we can safely remove B and D

Figure 2-38. Read-Copy-Update: inserting a node in the tree and then removing a branch—all without locks

A bit of history

- Introduced concurrently in
  - Sequent's large MP ptx system
  - K42/Tornado systems Toronto/IBM
- We presented Ottawa Linux Symposium 2001
- Immediately started getting wide use in Linux
- Forced Paul to make it his PhD
- Subject of $3B SCO lawsuit in 2003
- oops
- Paul finally could release his PhD in 2004

Using RCU pervasively

- You already saw deadlock (topic of wed lecture) in dining philosophers
- We avoid deadlock in OS by acquiring locks in order
- Most ordering problems turn out to be existence locks, e.g., process doesn't go away while you are handling a page fault
- K42/Tornado had no global locks, no locking hierarchy, ... used RCU for everything...