



Thread-Level Parallelism

15-213/14-513/15-513: Introduction to Computer Systems
25th Lecture, December 5, 2023

Logistics

- **Proxy Final due Thursday 12/7 by 11:59pm, one grace day**
- **SFS lab (optional, highest of proxy final and sfslab score) due Thursday 12/7 by 11:59pm, one grace day**
- **Final Exam Tuesday 12/12 at 8:30-11:30am ET**
 - Rooms to be announced (see Piazza)
 - Exam is on Gradescope. Bring a laptop to do the exam.
 - You can bring two 8.5"x11" / A4 cheat sheets, written or printed
 - Review session this weekend to be announced (see Piazza)
- **Next lecture Thursday 12/7: Frontiers of Computing**
 - Not recorded, not on the final
 - No separate 14513 lecture
 - 15513 and 14513 students are welcome to attend, in GHC 4401

Today

- **Parallel Computing Hardware** CSAPP 12.6
- **Memory Consistency** CSAPP 12.6
- **Thread-Level Parallelism** CSAPP 12.6

Today

■ Parallel Computing Hardware

- Multicore
 - Multiple separate processors on single chip
- Hyperthreading
 - Efficient execution of multiple threads on single core

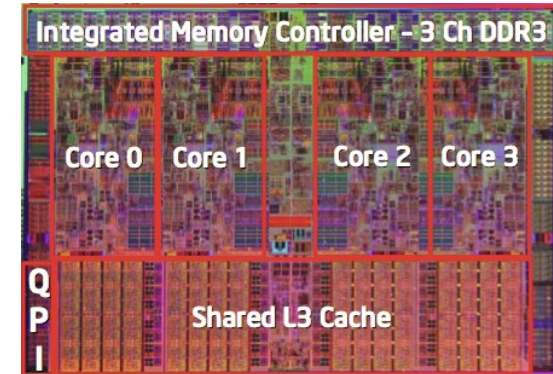
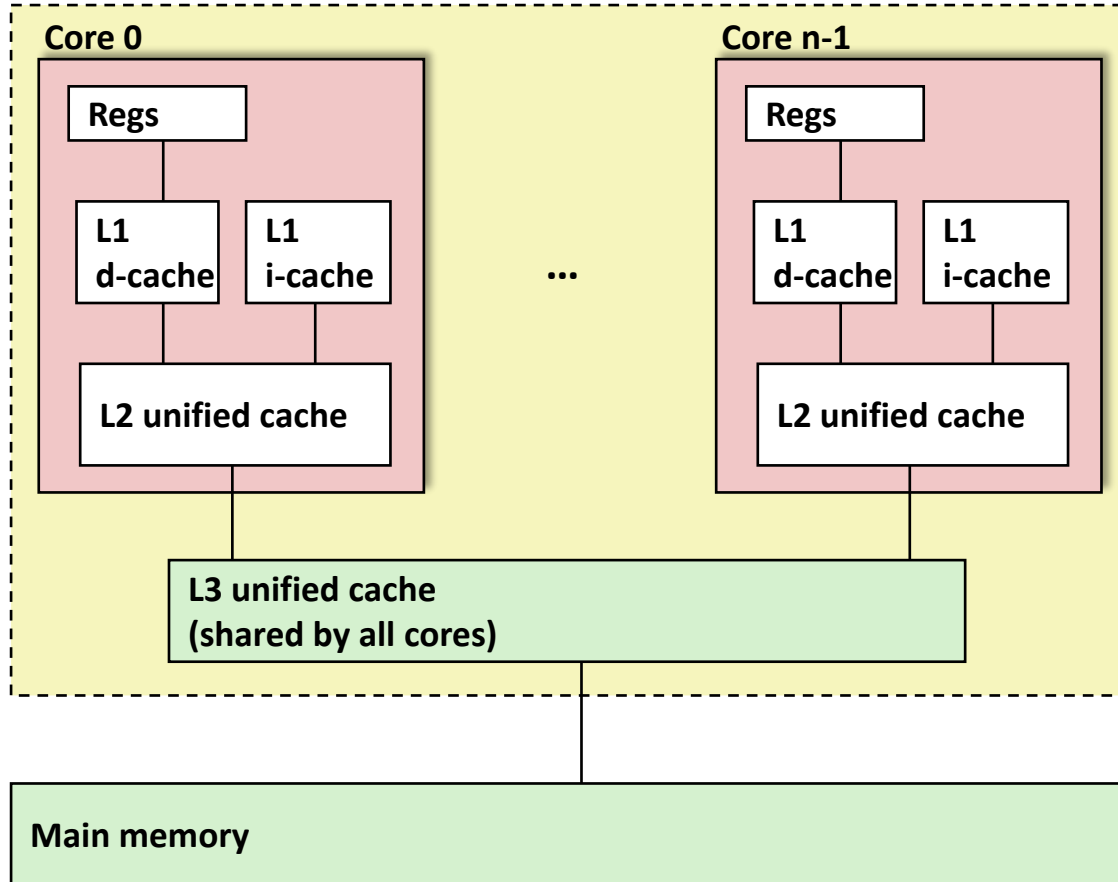
■ Memory Consistency

- What happens when multiple threads are reading & writing shared state

■ Thread-Level Parallelism

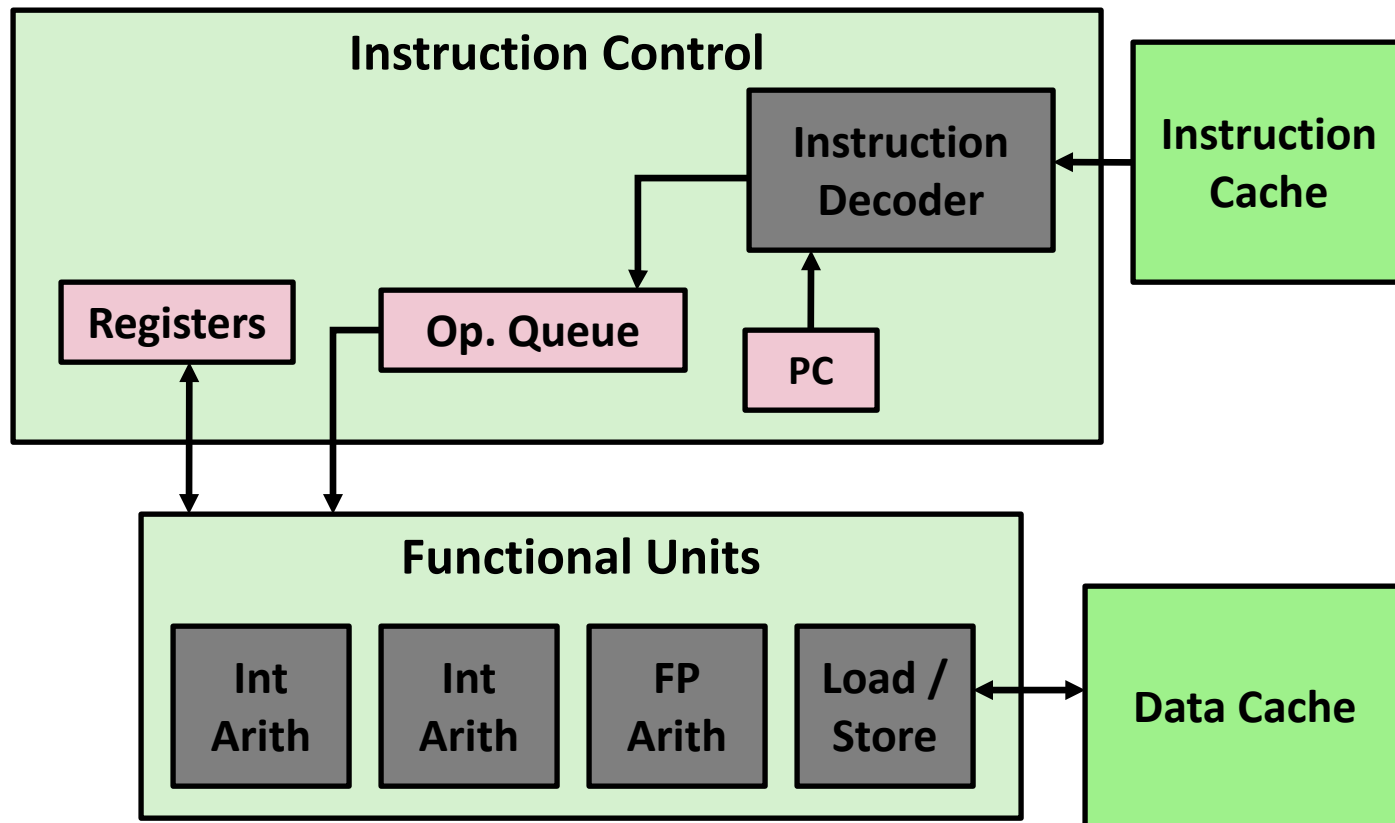
- Splitting program into independent tasks
 - Example: Parallel summation
 - Examine some performance artifacts
- Divide-and conquer parallelism
 - Example: Parallel quicksort

Typical Multicore Processor



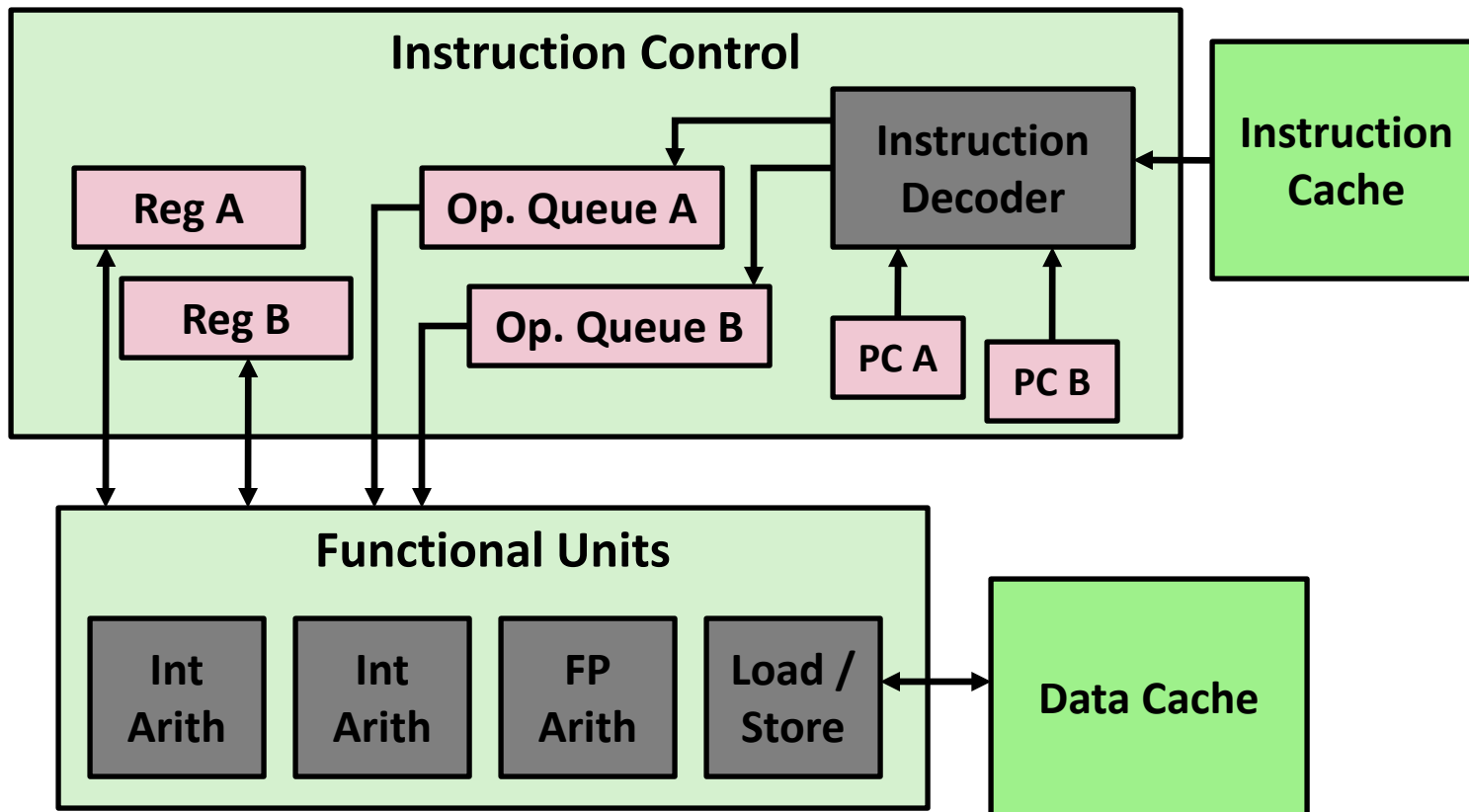
- Multiple processors operating with coherent view of memory

