Thread-Level Parallelism

15-213 / 18-213: Introduction to Computer Systems
26th Lecture, April 21, 2015

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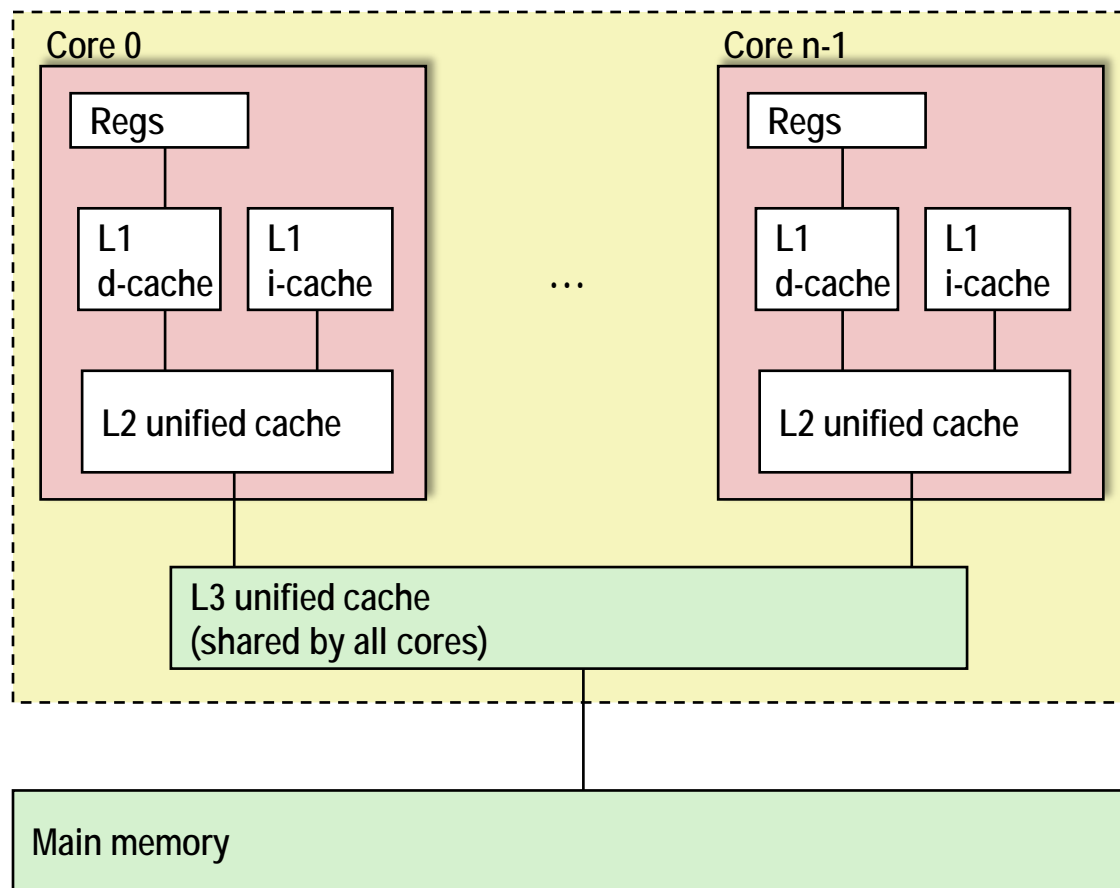
Today

