

# Thread-Level Parallelism

15-213/15-513: Introduction to Computer Systems  
26<sup>th</sup> Lecture, July 28, 2023

## **Instructors:**

Brian Railing

# Logistics

- **Proxy final due Friday August 11 at 11:59pm**
  - NO late submissions
  - No extensions except for exceptional circumstances
  
- **Final Exam**
  - Final will be on Thursday, August 10 at 1-4pm
    - Unless 8/26 at 1-4pm
    - Unless 12/? at ?
  - Exam is on Gradescope. Bring a laptop to do the exam.
  - You can bring two 8.5"x11" / A4 cheat sheets, written or printed

# Disclaimer

- **We do not have time to fully cover the following content**
  - Take -346, -410, -418 ...
- **Valuable to know as you start writing parallel programs**
- **More practice through SFSLab (see appendix)**

# Today

## ■ Parallel Computing Hardware

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

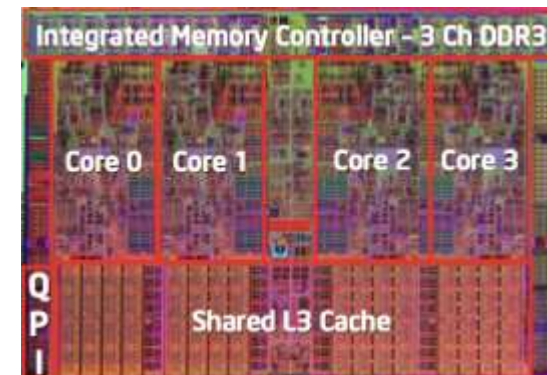
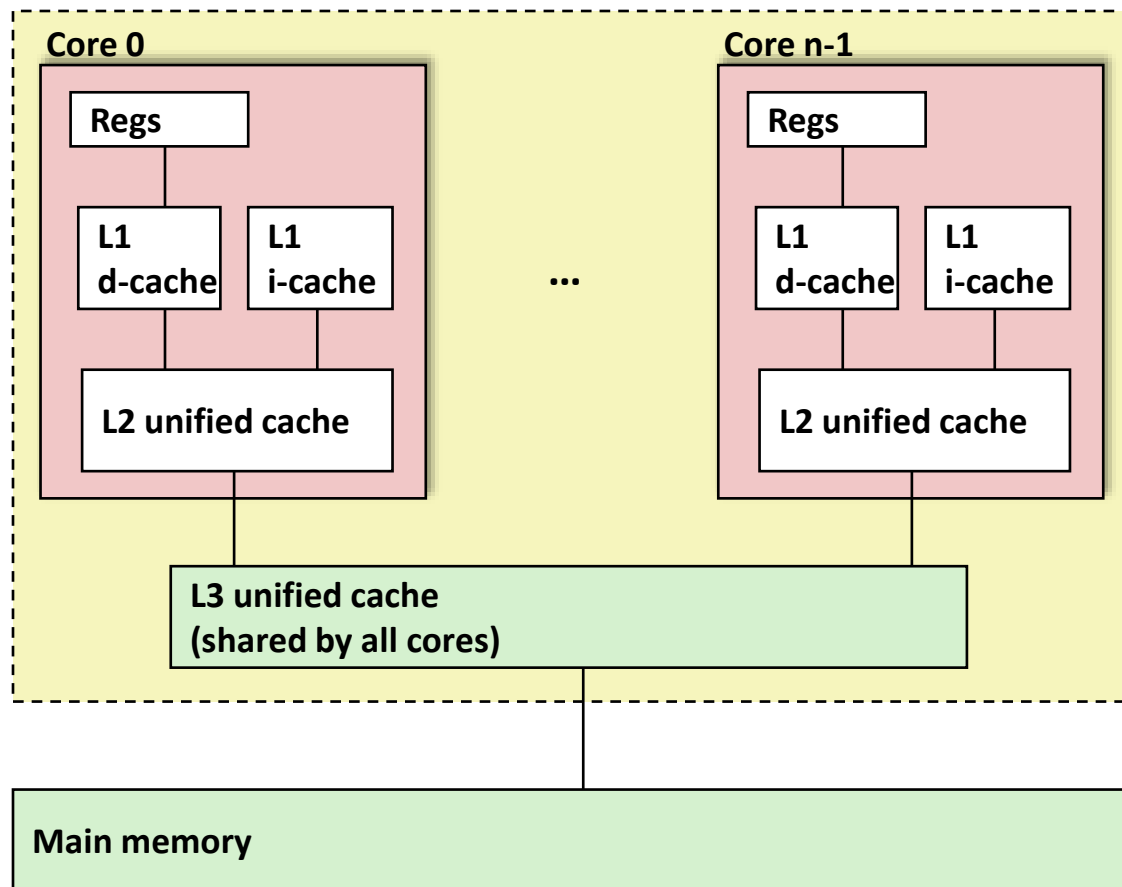
## ■ Consistency Models

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

## ■ Thread-Level Parallelism

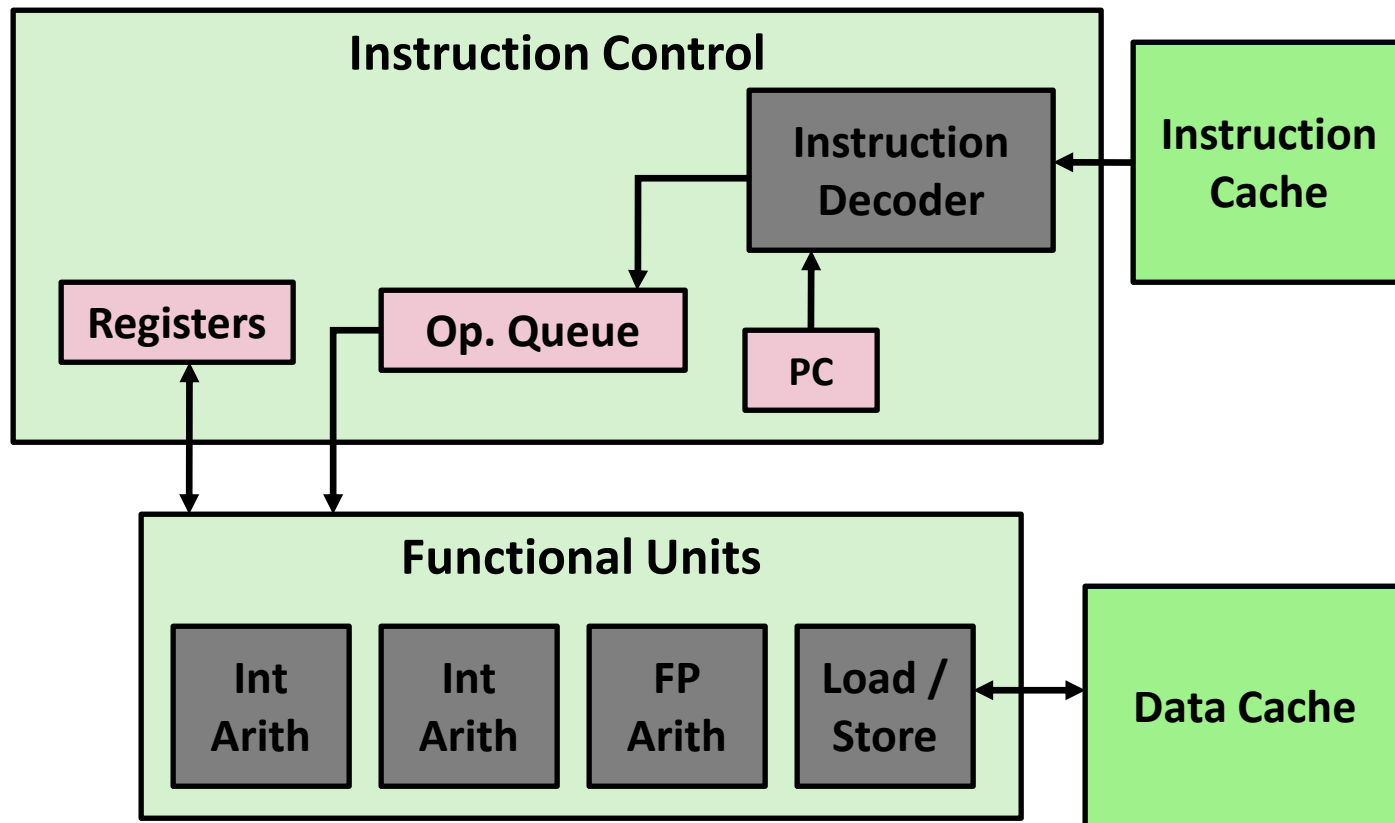
- Splitting program into independent tasks
  - Example: Parallel summation
  - Examine some performance artifacts
- Divide-and conquer parallelism
  - Example: Parallel quicksort

# Typical Multicore Processor



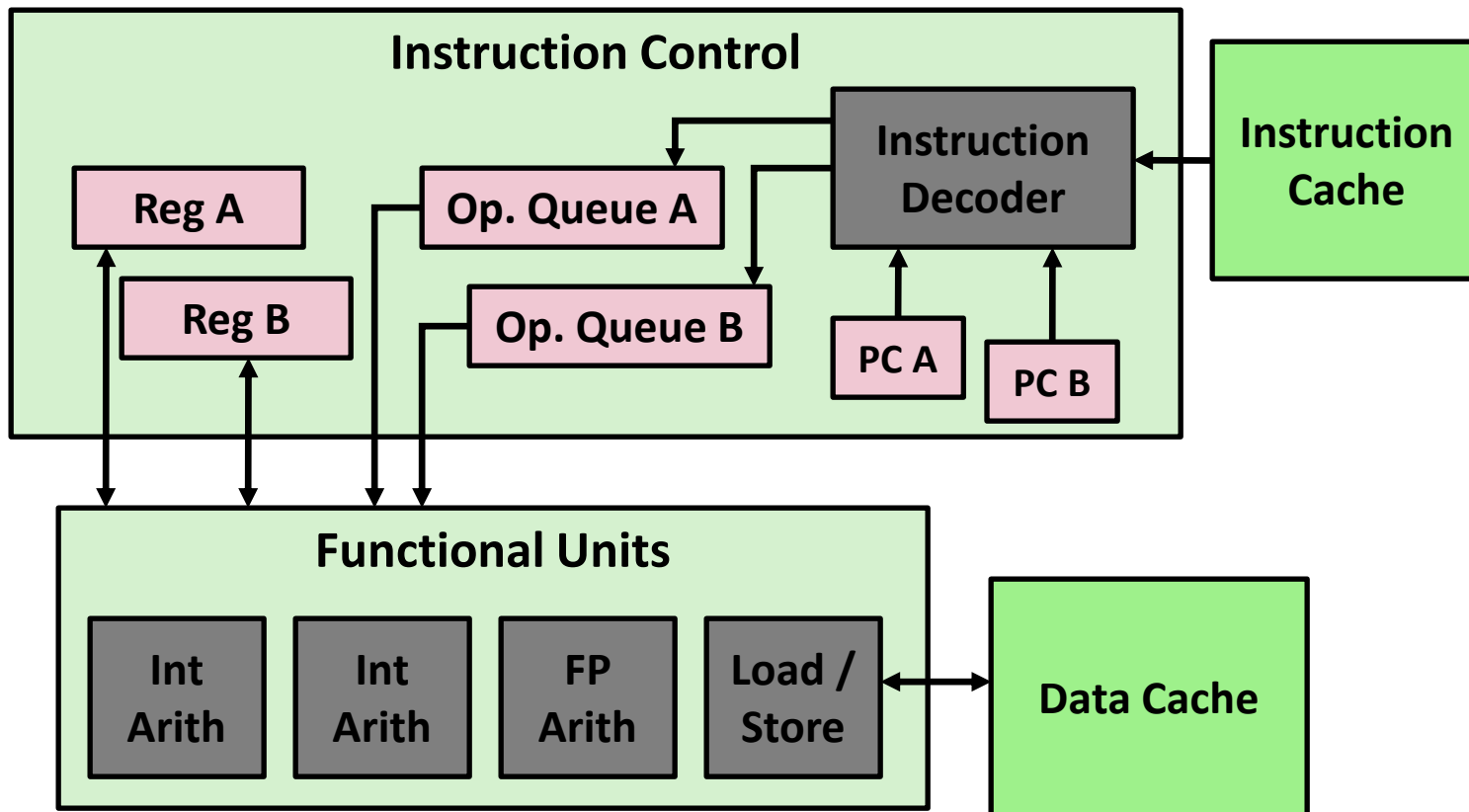
- Multiple processors operating with coherent view of memory