Out-of-Order Processor Structure



- Instruction control dynamically converts program into stream of operations
- Operations mapped onto functional units to execute in parallel

Hyperthreading Implementation



- Replicate instruction control to process K instruction streams
- K copies of all registers
- Share functional units

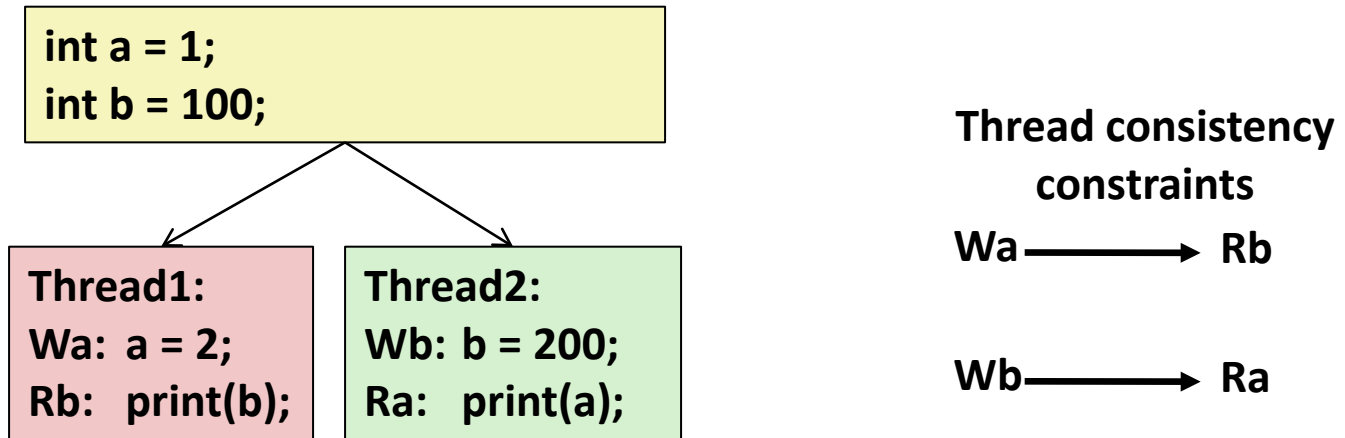
Benchmark Machine

- **Get data about machine from `/proc/cpuinfo`**
- **Shark Machines**
 - Intel Xeon E5520 @ 2.27 GHz
 - Nehalem, ca. 2010
 - 8 Cores
 - Each can do 2x hyperthreading

Exploiting parallel execution

- **So far, we've used threads to deal with I/O delays**
 - e.g., one thread per client to prevent one from delaying another
- **Multi-core CPUs offer another opportunity**
 - Spread work over threads executing in parallel on N cores
 - Happens automatically, if many independent tasks
 - e.g., running many applications or serving many clients
 - Can also write code to make one big task go faster
 - by organizing it as multiple parallel sub-tasks
- **Shark machines can execute 16 threads at once**
 - 8 cores, each with 2-way hyperthreading
 - Theoretical speedup of 16X
 - never achieved in our benchmarks

Memory Consistency

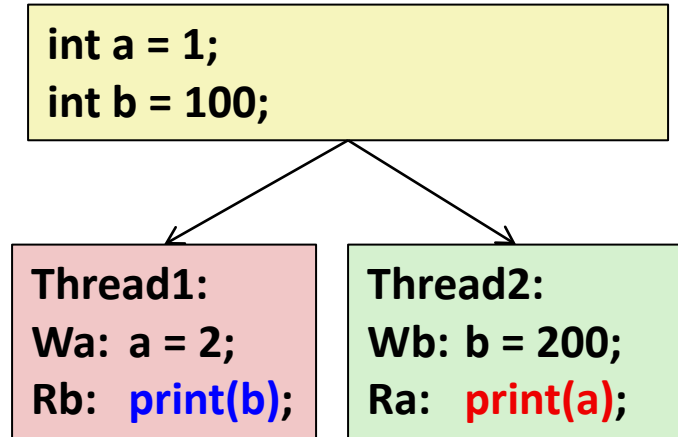
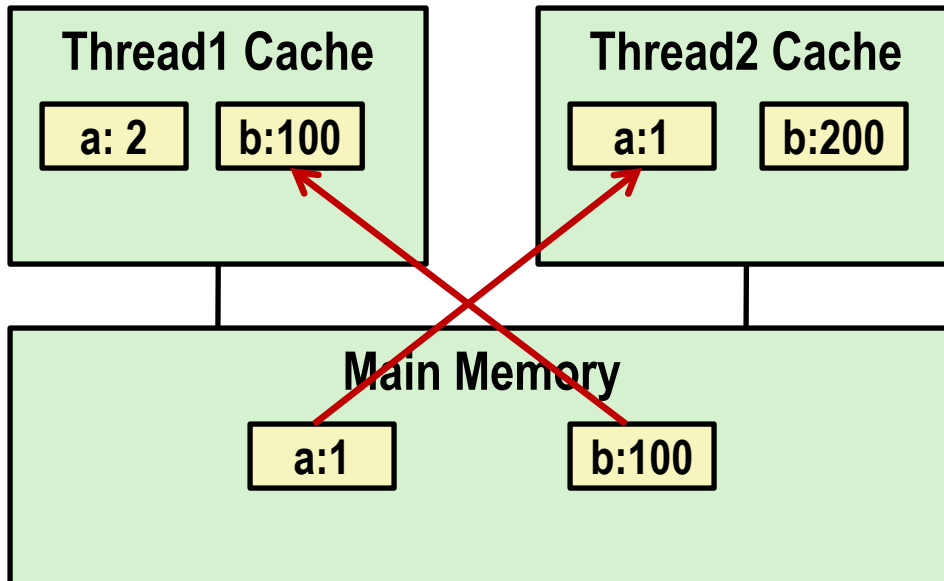


■ What are the possible values printed?

- Depends on memory consistency model
- Abstract model of how hardware handles concurrent accesses

Non-Coherent Cache Scenario

- Write-back caches, without coordination between them



`print 1`

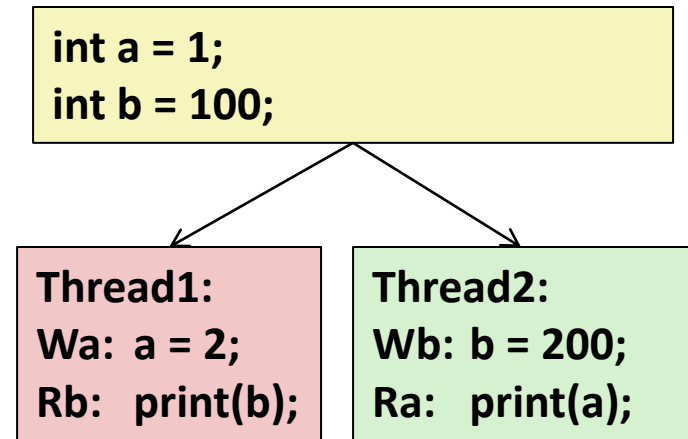
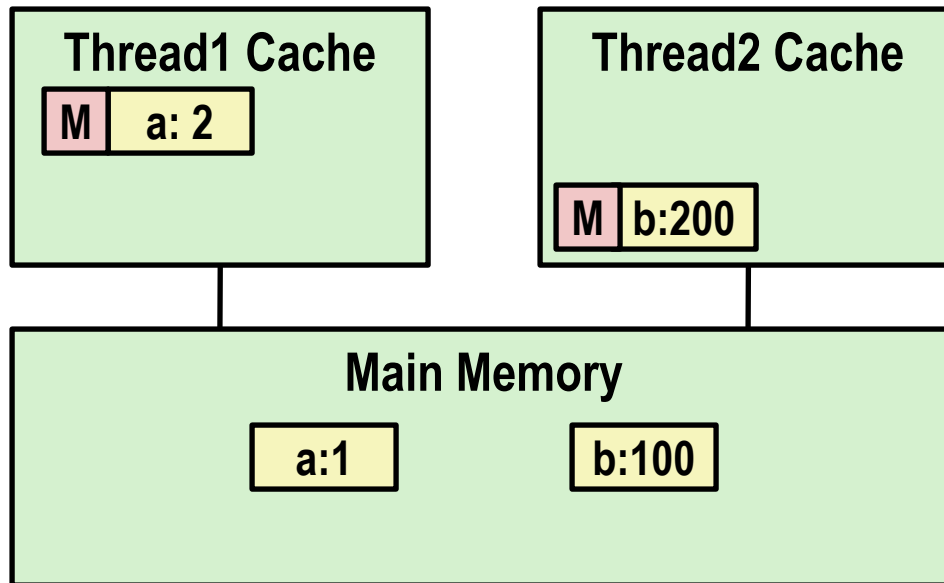
`print 100`

At later points, `a:2` and `b:200` are written back to main memory

Snoopy Caches

■ Tag each cache block with state

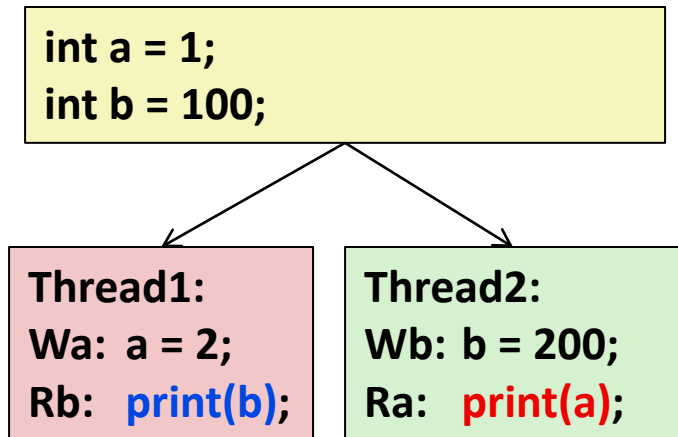
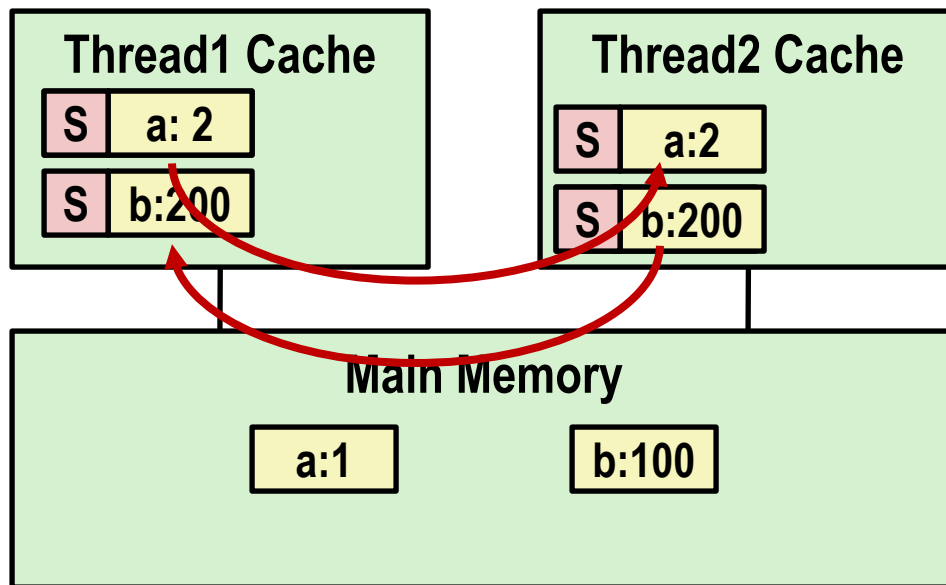
Invalid	Cannot use value
Shared	Readable copy
Modified	Writeable copy