- **Parallel Computing Hardware**
  - Multicore
    - Multiple separate processors on single chip
    - How they maintain consistent view of memory
  - Hyperthreading
    - Efficient execution of multiple threads on single core
- **Thread-Level Parallelism**
  - Splitting program into independent tasks
    - Example: Parallel summation
    - Some performance artifacts
  - Divide-and conquer parallelism
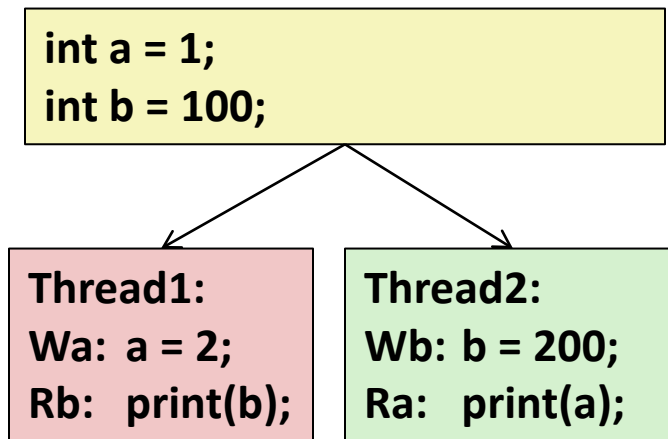   - Example: Parallel quicksort

Multicore Processor

Core 0 ... Core n-1

Regs | L1 d-cache | L1 i-cache | L2 unified cache

L3 unified cache (shared by all cores)

Main memory

- **Intel Nehalem Processor**
  - E.g., Shark machines (8 cores / machine)
  - Multiple processors operating with coherent view of memory

Memory Consistency

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

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

```
Thread2:
Wb: b = 200;
Ra:   print(a);
```
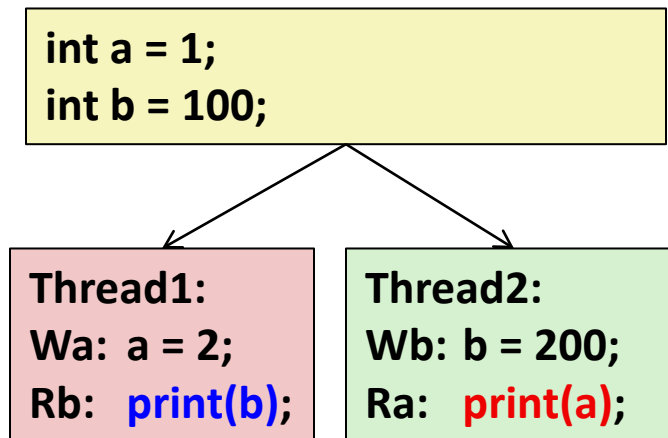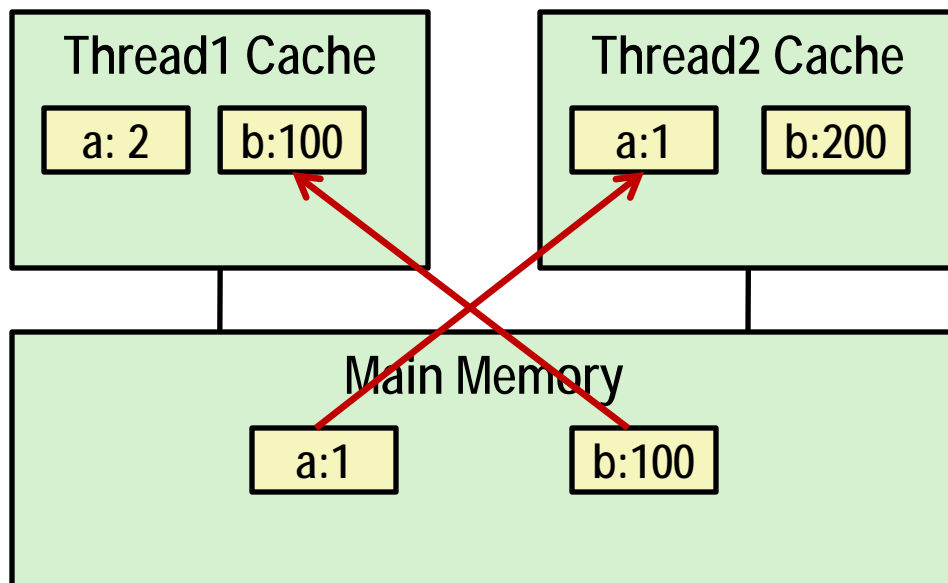
- **What are the possible values printed?**
  - Depends on memory consistency model
  - Abstract model of how hardware handles concurrent accesses
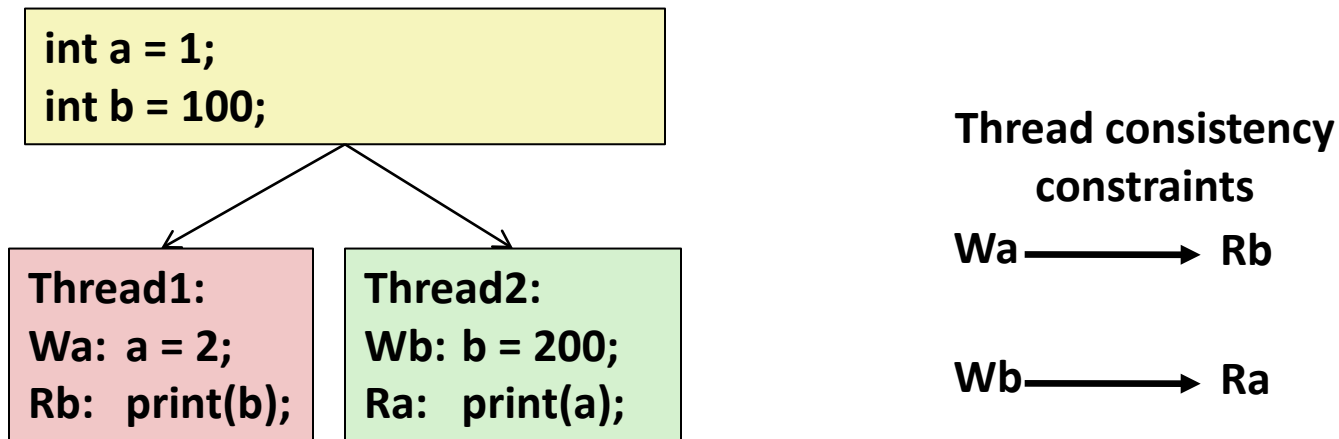
Non-Coherent Cache Scenario