# 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

# Powerful, Parallel Computing Is

- Two threads, X and Y initialized to 0

X = 1

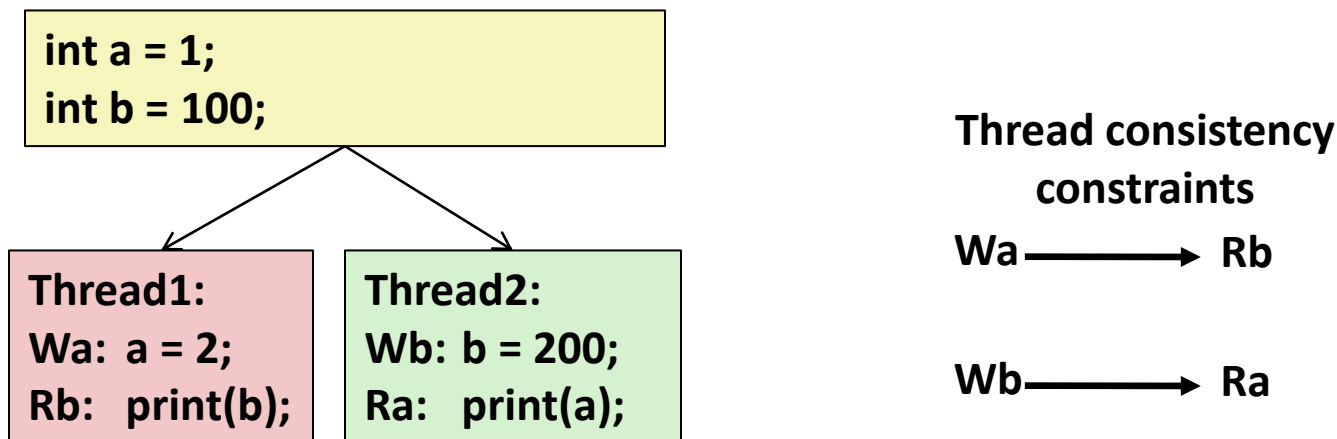
if (Y == 0) print Hello

Y = 1

if (X == 0) print World



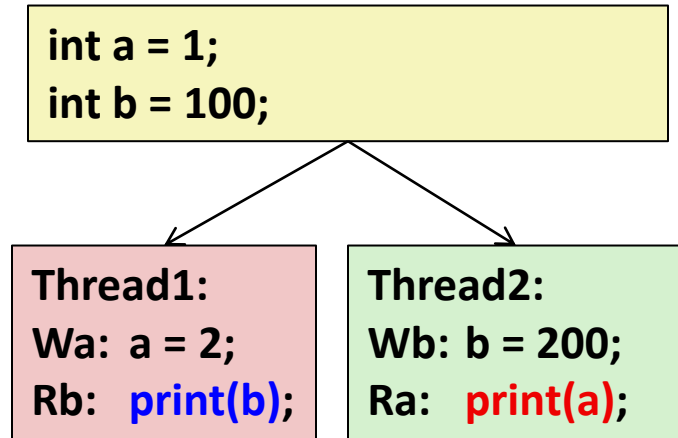
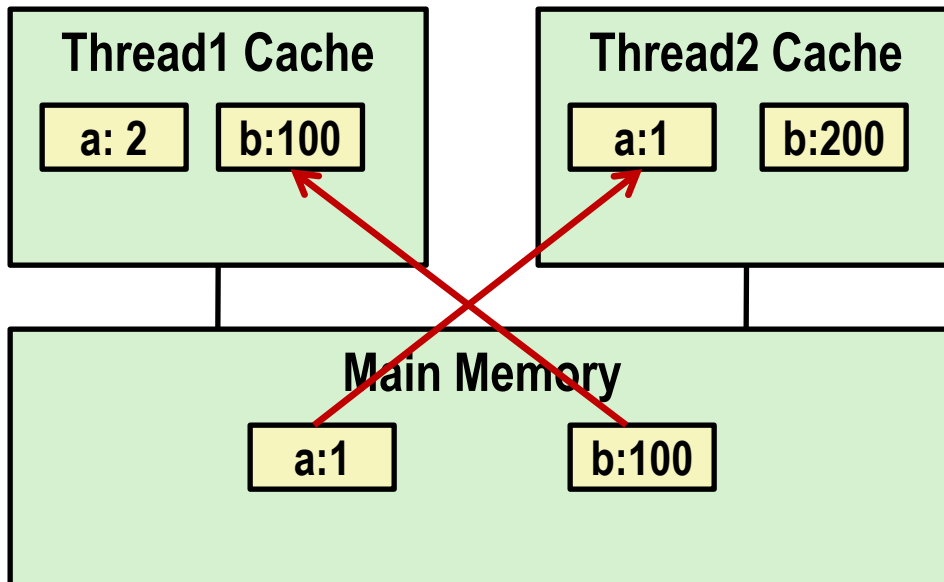
# Memory Coherence / Consistency



- **What are the possible values printed?**
  - Depends on memory consistency model
  - Abstract model of how hardware handles concurrent accesses
  
- **How do the two threads really see the writes?**

# Non-Coherent Cache Scenario

- Write-back caches, without coordination between them



`print 1`

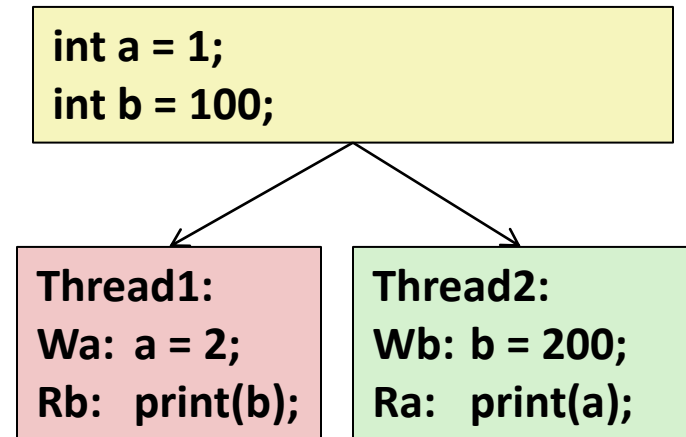
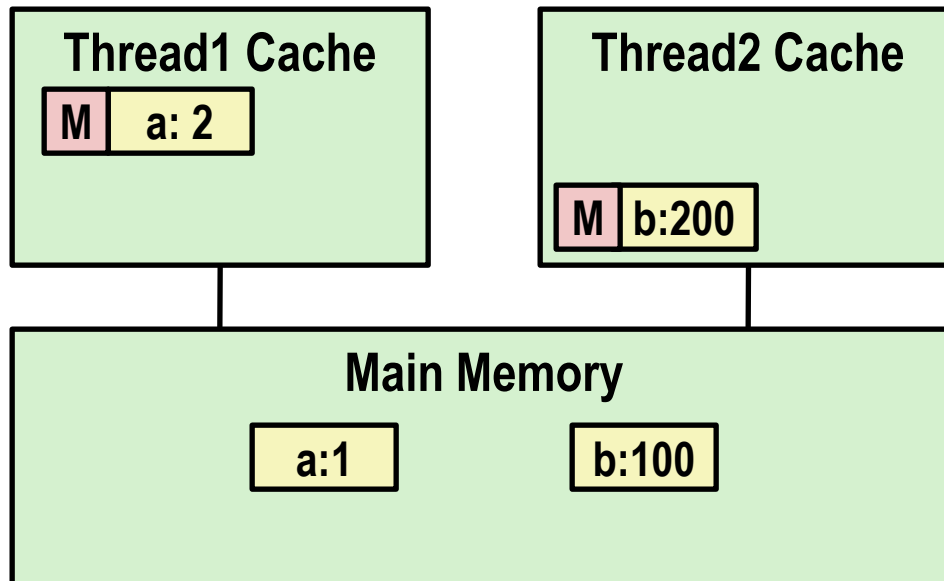
`print 100`

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

# Snoopy Caches

## ■ Tag each cache block with state

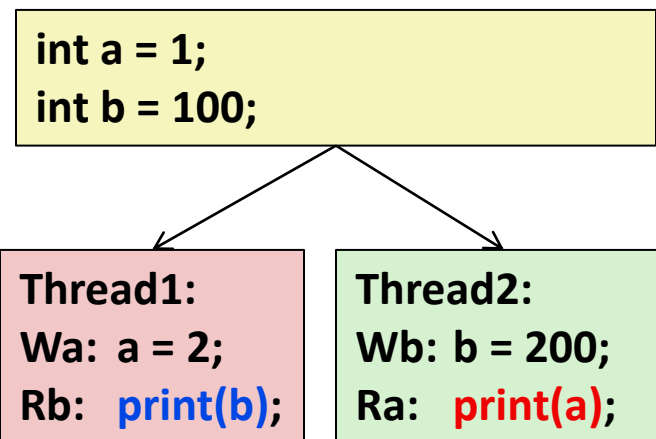
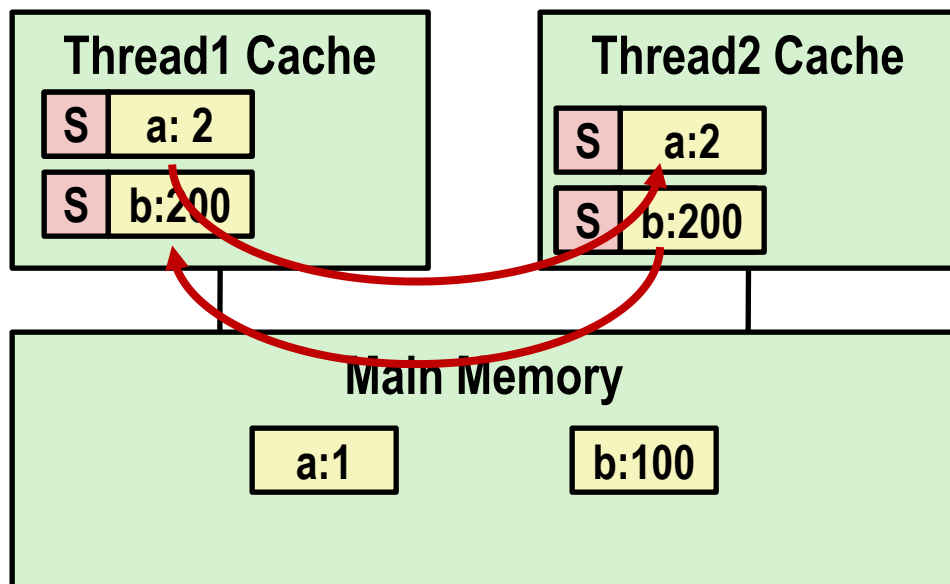
Invalid	Cannot use value
Shared	Readable copy
Modified	Writeable copy