Snoopy Caches

■ Tag each cache block with state

Invalid	Cannot use value
Shared	Readable copy
Modified	Writeable copy

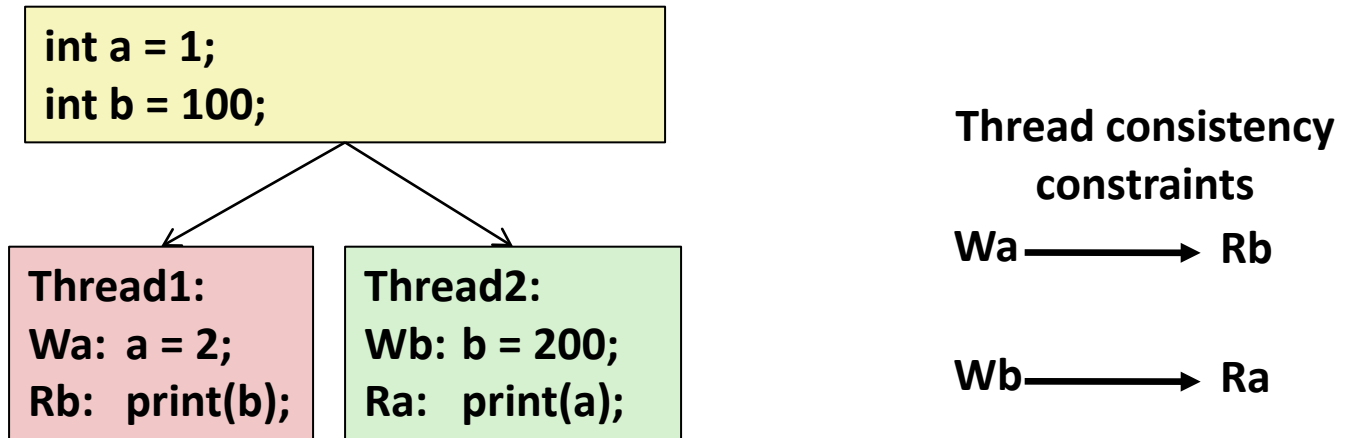


print 2

print 200

- When cache sees request for one of its M-tagged blocks
 - Supply value from cache (Note: value in memory may be stale)
 - Set tag to S

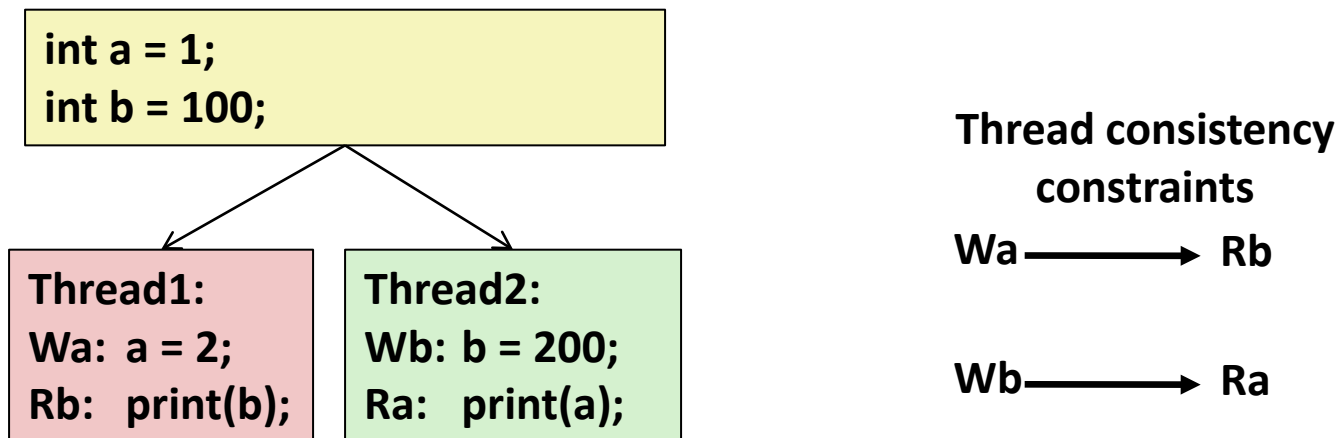
Memory Consistency



■ What are the possible values printed?

- Depends on memory consistency model
- Abstract model of how hardware handles concurrent accesses

Memory Consistency



■ What are the possible values printed?

- Depends on memory consistency model
- Abstract model of how hardware handles concurrent accesses

■ Sequential consistency

- As if only one operation at a time, in an order consistent with the order of operations within each thread
- Thus, overall effect consistent with each individual thread but otherwise allows an arbitrary interleaving

Sequential Consistency Example

```
int a = 1;
int b = 100;
```

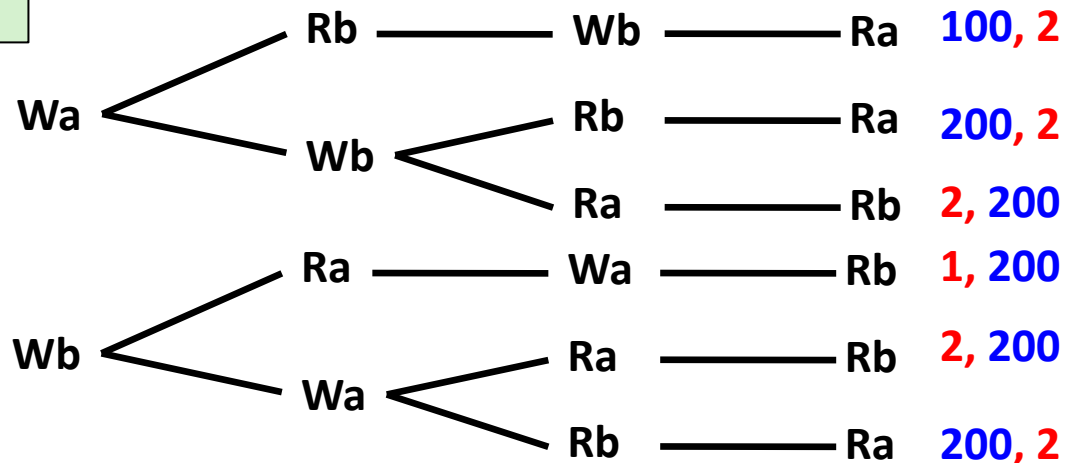
Thread1:
 Wa: a = 2;
 Rb: **print(b);**

Thread2:
 Wb: b = 200;
 Ra: **print(a);**

Thread consistency
 constraints

Wa ————— Rb

Wb ————— Ra

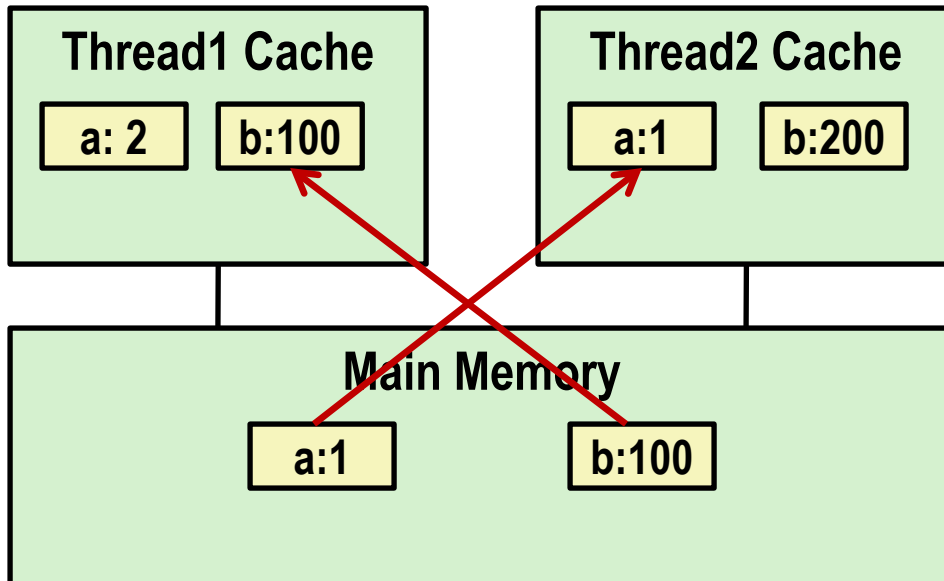


■ Impossible outputs

- **100, 1** and **1, 100**
- Would require reaching *both* Ra and Rb before *either* Wa or Wb

Non-Coherent Cache Scenario

- Write-back caches, without coordination between them



```
int a = 1;
int b = 100;
```

```
Thread1:
Wa: a = 2;
Rb: print(b);
```

```
Thread2:
Wb: b = 200;
Ra: print(a);
```

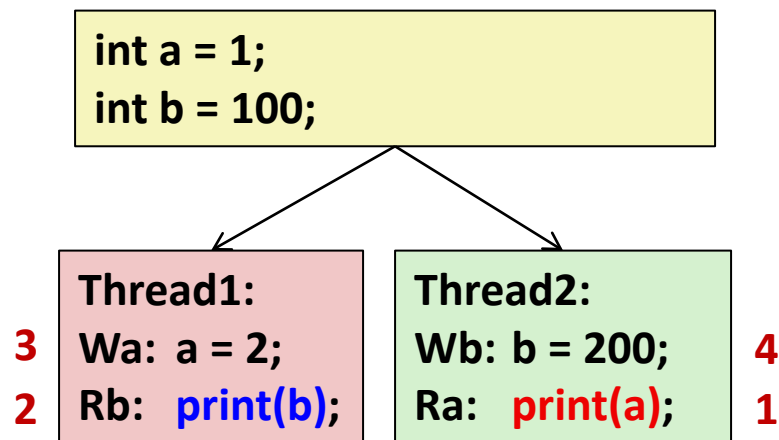
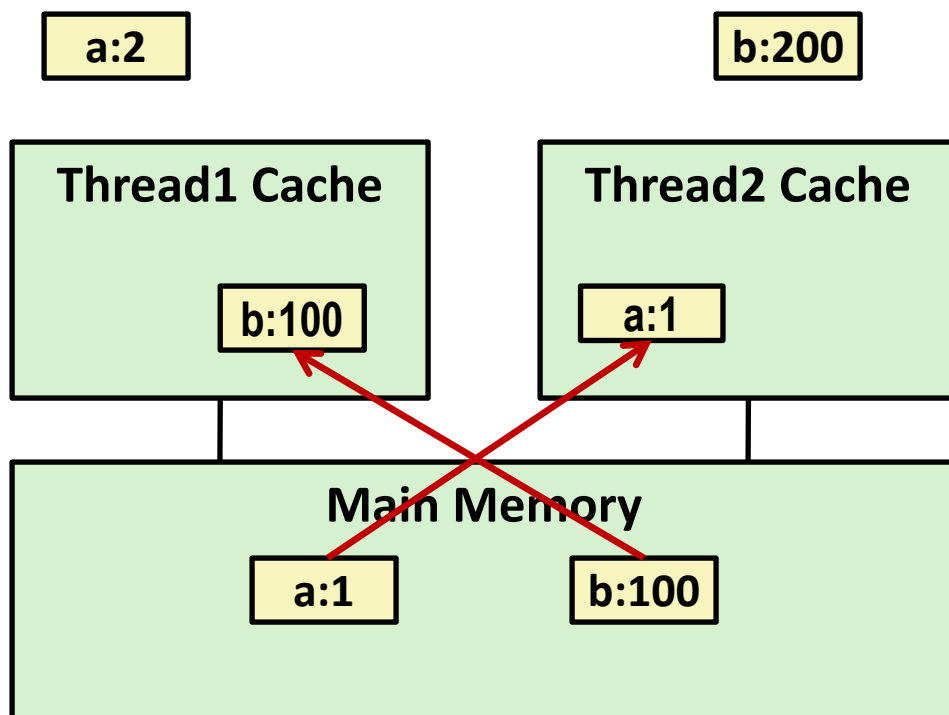
print 1

print 100

Sequentially consistent? **No!**

Non-Sequentially Consistent Scenario

- Coherent caches, but thread consistency constraints violated due to *operation reordering*