- **Write-back caches, without coordination between them**

```
int a = 1;
int b = 100;
```
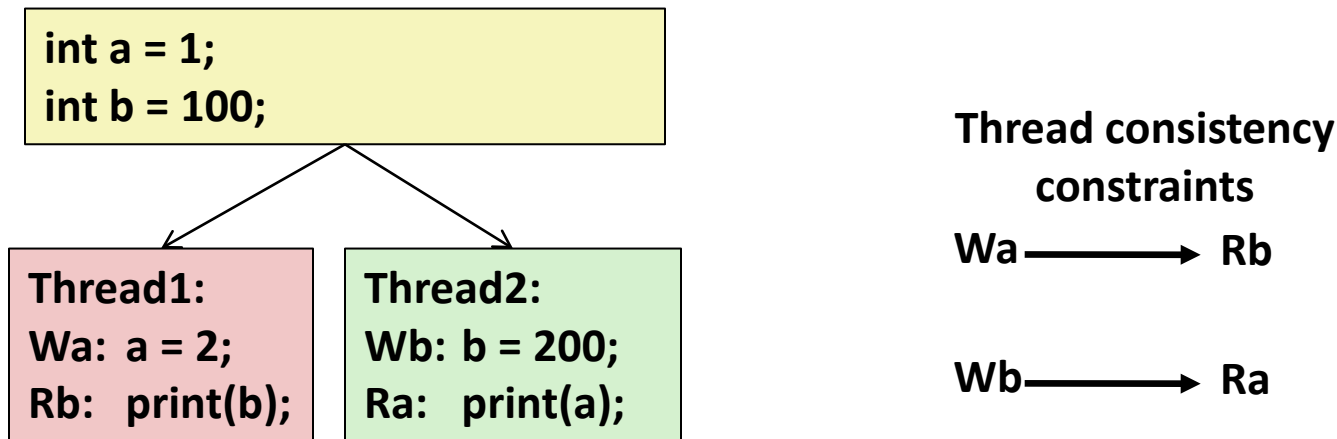
Thread1:
Wa: a = 2;
Rb: print(b);