# Snoopy Caches

## ■ Tag each cache block with state

Invalid	Cannot use value
Shared	Readable copy
Modified	Writeable copy

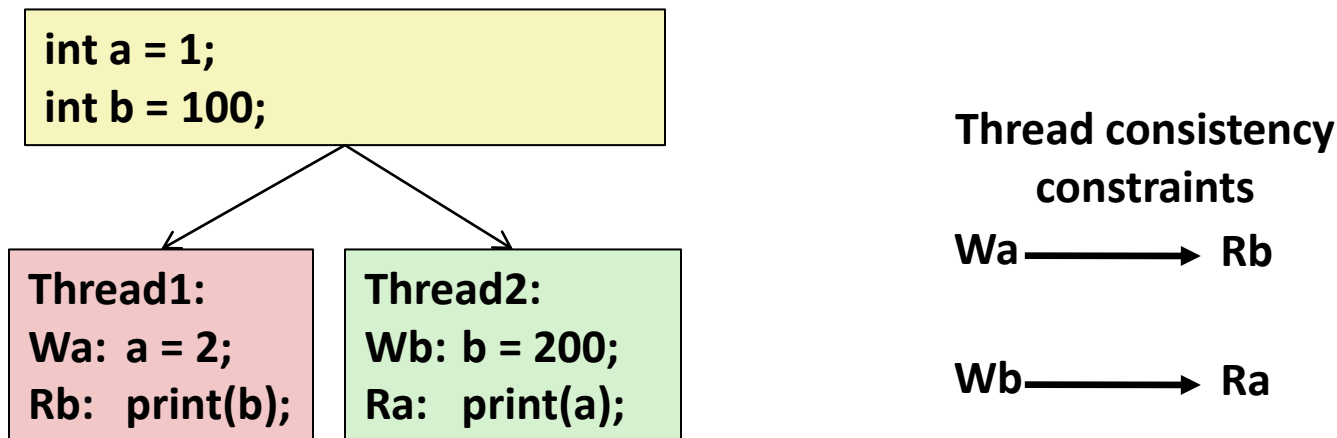


**print 2**

**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

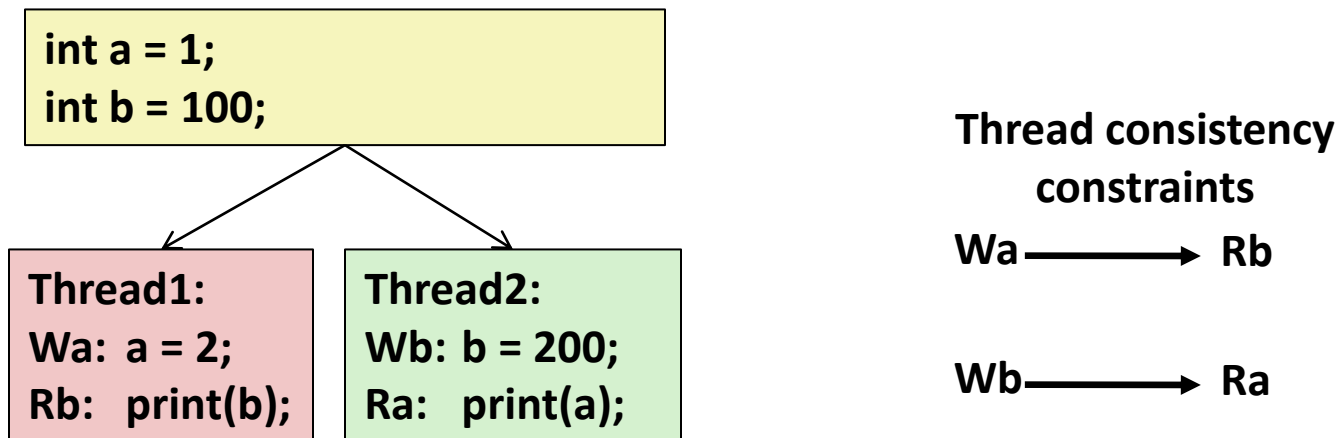
# Memory Consistency



## ■ 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;
```

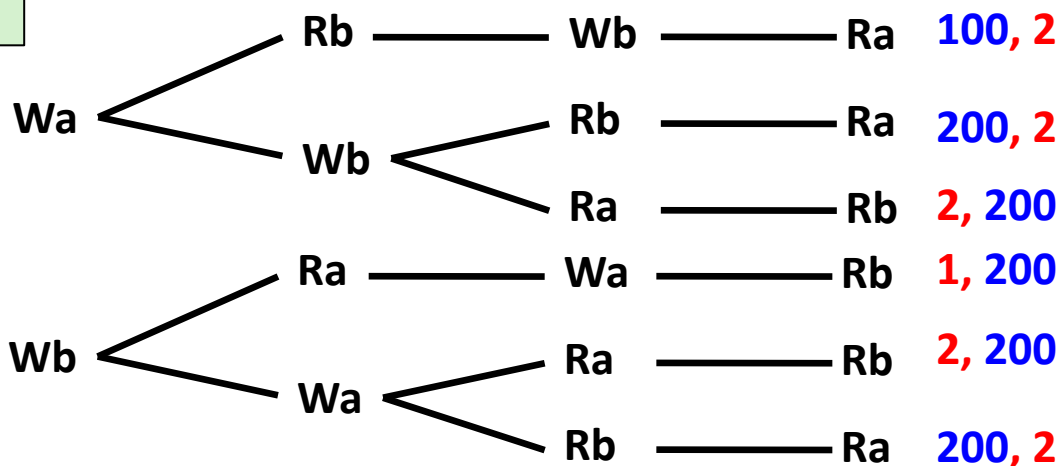
Thread1:  
 Wa: a = 2;  
 Rb: **print(b);**

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

Thread consistency  
 constraints

Wa ————— Rb

Wb ————— Ra

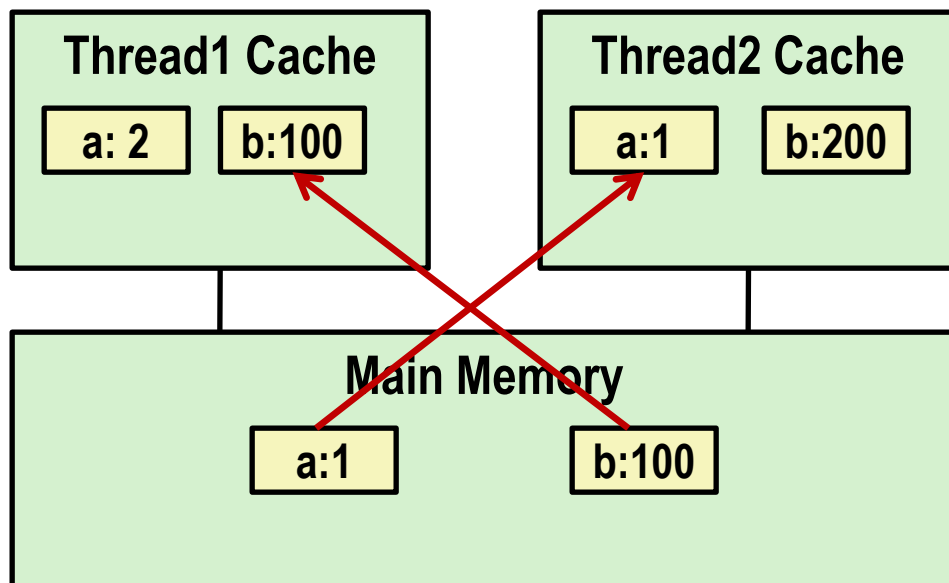


## ■ Impossible outputs

- **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);
```

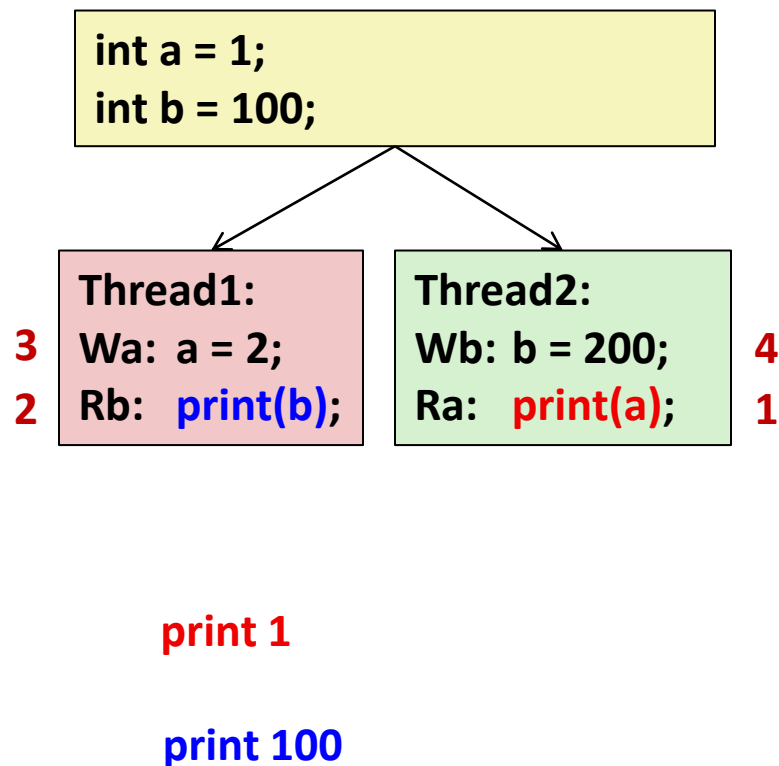
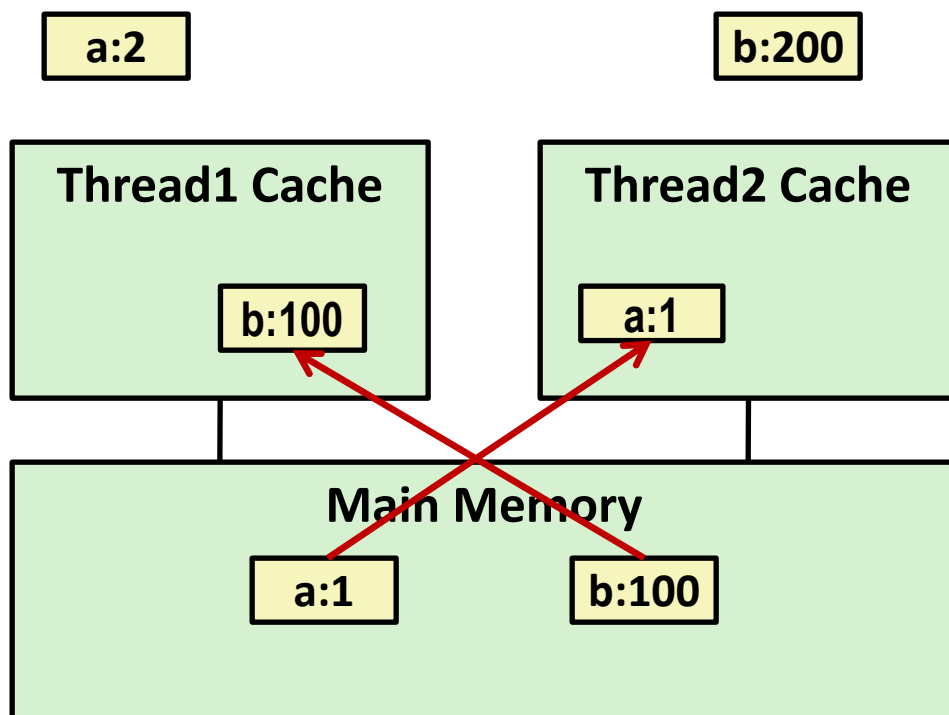
**print 1**