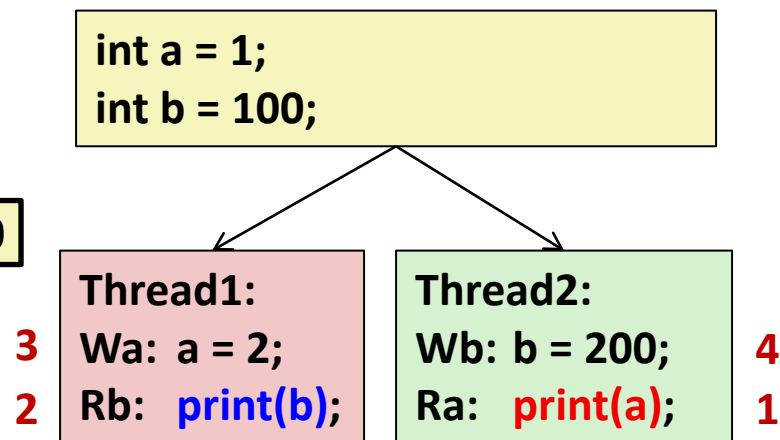
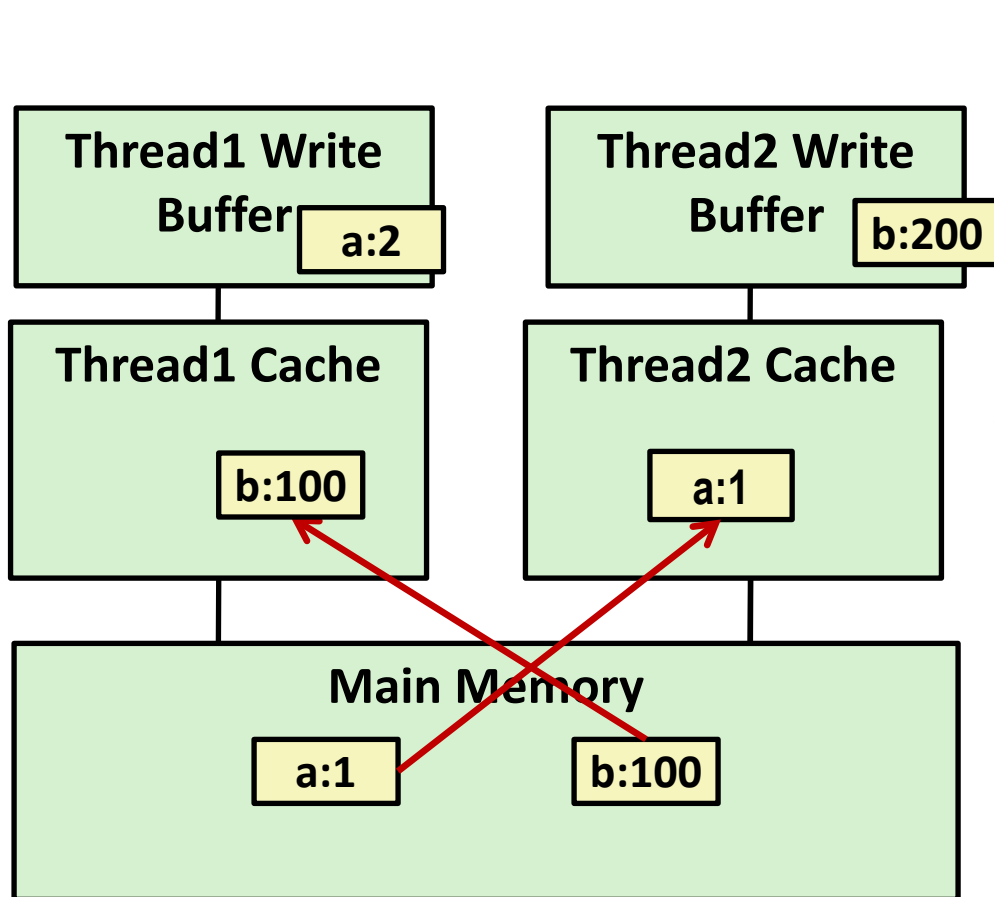


print 1

print 100

- Architecture lets reads finish before writes because single thread accesses different memory locations

Non-Sequentially Consistent Scenario



- **Why Reordered? Writes take long time. Buffer write, let read go ahead. *Instruction-level parallelism***

- **Fix: Add `SFENCE` instructions between `Wa` & `Rb` and `Wb` & `Ra`**

Memory Consistency

- **Sequentially Consistent:**

- Each thread executes in proper order, any interleaving

- **To ensure, requires**

- Proper cache/memory behavior
- Proper intra-thread ordering constraints

- **Thread ordering constraints**

- Use synchronization to ensure the program is free of data races

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- What happens when multiple threads are reading & writing shared state

■ Thread-Level Parallelism

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Summation Example

- **Sum numbers 0, ..., N-1**
 - Should add up to $(N-1)*N/2$
- **Partition into K ranges**
 - $\lfloor N/K \rfloor$ values each
 - Each of the t threads processes 1 range
 - Accumulate leftover values serially
- **Method #1: All threads update single global variable**
 - 1A: No synchronization
 - 1B: Synchronize with pthread semaphore
 - 1C: Synchronize with pthread mutex
 - “Binary” semaphore. Only values 0 & 1

Accumulating in Single Global Variable: Declarations

```
typedef unsigned long data_t;  
/* Single accumulator */  
volatile data_t global_sum;
```


Accumulating in Single Global Variable: Declarations

```
typedef unsigned long data_t;  
/* Single accumulator */  
volatile data_t global_sum;  
  
/* Mutex & semaphore for global sum */  
sem_t semaphore;  
pthread_mutex_t mutex;
```

Accumulating in Single Global Variable: Declarations

```
typedef unsigned long data_t;
/* Single accumulator */
volatile data_t global_sum;

/* Mutex & semaphore for global sum */
sem_t semaphore;
pthread_mutex_t mutex;

/* Number of elements summed by each thread */
size_t nelems_per_thread;

/* Keep track of thread IDs */
pthread_t tid[MAXTHREADS];

/* Identify each thread */
int myid[MAXTHREADS];
```

Accumulating in Single Global Variable: Operation

```
nelems_per_thread = nelems / nthreads;
```

```
/* Set global value */
```

```
global_sum = 0;
```

```
/* Create threads and wait for them to finish */
```

```
for (i = 0; i < nthreads; i++) {
```

```
    myid[i] = i;
```

```
    Pthread_create(&tid[i], NULL, thread_fun, &myid[i]);
```

```
}
```

```
for (i = 0; i < nthreads; i++)
```

```
    Pthread_join(tid[i], NULL);
```

```
result = global_sum;
```

```
/* Add leftover elements */
```

```
for (e = nthreads * nelems_per_thread; e < nelems; e++)
```

```
    result += e;
```

Thread ID

Thread routine

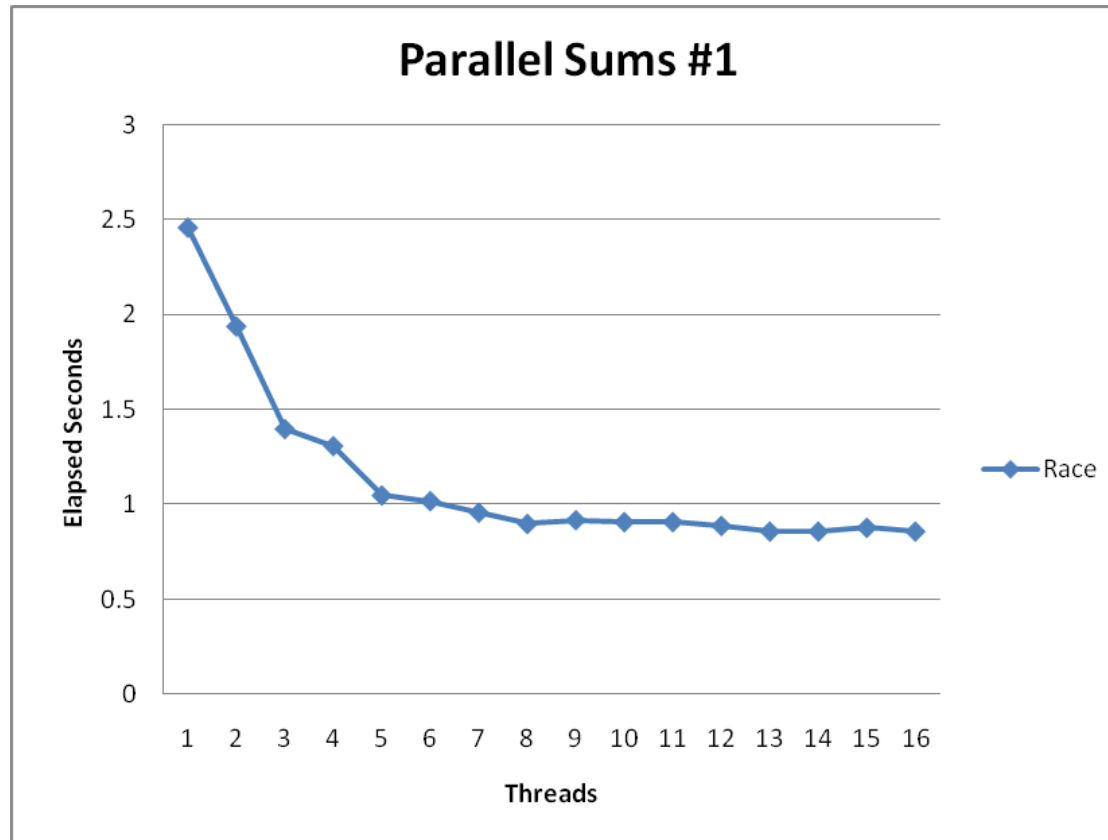
**Thread arguments
(void *p)**

Thread Function: No Synchronization

```
void *sum_race(void *vargp)
{
    int myid = *((int *)vargp);
    size_t start = myid * nelems_per_thread;
    size_t end = start + nelems_per_thread;
    size_t i;

    for (i = start; i < end; i++) {
        global_sum += i;
    }
    return NULL;
}
```

Unsynchronized Performance



- $N = 2^{30}$
- Best speedup = 2.86X
- Gets **wrong answer** when > 1 thread! Why?

Thread Function: Semaphore / Mutex

Semaphore

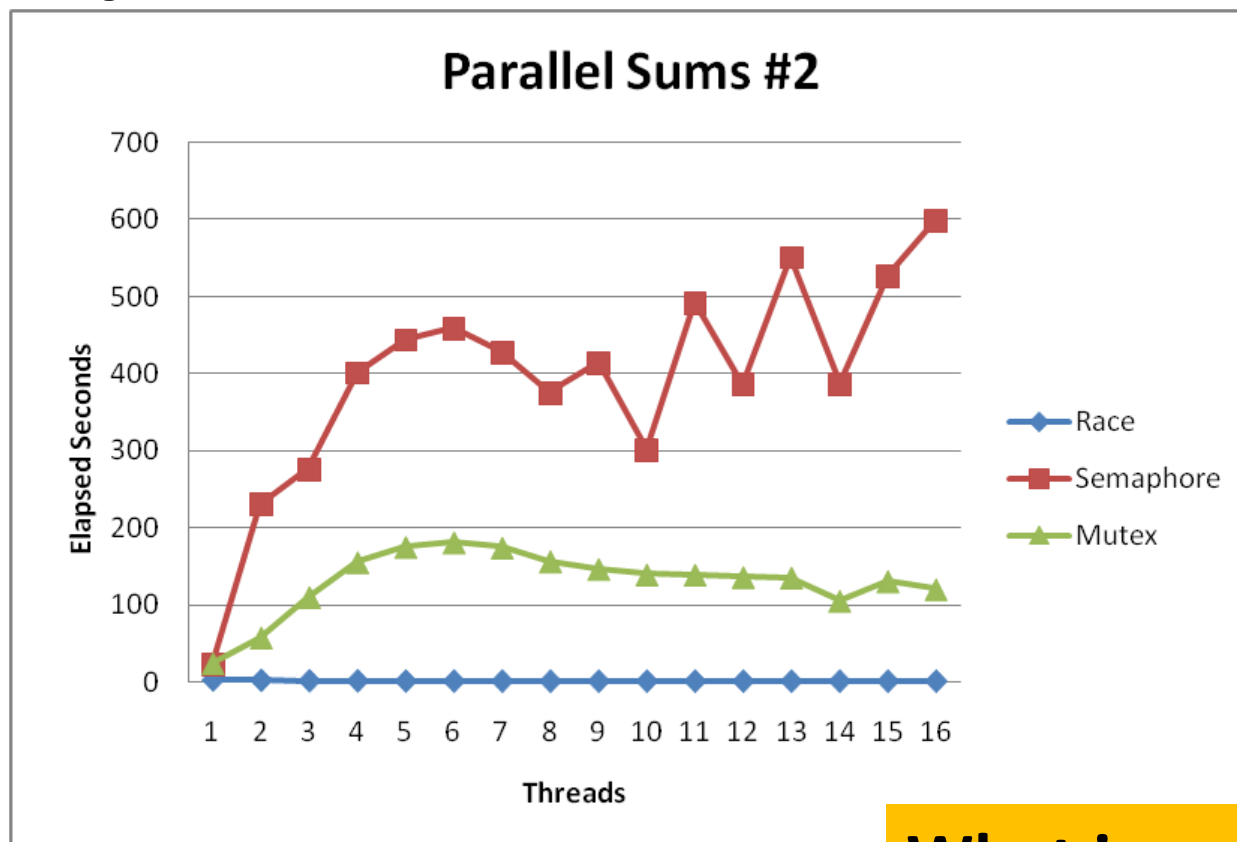
```
void *sum_sem(void *vargp)
{
    int myid = *((int *)vargp);
    size_t start = myid * nelems_per_thread;
    size_t end = start + nelems_per_thread;
    size_t i;

    for (i = start; i < end; i++) {
        sem_wait(&semaphore);
        global_sum += i;
        sem_post(&semaphore);
    }
    return NULL;
}
```