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

Thread1 Cache

| a: 2 | b:100 |

Thread2 Cache

| a:1 | b:200 |

Main Memory

| a:1 | b:100 |

print 1

print 100

Memory Consistency

```
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

■ **What are the possible values printed?**

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

Memory Consistency

```
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

- **What are the possible values printed?**
  - Depends on memory consistency model
  - Abstract model of how hardware handles concurrent accesses
- **Sequential consistency**
  - Overall effect consistent with each individual thread
  - Otherwise, arbitrary interleaving

Sequential Consistency Example
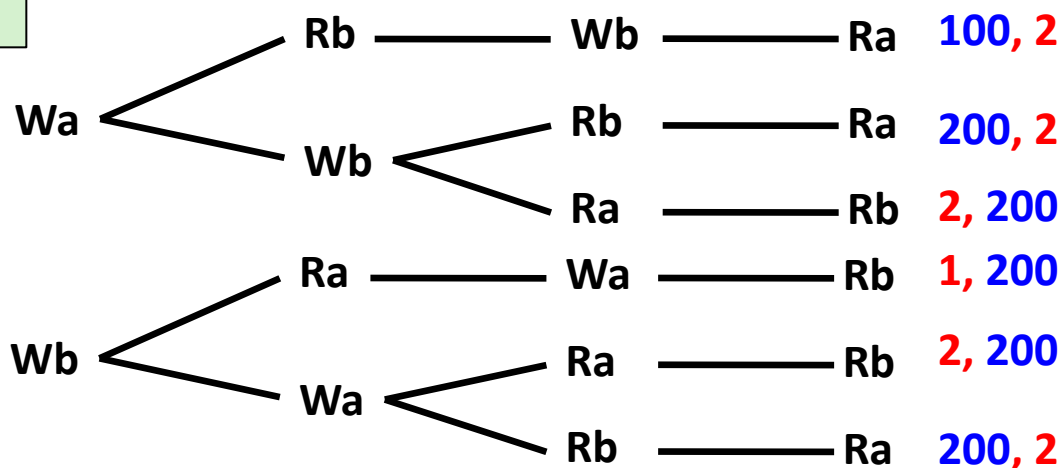
```
int a = 1;
int b = 100;
```

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

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

Thread consistency constraints

Wa ———————— Rb

Wb ———————— Ra

Wa
- Rb ———— Wb ———— Ra   **100, 2**
- Wb
  - Rb ———— Ra   **200, 2**
  - Ra ———— Rb   **2, 200**

Wb
- Ra ———— Wa ———— Rb   **1, 200**
- Wa
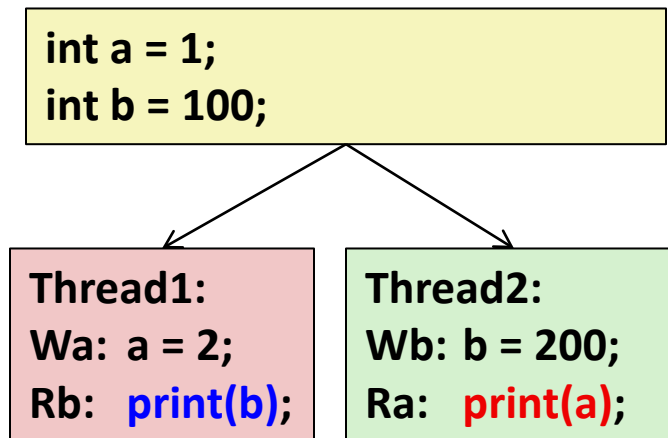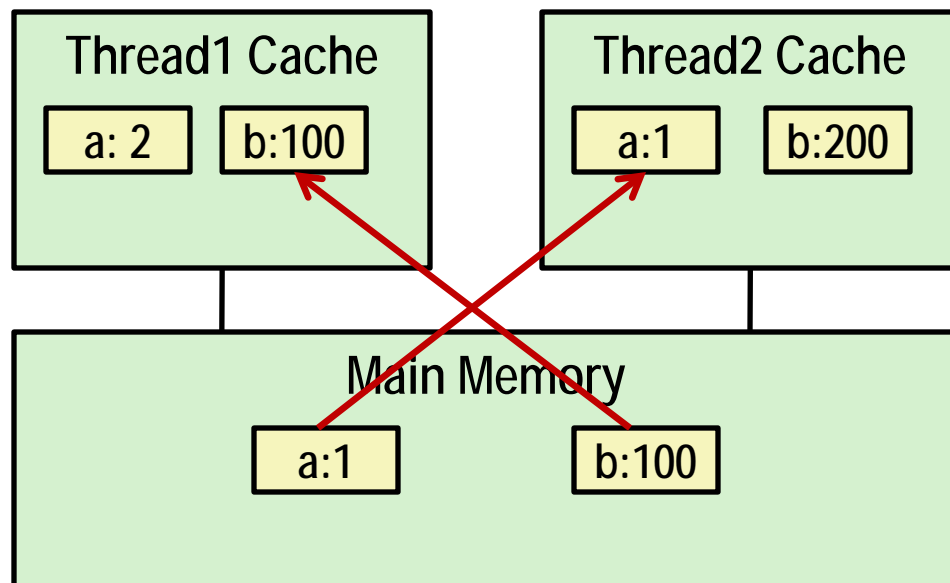 - Ra ———— Rb   **2, 200**
  - Rb ———— Ra   **200, 2**