**print 100**

Sequentially consistent? **No!**

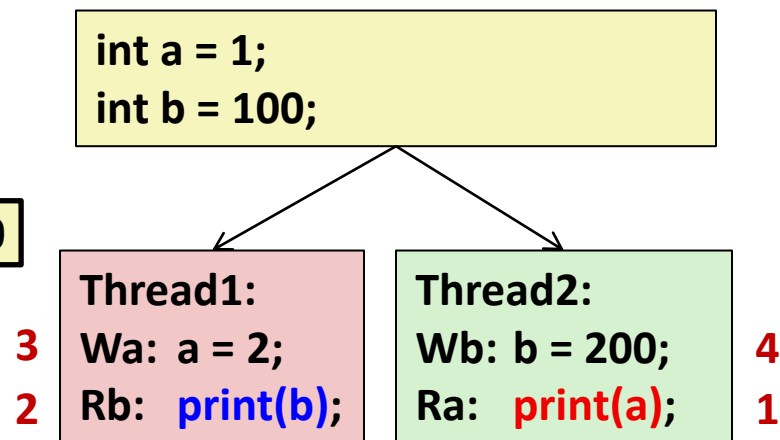
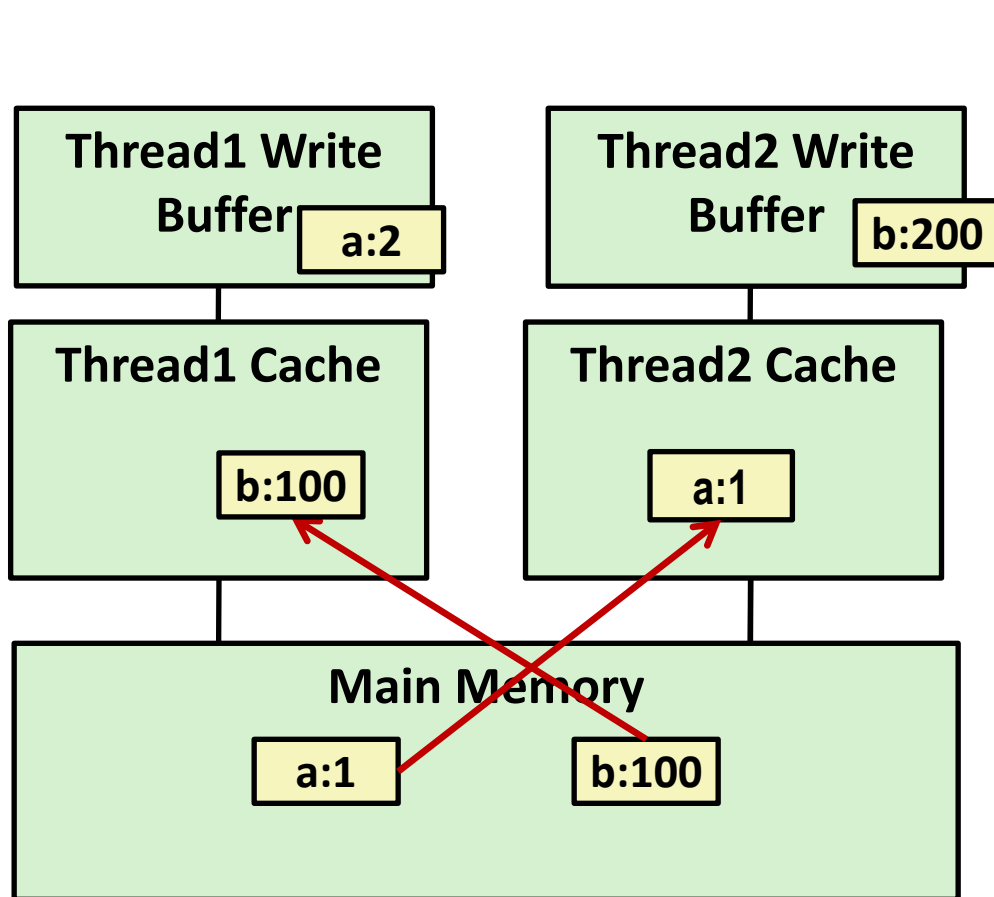
# Non-Sequentially Consistent Scenario

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



- 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`**
- **Fix: Use synchronization (properly written, it fences)**

# Memory Models

- **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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## ■ Consistency Models

- 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

# 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**

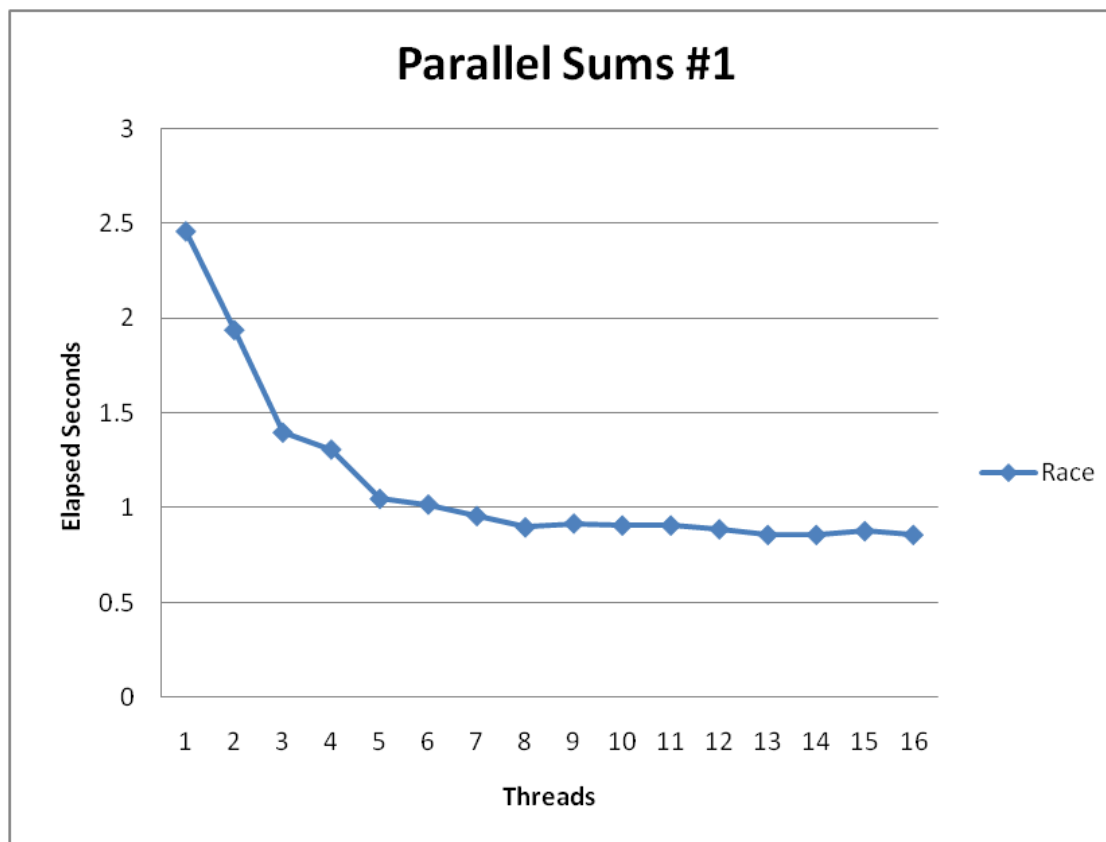
**Thread arguments  
(void \*p)**

# 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

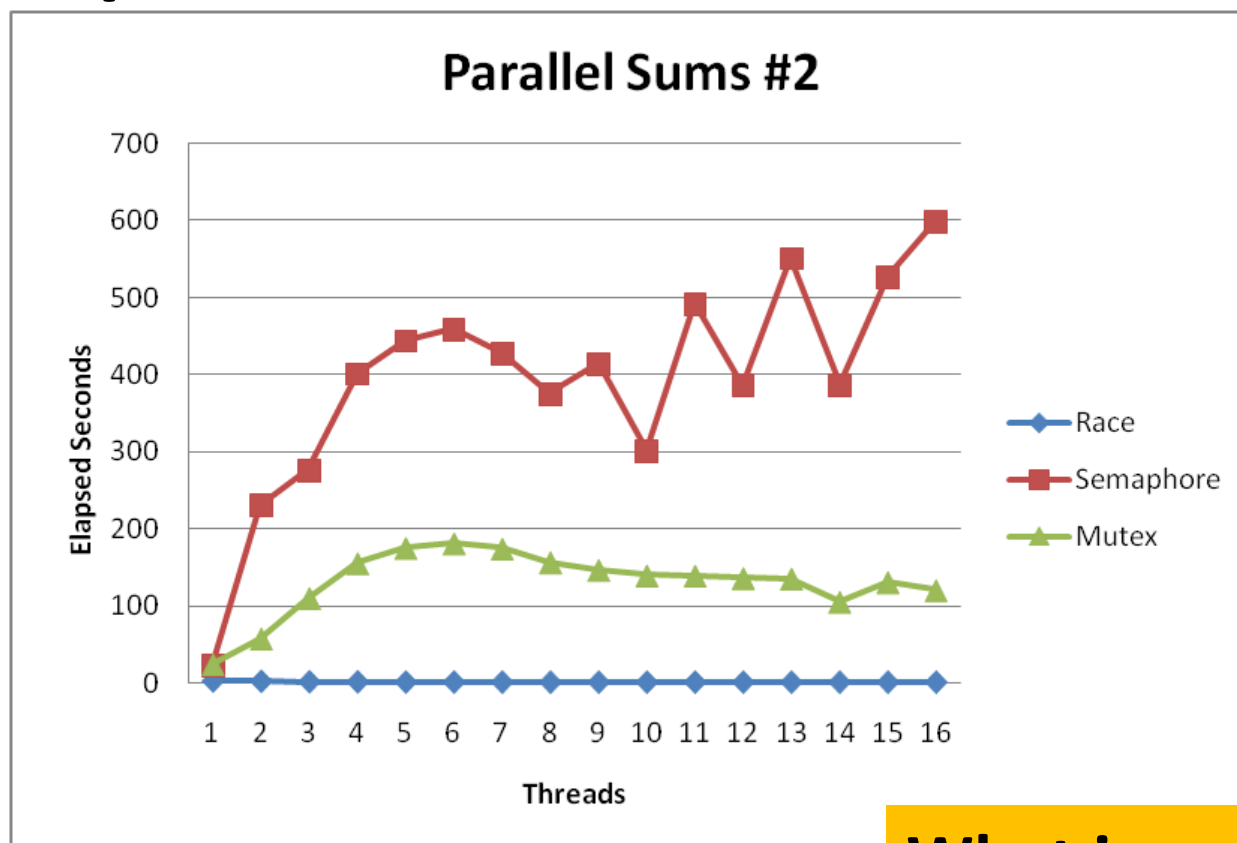
```
void *sum_sem(void *vargp)
{
    int myid = *((int *)vargp);
    size_t start = myid * nelems_per_thread;
    size_t end = start + nelems_per_thread;
    size_t i;

    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;
```