Mutex

```
pthread_mutex_lock(&mutex);
global_sum += i;
pthread_mutex_unlock(&mutex);
```

Semaphore / Mutex Performance



- **Terrible Performance**
 - 2.5 seconds → ~10 minutes
- **Mutex 3X faster than semaphore**
- **Clearly, neither is successful**

What is main reason for poor performance?

Separate Accumulation

- **Method #2: Each thread accumulates into separate variable**
 - 2A: Accumulate in contiguous array elements
 - 2B: Accumulate in spaced-apart array elements
 - 2C: Accumulate in registers

```
/* Partial sum computed by each thread */  
data_t psum[MAXTHREADS*MAXSPACING];  
  
/* Spacing between accumulators */  
size_t spacing = 1;
```


Separate Accumulation: Operation

```
nelems_per_thread = nelems / nthreads;

/* Create threads and wait for them to finish */
for (i = 0; i < nthreads; i++) {
    myid[i] = i;
    psum[i*spacing] = 0;
    Pthread_create(&tid[i], NULL, thread_fun, &myid[i]);
}
for (i = 0; i < nthreads; i++)
    Pthread_join(tid[i], NULL);

result = 0;

/* Add up the partial sums computed by each thread */
for (i = 0; i < nthreads; i++)
    result += psum[i*spacing];

/* Add leftover elements */
for (e = nthreads * nelems_per_thread; e < nelems; e++)
    result += e;
```

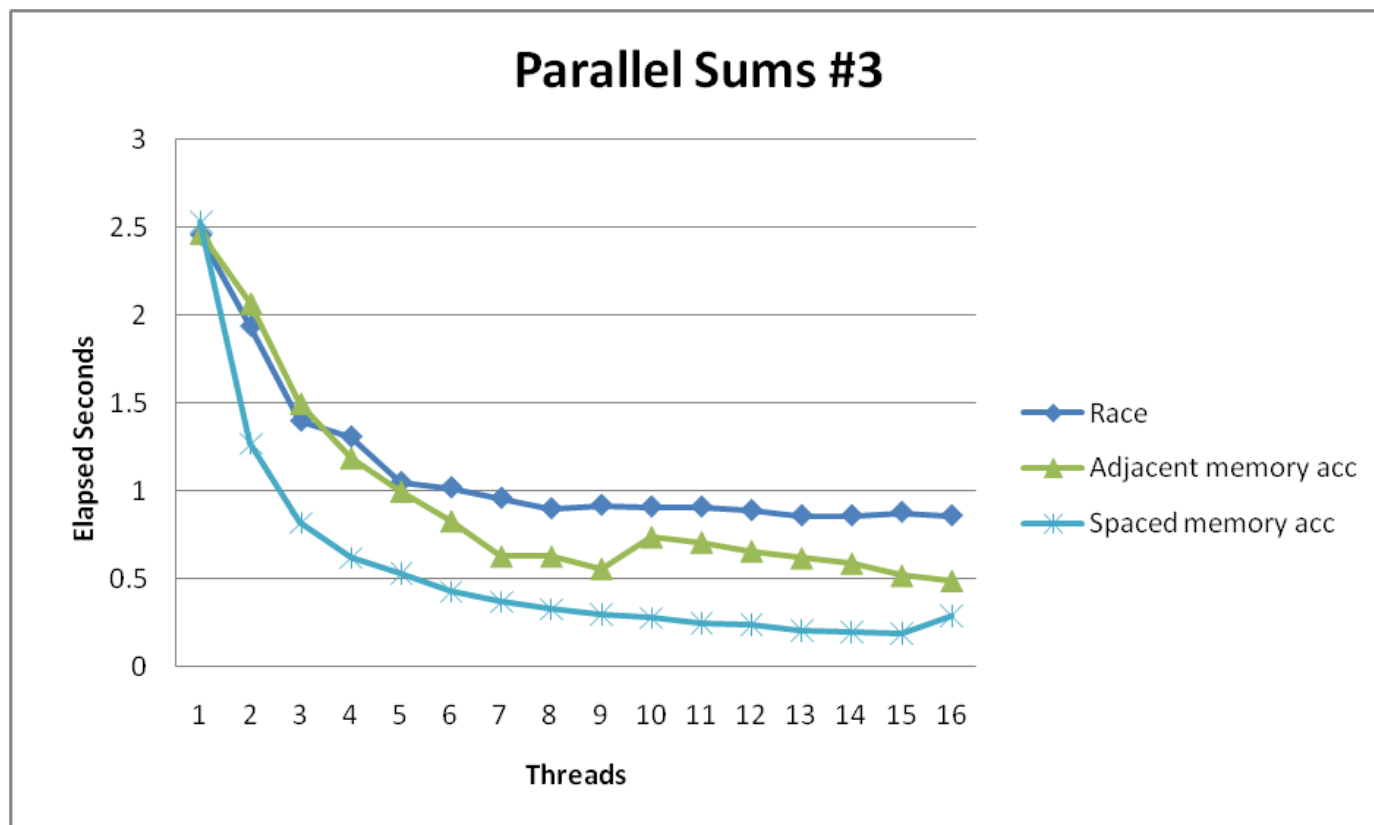
Thread Function: Memory Accumulation

Where is the mutex?

```
void *sum_global(void *vargp)
{
    int myid = *((int *)vargp);
    size_t start = myid * nelems_per_thread;
    size_t end = start + nelems_per_thread;
    size_t i;

    size_t index = myid*spacing;
    psum[index] = 0;
    for (i = start; i < end; i++) {
        psum[index] += i;
    }
    return NULL;
}
```

Memory Accumulation Performance

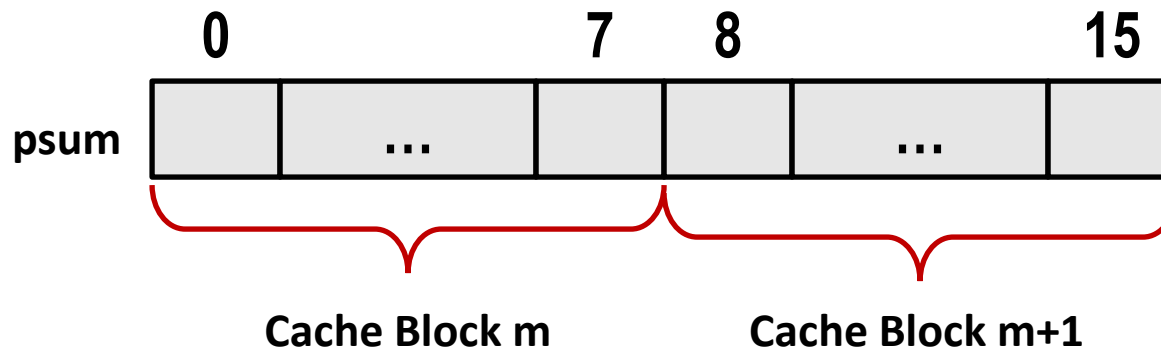


■ Clear threading advantage

- Adjacent speedup: 5 X
- Spaced-apart speedup: 13.3 X (Only observed speedup > 8)

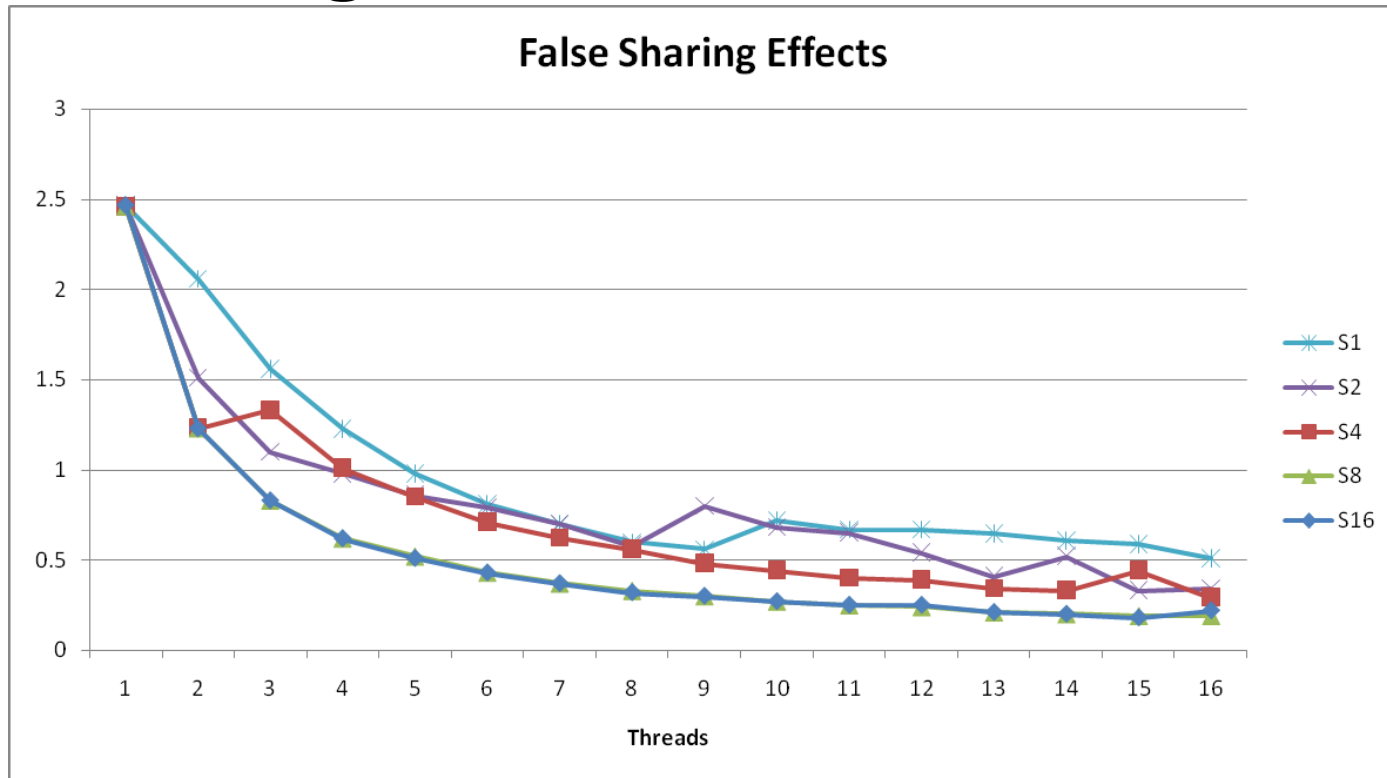
■ Why does spacing the accumulators apart matter?