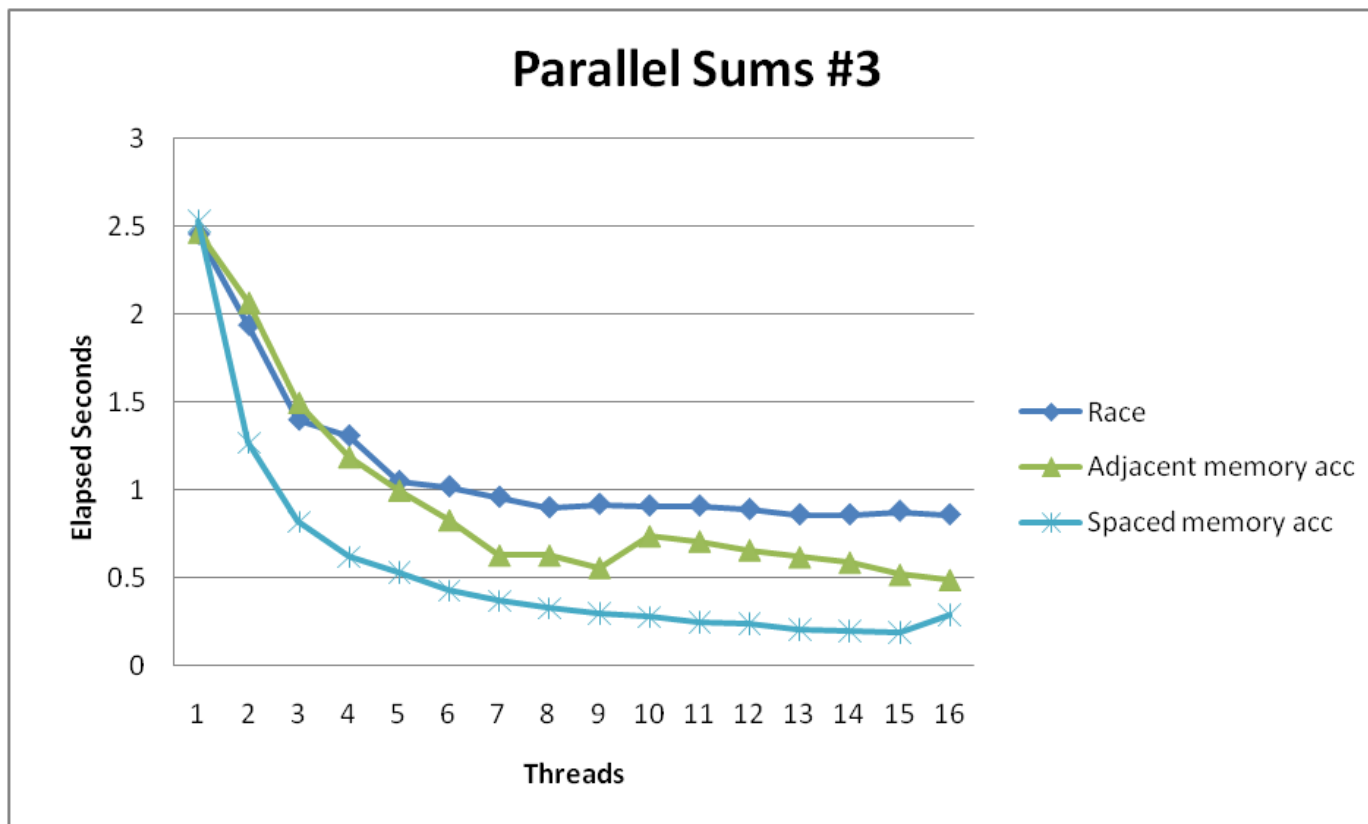
# Thread Function: Memory Accumulation

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

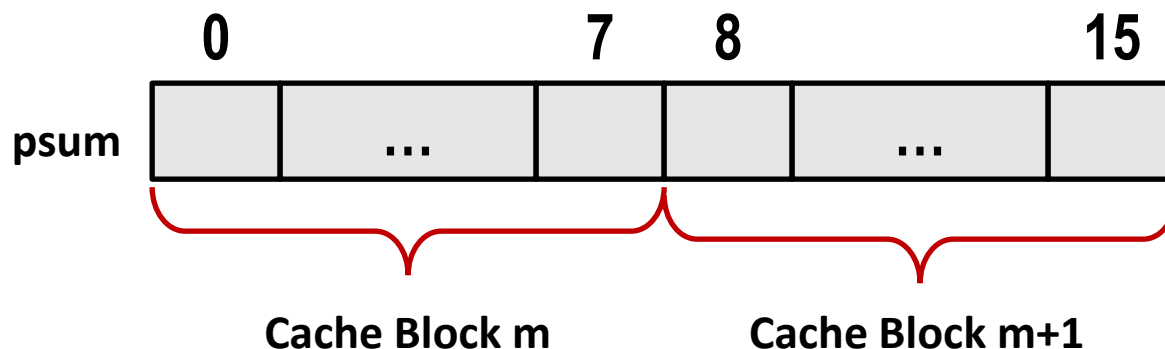


## ■ Clear threading advantage

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

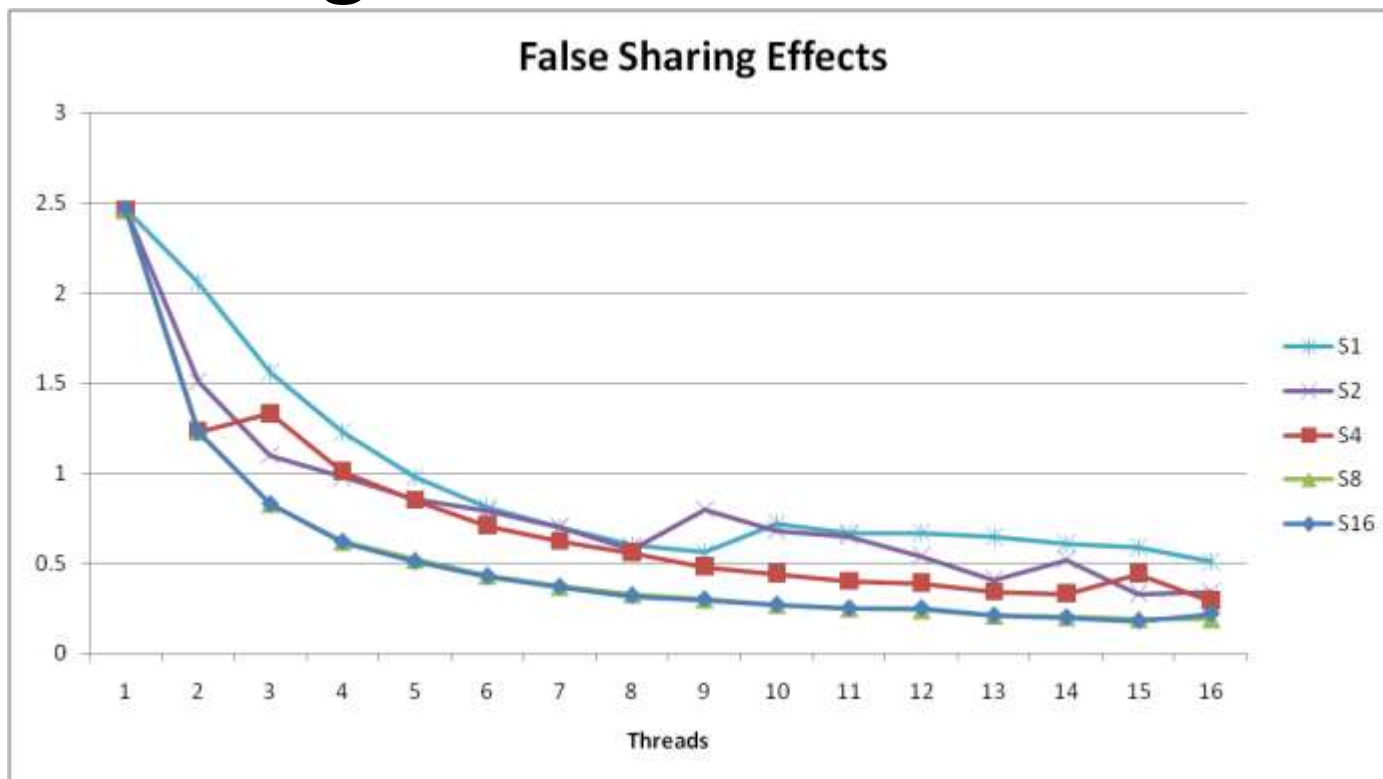
## ■ Why does spacing the accumulators apart matter?

# 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

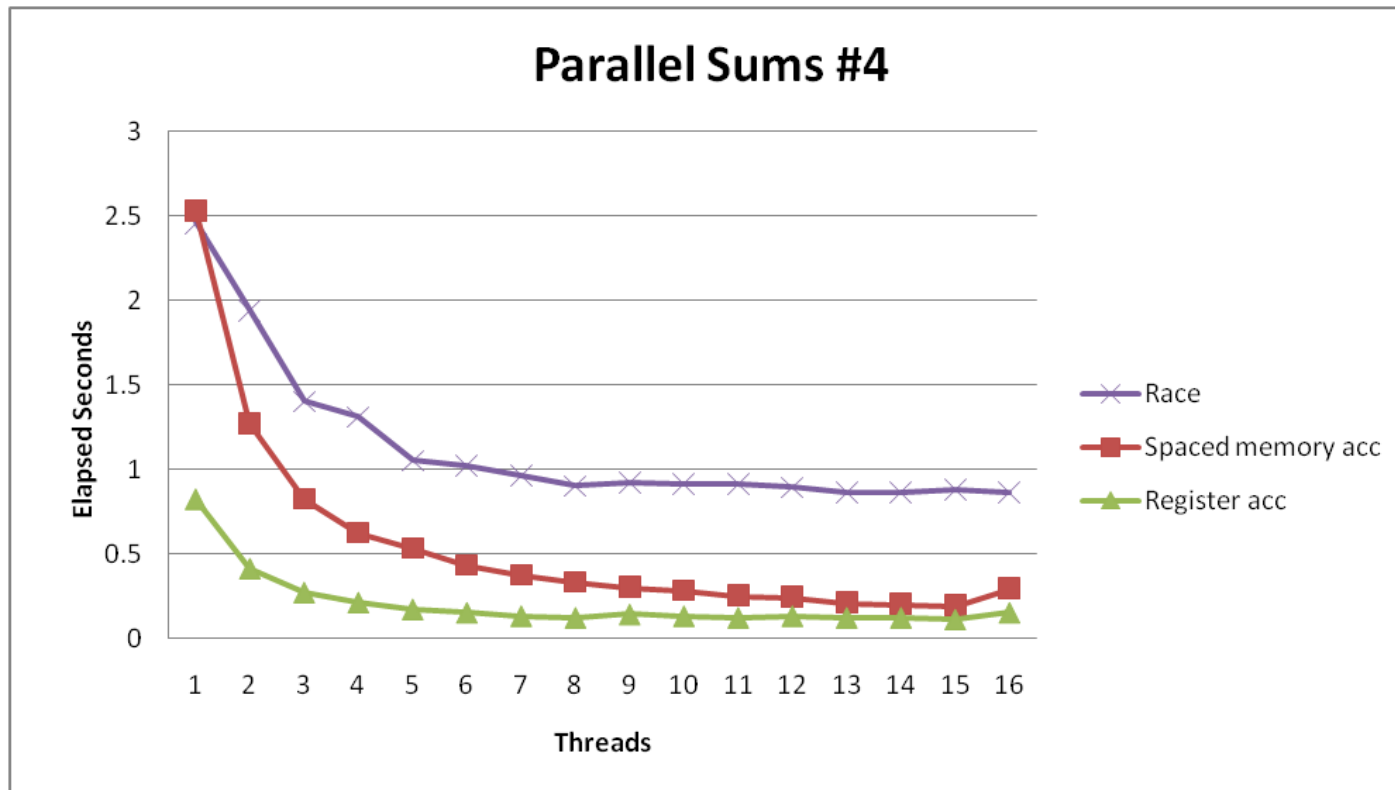


- Best spaced-apart performance 2.8 X better than best adjacent
- **Demonstrates cache block size = 64**
  - 8-byte values
  - No benefit increasing spacing beyond 8

# 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

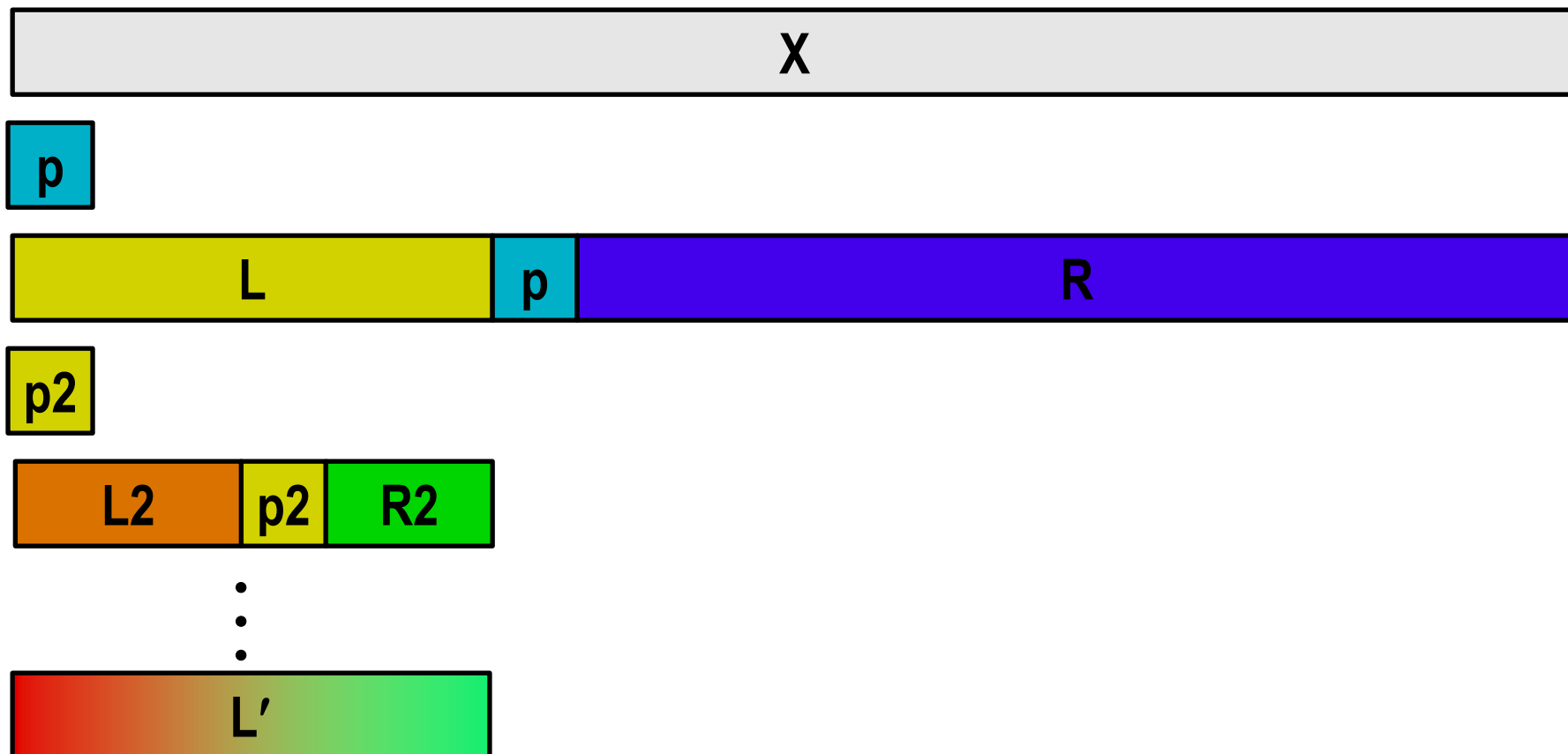
- **Sharing memory can be expensive**
  - Pay attention to true sharing
  - Pay attention to false sharing
- **Use registers whenever possible**
  - (Remember cachelab)
  - Use local cache whenever possible
- **Deal with leftovers**
- **When examining performance, compare to best possible sequential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