False Sharing



- **Coherence maintained on cache blocks**
- **To update `psum[i]`, thread `i` must have exclusive access**
 - Threads sharing common cache block will keep fighting each other for access to block

False Sharing Performance

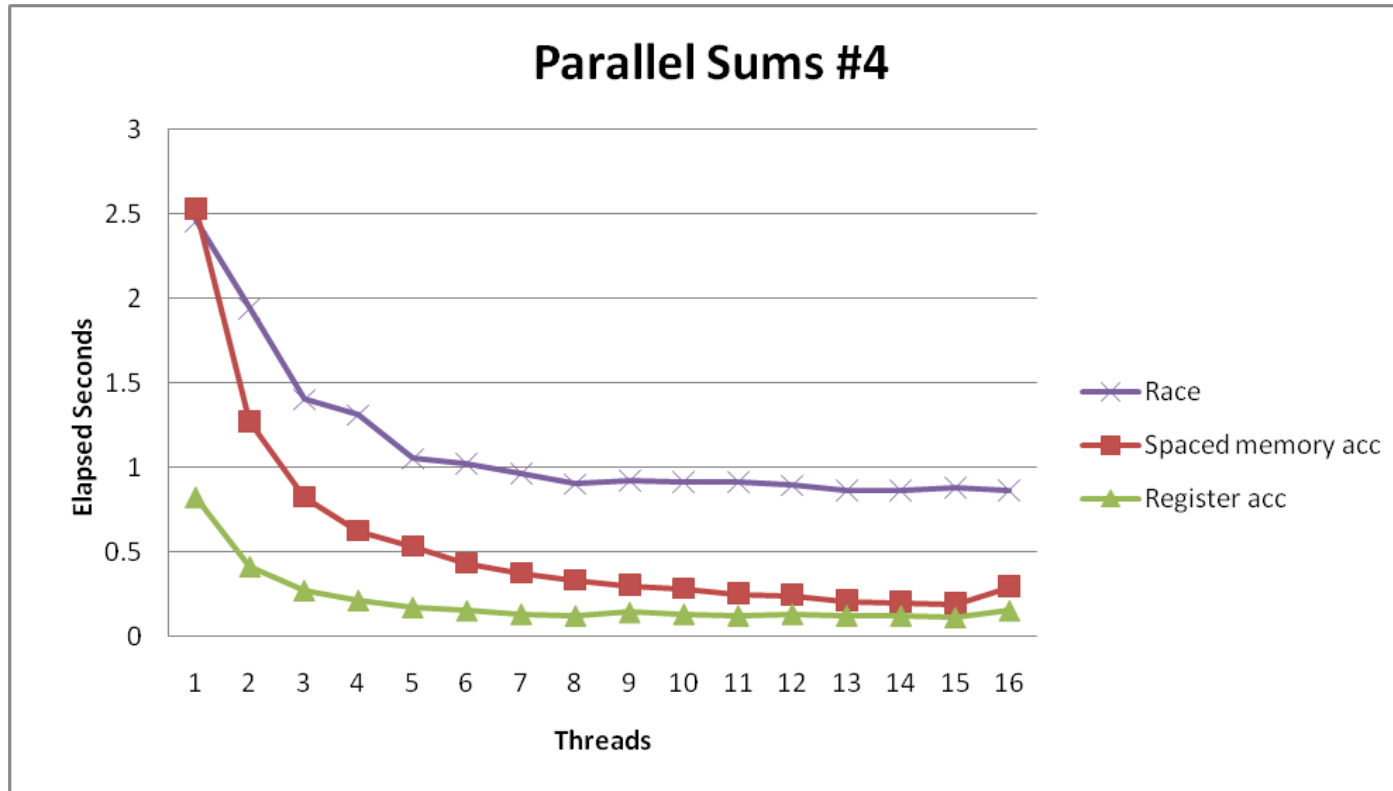


- Best spaced-apart performance 2.8 X better than best adjacent
- **Demonstrates cache block size = 64**
 - 8-byte values
 - No benefit increasing spacing beyond 8

Thread Function: Register Accumulation

```
void *sum_local(void *vargp)
{
    int myid = *((int *)vargp);
    size_t start = myid * nelems_per_thread;
    size_t end = start + nelems_per_thread;
    size_t i;
    size_t index = myid*spacing;
    data_t sum = 0;
    for (i = start; i < end; i++) {
        sum += i;
    }
    psum[index] = sum;
    return NULL;
}
```

Register Accumulation Performance



- Clear threading advantage

- Speedup = 7.5 X

Beware the speedup metric!

- 2X better than fastest memory accumulation

Lessons learned

- **Sharing memory can be expensive**
 - Pay attention to true sharing
 - Pay attention to false sharing
- **Use registers whenever possible**
 - (Remember cachelab)
 - Use local cache whenever possible
- **Deal with leftovers**
- **When examining performance, compare to best possible sequential implementation**

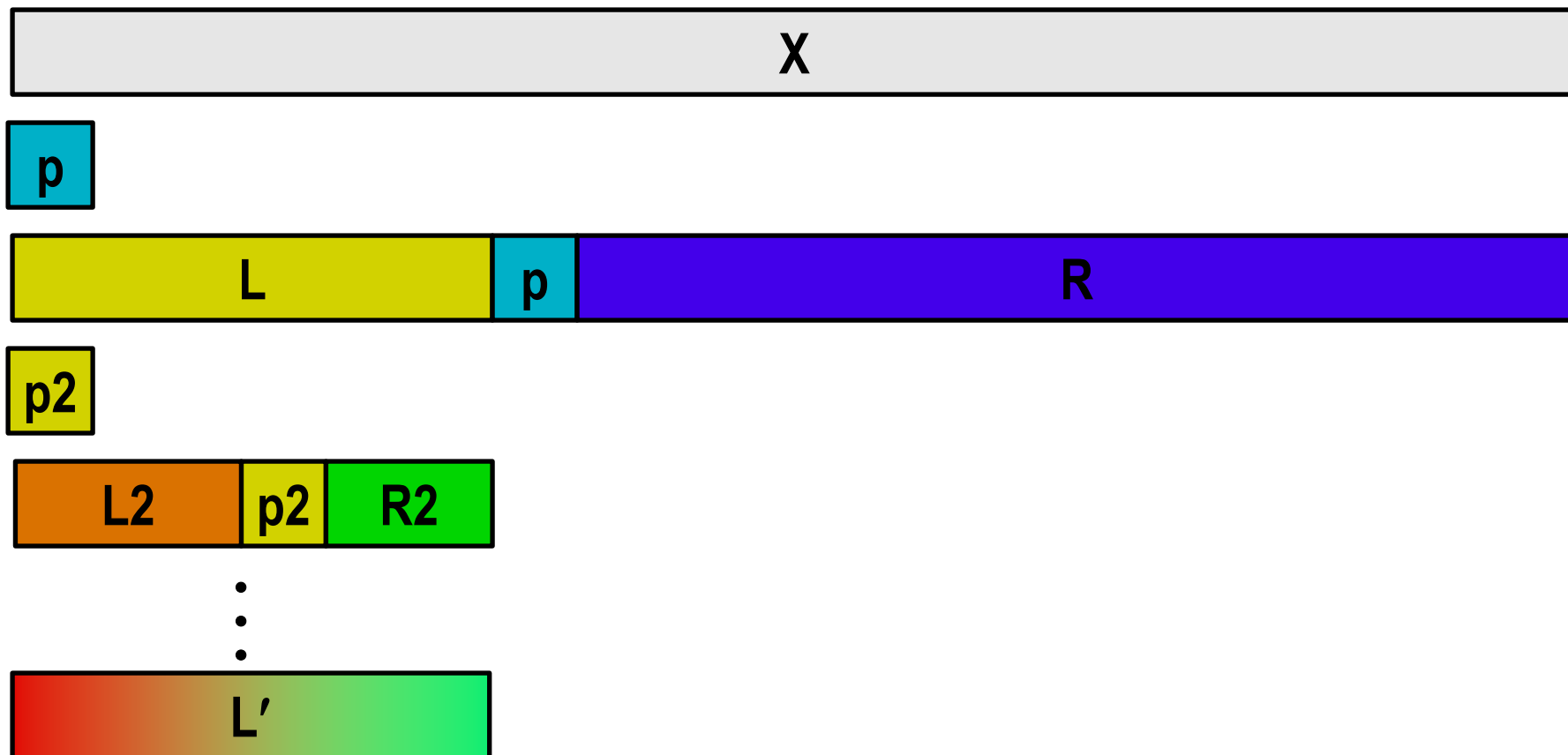
Quiz Time!

Canvas Quiz: Day 25 – Thread Level Parallelism

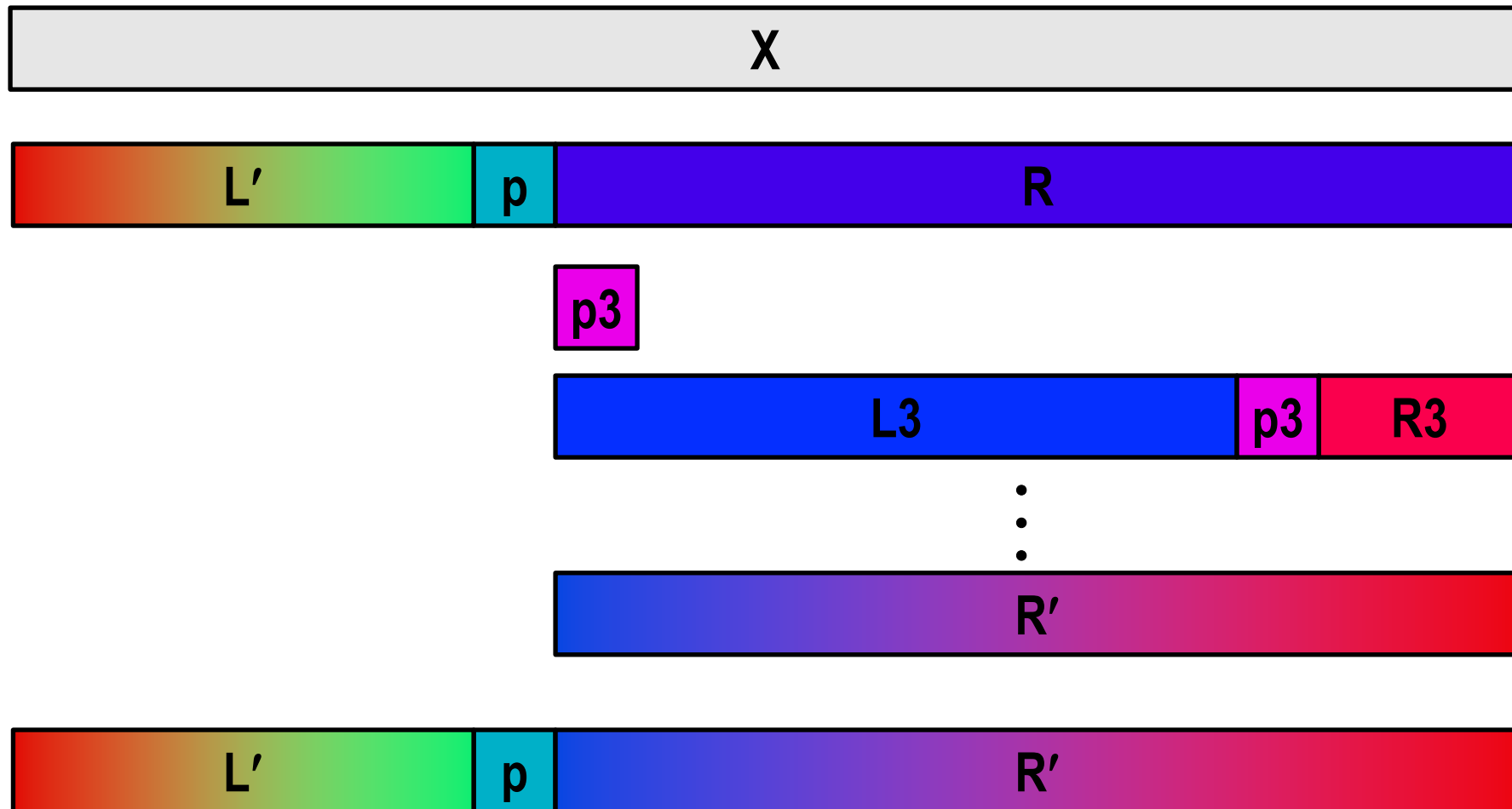
A More Substantial Example: Sort

- **Sort set of N random numbers**
- **Multiple possible algorithms**
 - Use parallel version of quicksort
- **Sequential quicksort of set of values X**
 - Choose “pivot” p from X
 - Rearrange X into
 - L : Values $\leq p$
 - R : Values $\geq p$
 - Recursively sort L to get L'
 - Recursively sort R to get R'
 - Return $L' : p : R'$