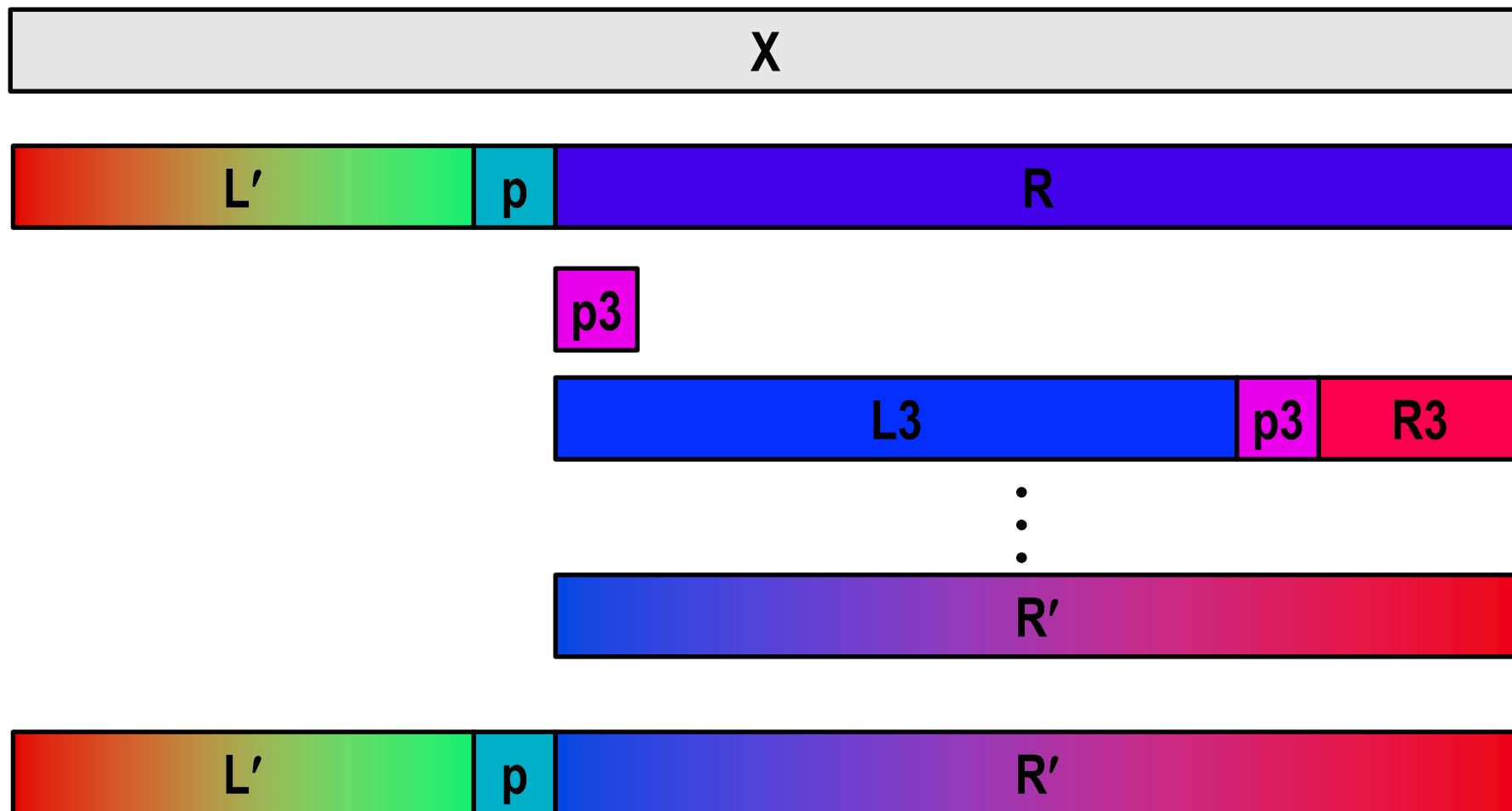
# A More Substantial Example: Sort

- **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;
    }

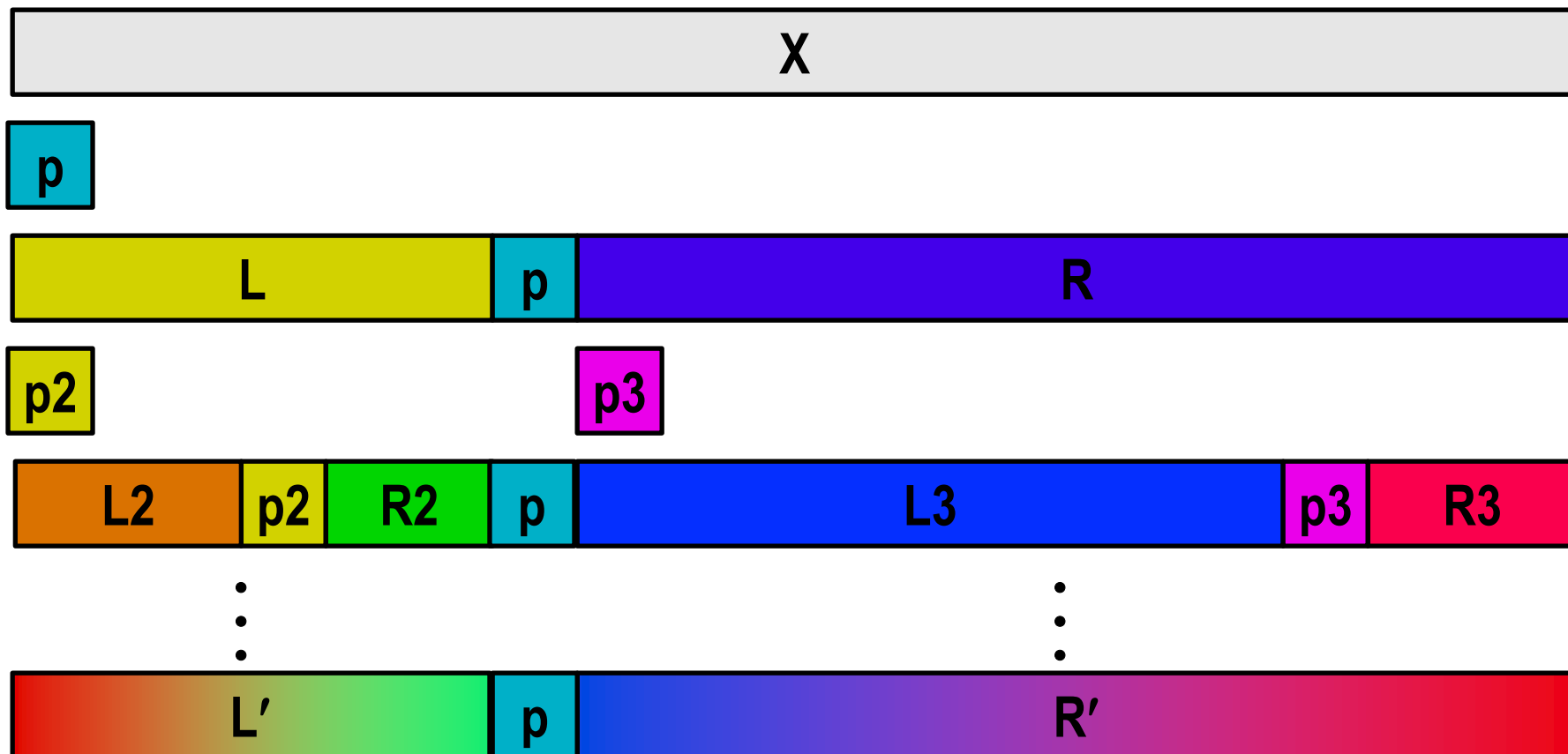
    /* Partition returns index of pivot */
    size_t m = partition(base, nele);
    if (m > 1)
        qsort_serial(base, m);
    if (nele-1 > m+1)
        qsort_serial(base+m+1, nele-m-1);
}
```

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

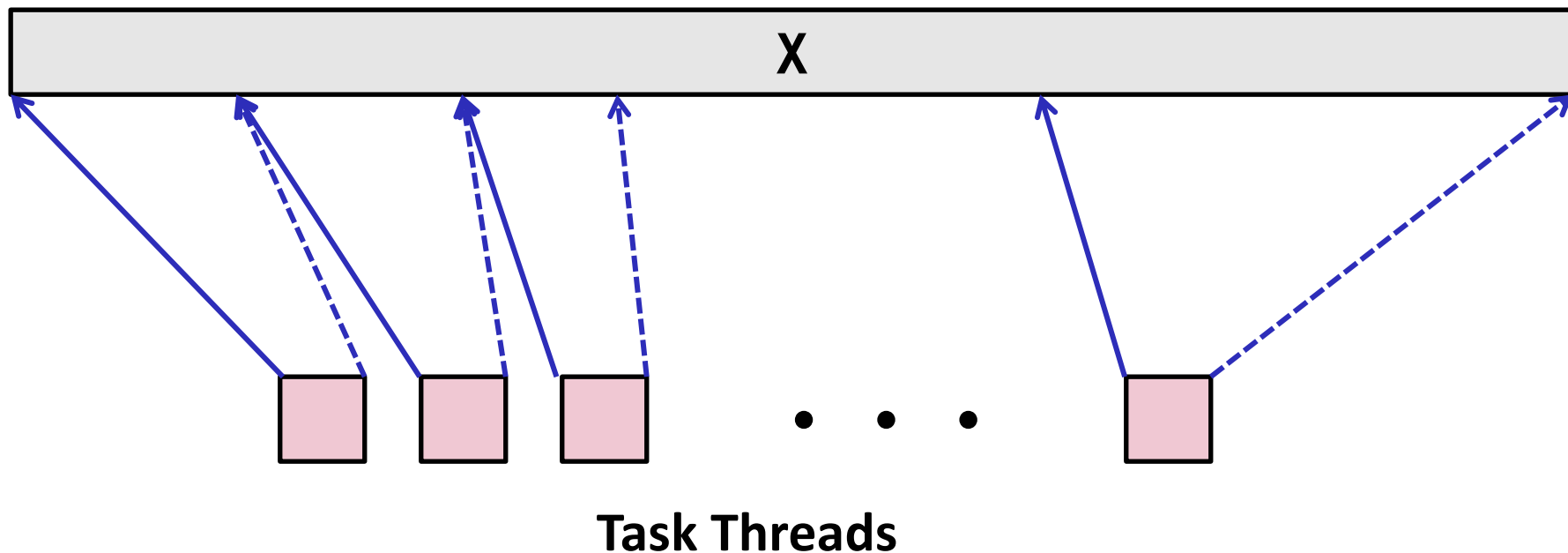
# Parallel Quicksort

- **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**

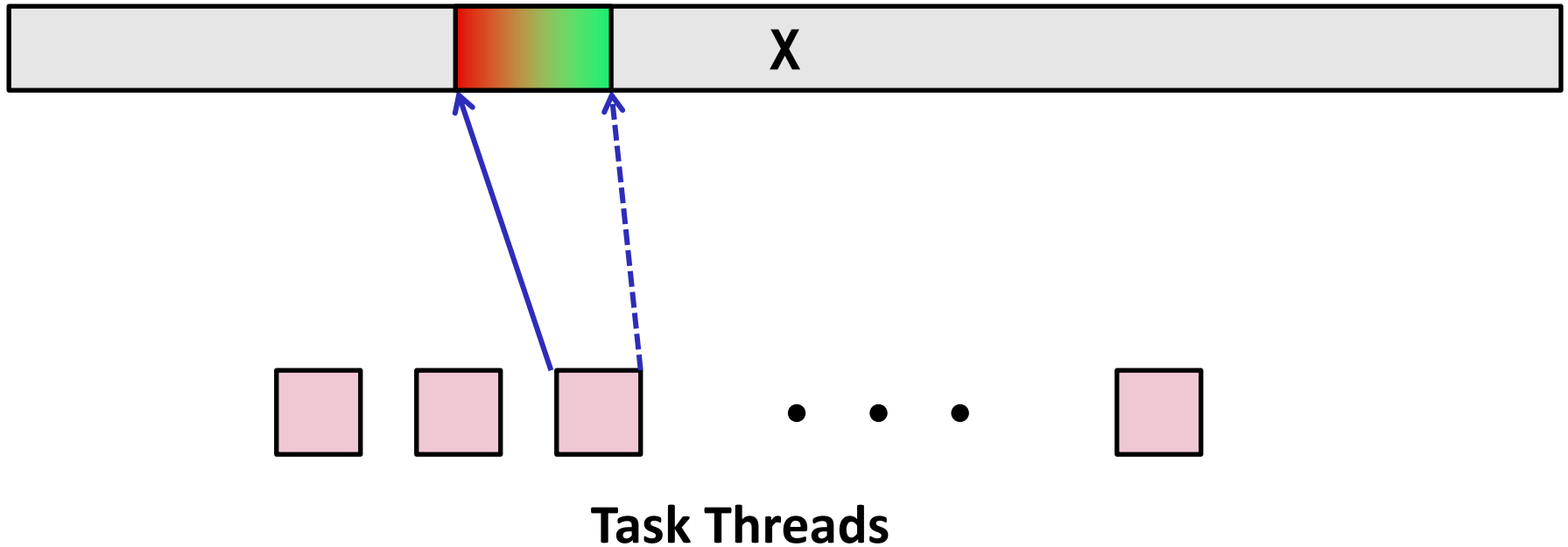
- Specify as:

- **base**: Starting address

- **ne1e**: Number of elements in subrange

- **Run as separate thread**

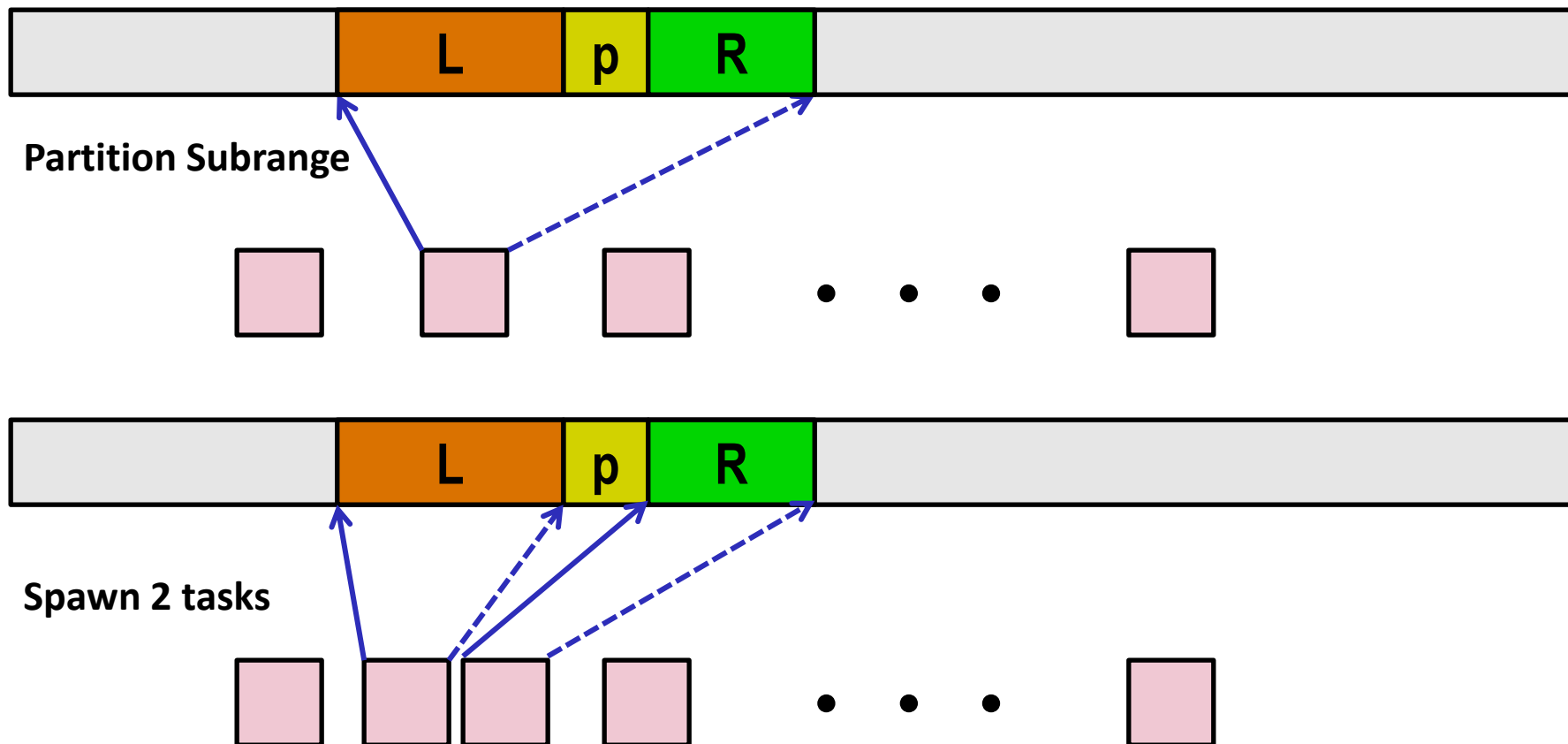
# Small Sort Task Operation



- Sort subrange using serial quicksort



# Large Sort Task Operation



# 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);
}
```