Sequential Quicksort Visualized



Sequential Quicksort Visualized



Sequential Quicksort Code

```
void qsort_serial(data_t *base, size_t nele) {
    if (nele <= 1)
        return;
    if (nele == 2) {
        if (base[0] > base[1])
            swap(base, base+1);
        return;
    }

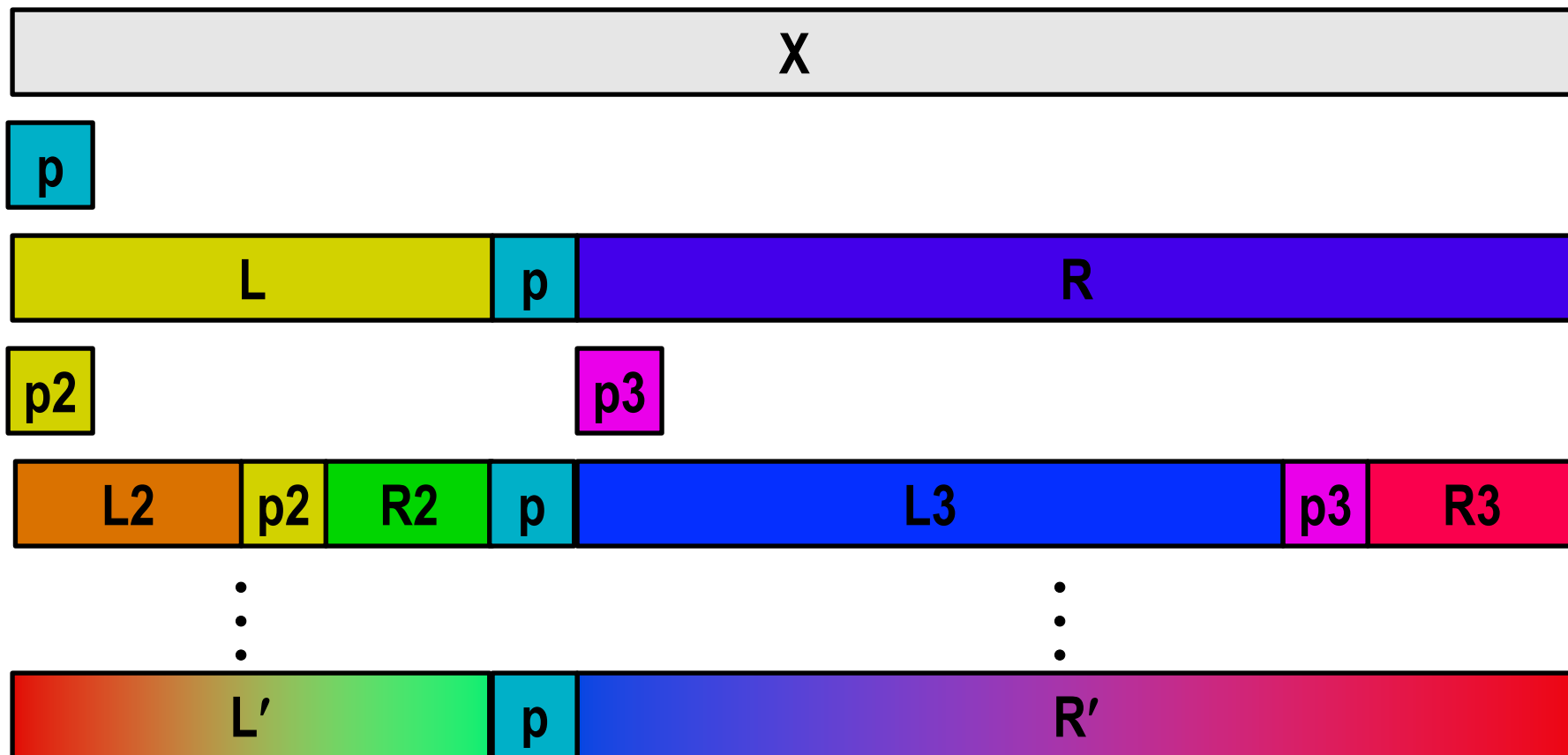
    /* Partition returns index of pivot */
    size_t m = partition(base, nele);
    if (m > 1)
        qsort_serial(base, m);
    if (m+1 < nele-1)
        qsort_serial(base+m+1, nele-m-1);
}
```

- Sort nele elements starting at base
 - Recursively sort L or R if has more than one element

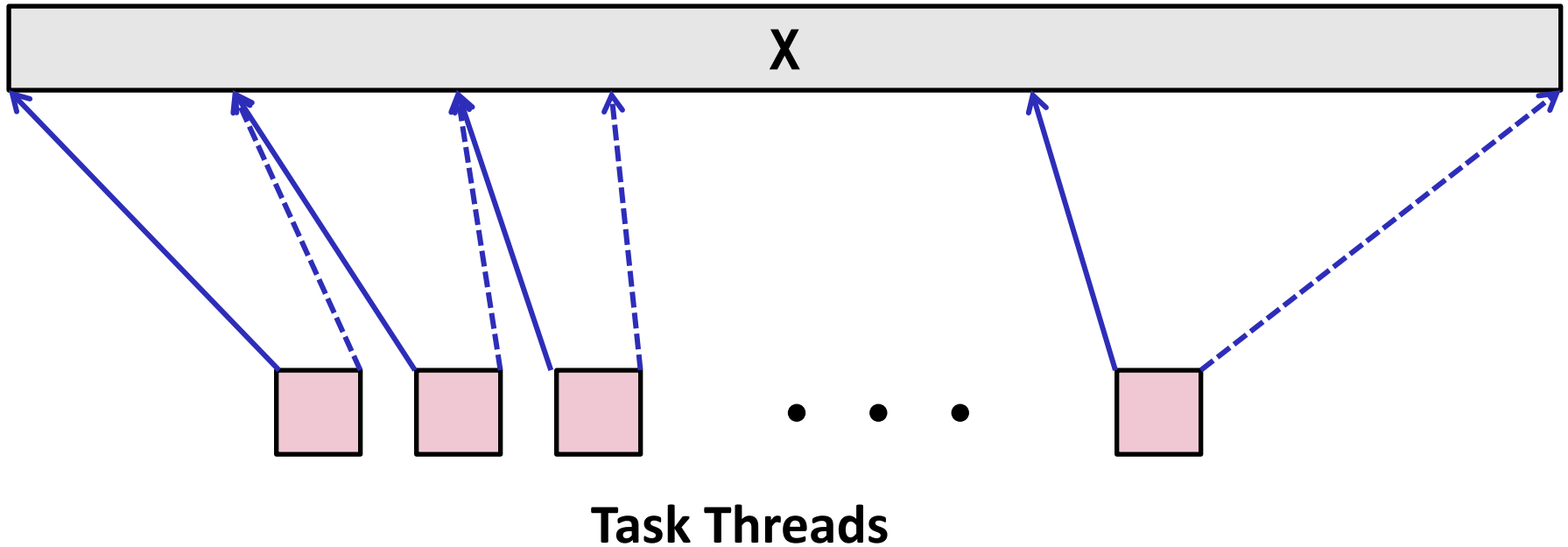
Parallel Quicksort

- **Parallel quicksort of set of values X**
 - If $N \leq N_{\text{thresh}}$, do sequential quicksort
 - Else
 - Choose “pivot” p from X
 - Rearrange X into
 - L : Values $\leq p$
 - R : Values $\geq p$
 - Recursively spawn separate threads
 - Sort L to get L'
 - Sort R to get R'
 - Return $L' : p : R'$

Parallel Quicksort Visualized

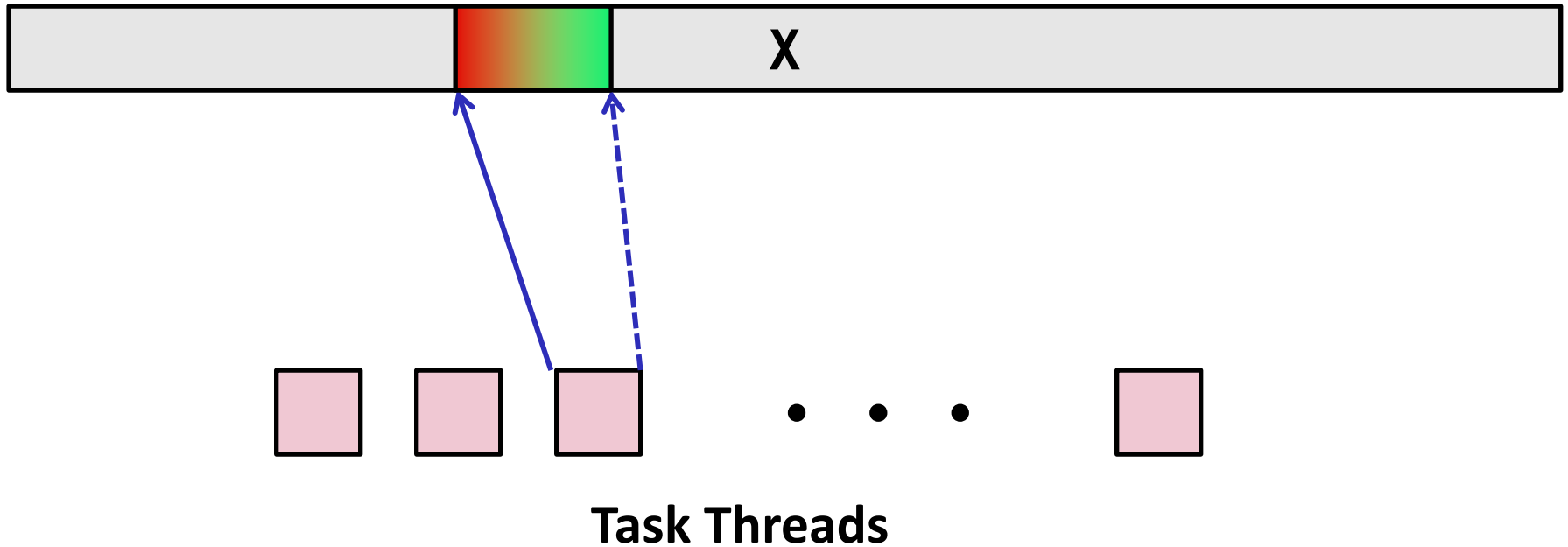


Thread Structure: Sorting Tasks



- **Task: Sort subrange of data**
 - Specify as:
 - **base**: Starting address
 - **ne1e**: Number of elements in subrange
- **Run as separate thread**