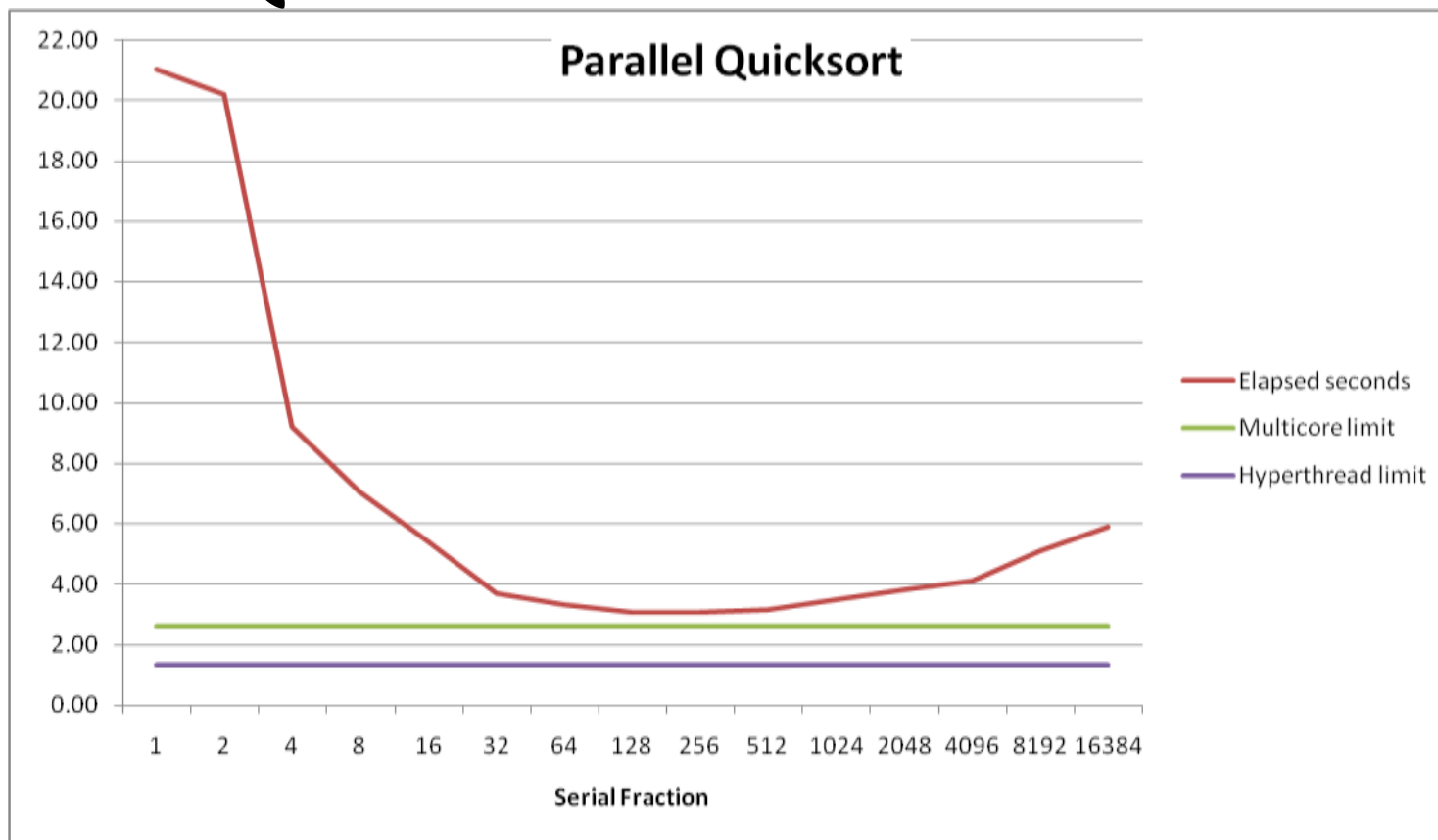
- Small partition: Sort serially
- Large partition: Spawn new sort task

# 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;
}
```

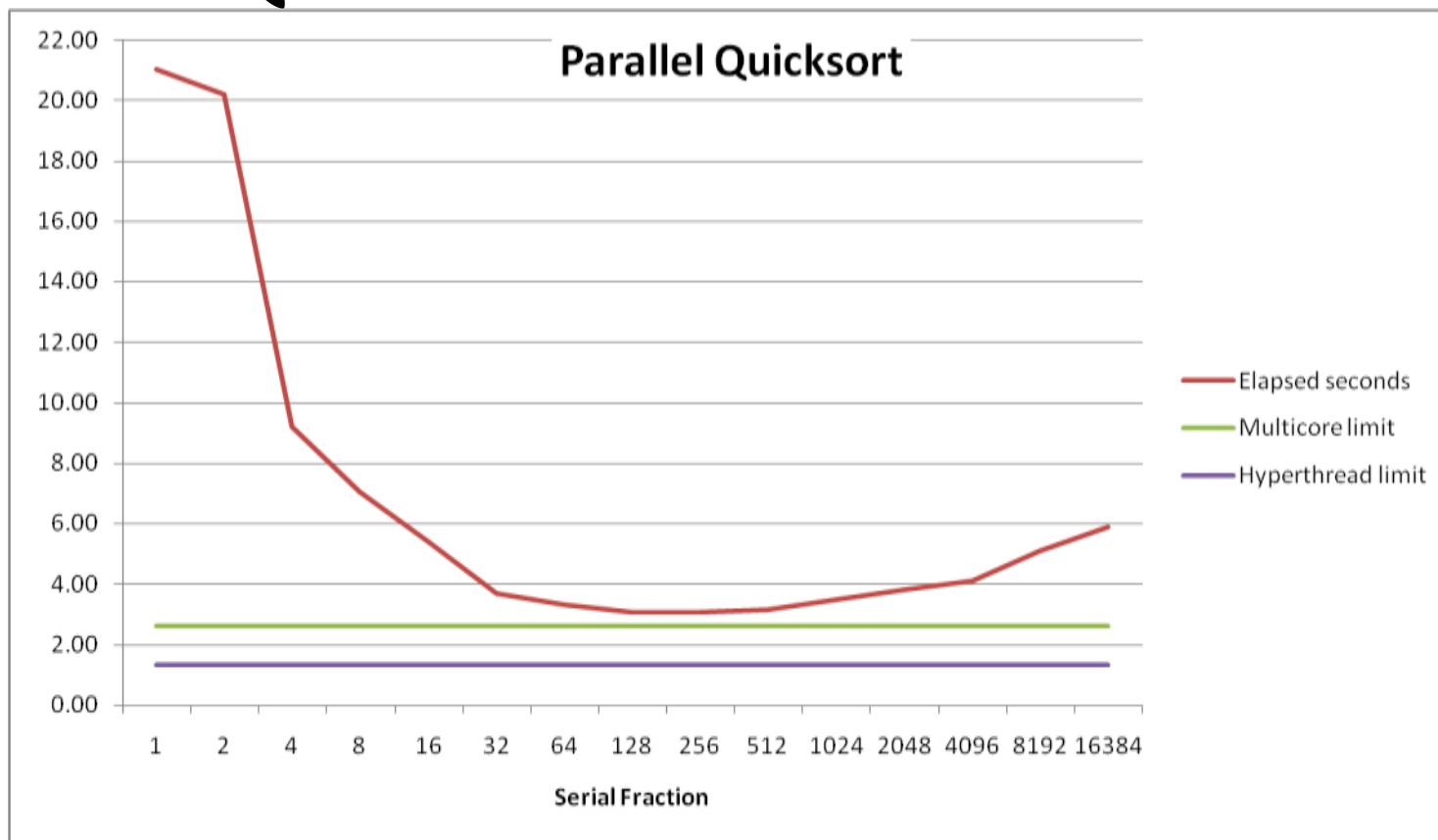
- Get task parameters
- Perform partitioning step
- Call recursive sort routine on each partition (if size of part > 1)

# 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:                                                               |            |          |
| ■ 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. |            |          |

# 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:                                                               |            |                  |
| ■ 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
- $k^{\text{th}}$  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

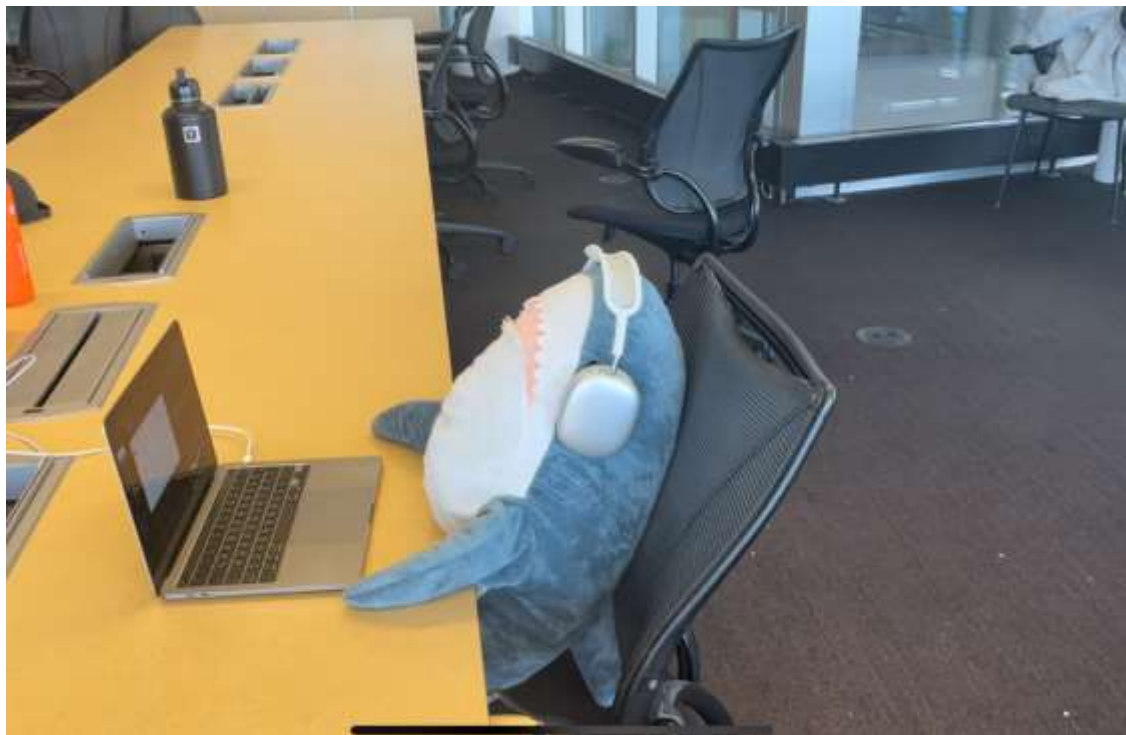
- **Must have parallelization strategy**
  - Partition into  $K$  independent parts
  - Divide-and-conquer
- **Inner loops must be synchronization free**
  - Synchronization operations very expensive
- **Watch out for hardware artifacts**
  - Need to understand processor & memory structure
  - Sharing 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

# Appendix: SFS Lab - Experimental

- Parallelism: Key idea in modern computing
  - Make the computer do more than one thing at the same time
  - Many tricky details
- Are we teaching it as effectively as we could be?
  - Shell lab, Proxy lab – some parallelism involved, but mostly *about* other things
- Course staff have been developing a new lab
  - It's not done, but we think we'd like to show it to you anyway
  - [?] Only for 213 students (to keep things small scale)

# Shark File System

- Requin wants somewhere to store all of his files!
- ...so, he wrote a file system.
- Problem: He has multiple programs, all sharing the file system
- How can he make sure that his file system is *safe/correct*?
- How can he make it *faster*?
- Multithreading!



Requin hard at work.

# SFS Lab

- Make Requin's file system concurrent
  - Able to handle concurrent accesses safely
  - ->able to look at separate files simultaneously
  - -> further concurrency improvements?
- Lab handout will be available via Autolab and GitHub Classroom
  - The same way you have done all labs since cache
- NOT FOR CREDIT (Just for fun)
  - We will not judge you if you turn in something incomplete
  - We appreciate any and all submissions!
  - Might be good practice for the exam...
- More detail on Tuesday