Small Sort Task Operation



- Sort subrange using serial quicksort

Large Sort Task Operation



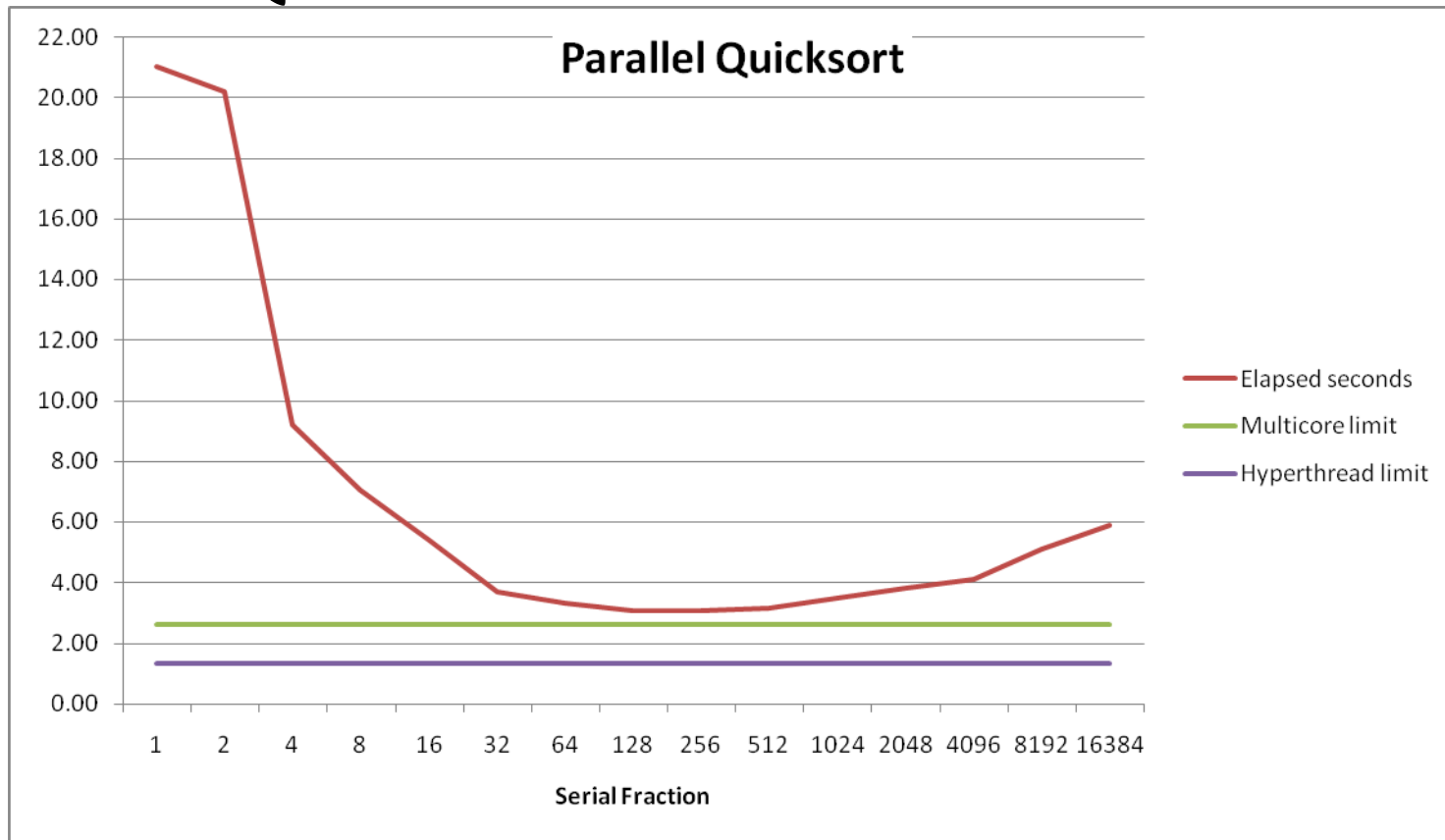
Partition Subrange



Spawn 2 tasks

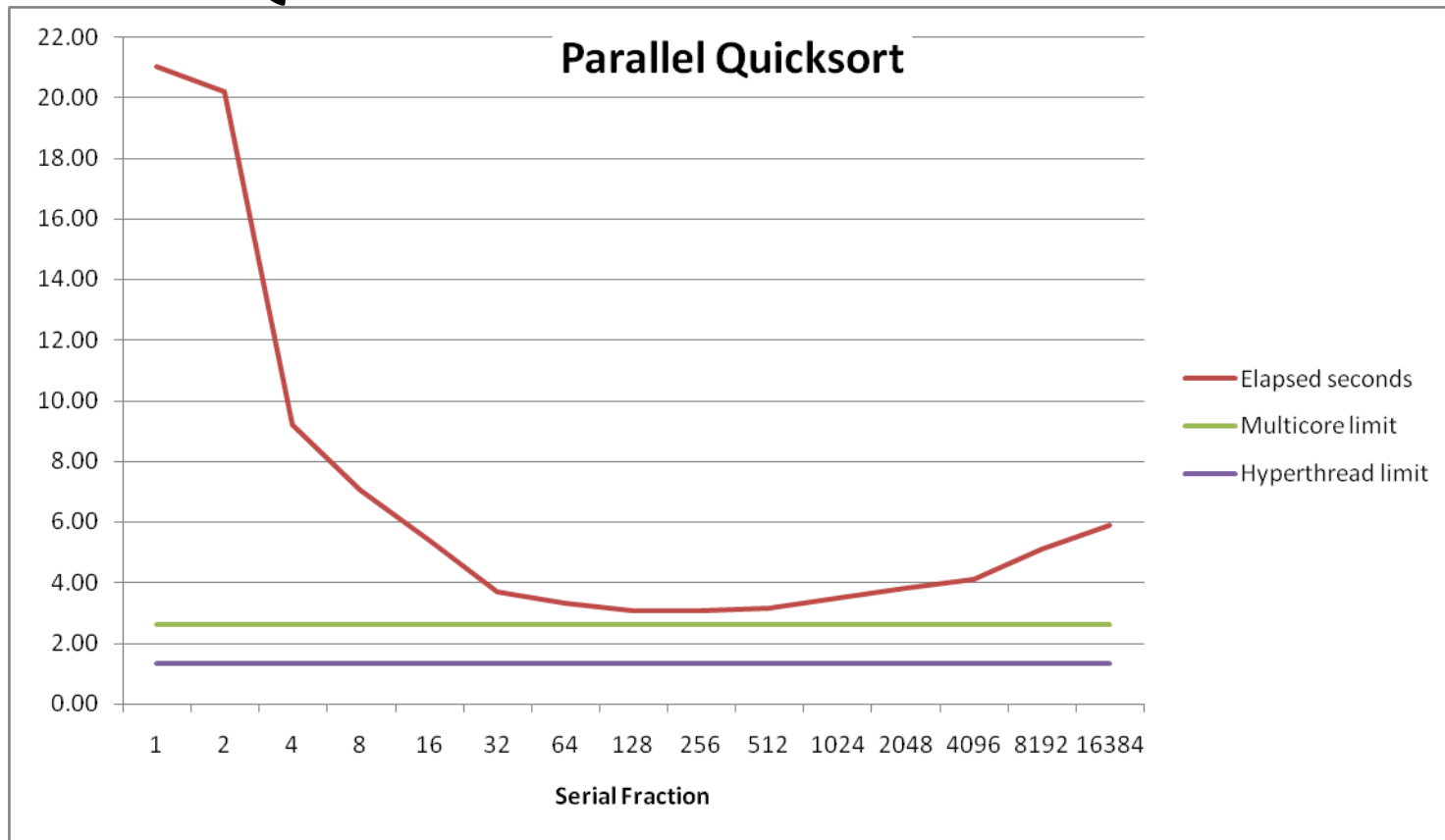


Parallel Quicksort Performance



- Serial fraction: Fraction of input at which do serial sort
- Sort 2^{27} (134,217,728) random values
- Best speedup = 6.84X

Parallel Quicksort Performance



- **Good performance over wide range of fraction values**
 - F too small: Not enough parallelism
 - F too large: Thread overhead too high

Amdahl's Law (Travel Analogy)

		Speed-Up
■ Flying jet non-stop from PIT -> LHR:	7.5 Hours	1
■ Or, old fashioned SST way:		
■ Fly jet from PIT -> JFK: 1.5 Hours		
■ Fly SST from JFK -> LHR: 3.5 Hours	5 Hours	1.5x
■ Or, Using FTL travel:		
■ Fly jet from PIT -> JFK: 1.5 Hours		
■ Fly FTL from JFK -> LHR: .01 Hours	1.51 Hours	~5x
■ Best possible speed up is 5X, even with FTL because have to get to New York.		

* FTL = Faster than light

Amdahl's Law

■ Overall problem

- T Total sequential time required
- p Fraction of total that can be sped up ($0 \leq p \leq 1$)
- k Speedup factor

■ Resulting Performance

- $T_k = pT/k + (1-p)T$
 - Portion which can be sped up runs k times faster
 - Portion which cannot be sped up stays the same
- Maximum possible speedup
 - $k = \infty$
 - $T_\infty = (1-p)T$

Amdahl's Law (Travel Analogy)

- | | | Speed-Up |
|--|------------|------------------|
| ■ Flying jet non-stop from PIT -> LHR: | 7.5 Hours | 1 |
| ■ Or, old fashioned SST way: | | |
| ■ Fly jet from PIT -> JFK: 1.5 Hours | | |
| ■ Fly SST from JFK -> LHR: 3.5 Hours | 5 Hours | 1.5x |
| ■ Or, Using FTL travel: | | |
| ■ Fly jet from PIT -> JFK: 1.5 Hours | | |
| ■ Fly FTL from JFK -> LHR: .01 Hours | 1.51 Hours | ~5x |
| ■ Best possible speed up is 5X, even with FTL because have to get to New York. | | |
| ■ $T=7.5, p=6/7.5=.8, k=\infty \Rightarrow T_{\infty} = (1-p)T=1.5$ | | max speed-up =5x |

Amdahl's Law Example

■ Overall problem

- $T = 10$ Total time required
- $p = 0.9$ Fraction of total which can be sped up
- $k = 9$ Speedup factor

■ Resulting Performance

- $T_9 = 0.9 * 10/9 + 0.1 * 10 = 1.0 + 1.0 = 2.0$ (a 5x speedup)

■ Maximum possible speedup

- $T_\infty = 0.1 * 10.0 = 1.0$ (a 10x speedup)
 - With **infinite** parallel computing resources!
- Limit speedup shows **algorithmic** limitation

Amdahl's Law & Parallel Quicksort

■ Sequential bottleneck

- Top-level partition: No speedup
- Second level: $\leq 2X$ speedup
- k^{th} level: $\leq 2^{k-1}X$ speedup

■ Implications

- Good performance for small-scale parallelism
- Would need to parallelize partitioning step to get large-scale parallelism
 - Parallel Sorting by Regular Sampling
 - H. Shi & J. Schaeffer, J. Parallel & Distributed Computing, 1992

Lessons Learned

- **Must have parallelization strategy**
 - Partition into K independent parts
 - Divide-and-conquer
- **Inner loops must be synchronization free**
 - Synchronization operations very expensive
- **Watch out for hardware artifacts**
 - Need to understand processor & memory structure
 - Sharing and false sharing of global data
- **Beware of Amdahl's Law**
 - Serial code can become bottleneck
- **You can do it!**
 - Achieving modest levels of parallelism is not difficult
 - Set up experimental framework and test multiple strategies

Thursday's Lecture: Frontiers of Computing

- **Juncheng Yang: FIFO queues are better than LRU for caching**
 - **Valerie Choung: Designing malloc to better serve programmers**
 - **Kaiyang Zhao: Why and how to defragment physical memory**
-
- Not recorded, not on the final
 - No separate 14513 lecture
 - 15513 and 14513 students are welcome to attend, in GHC 4401

Top-Level Function (Simplified)

```
void tqsort(data_t *base, size_t nele) {
    init_task(nele);
    global_base = base;
    global_end = global_base + nele - 1;
    task_queue_ptr tq = new_task_queue();
    tqsort_helper(base, nele, tq);
    join_tasks(tq);
    free_task_queue(tq);
}
```

- Sets up data structures
- Calls recursive sort routine
- Keeps joining threads until none left
- Frees data structures

Recursive sort routine (Simplified)

```
/* Multi-threaded quicksort */
static void tqsort_helper(data_t *base, size_t nele,
                          task_queue_ptr tq) {
    if (nele <= nele_max_sort_serial) {
        /* Use sequential sort */
        qsort_serial(base, nele);
        return;
    }
    sort_task_t *t = new_task(base, nele, tq);
    spawn_task(tq, sort_thread, (void *) t);
}
```

- Small partition: Sort serially
- Large partition: Spawn new sort task

Sort task thread (Simplified)

```
/* Thread routine for many-threaded quicksort */
static void *sort_thread(void *vargp) {
    sort_task_t *t = (sort_task_t *) vargp;
    data_t *base = t->base;
    size_t nele = t->nele;
    task_queue_ptr tq = t->tq;
    free(vargp);
    size_t m = partition(base, nele);
    if (m > 1)
        tqsort_helper(base, m, tq);
    if (nele-1 > m+1)
        tqsort_helper(base+m+1, nele-m-1, tq);
    return NULL;
}
```

- Get task parameters
- Perform partitioning step
- Call recursive sort routine on each partition (if size of part > 1)