- **Impossible outputs**
  - 100, 1 and 1, 100
  - Would require reaching both Ra and Rb before Wa and 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);

Thread1 Cache

a: 2   b:100

Thread2 Cache

a:1   b:200

Main Memory

a:1   b:100

print 1

print 100

Snoopy Caches

- **Tag each cache block with state**

  Invalid   Cannot use value

  Shared   Readable copy

  Exclusive   Writeable copy

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

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

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

Thread1 Cache

| E | a: 2 |

Thread2 Cache

| E | b:200 |

Main Memory

| a:1 | | b:100 |

10

Snoopy Caches

- **Tag each cache block with state**

  Invalid   Cannot use value

  Shared   Readable copy

  Exclusive   Writeable copy

```
int a = 1;
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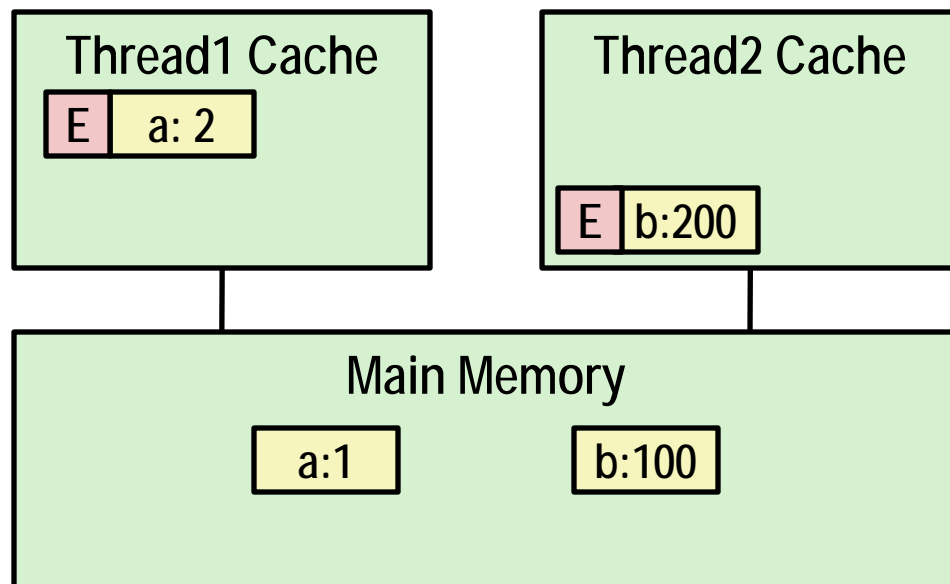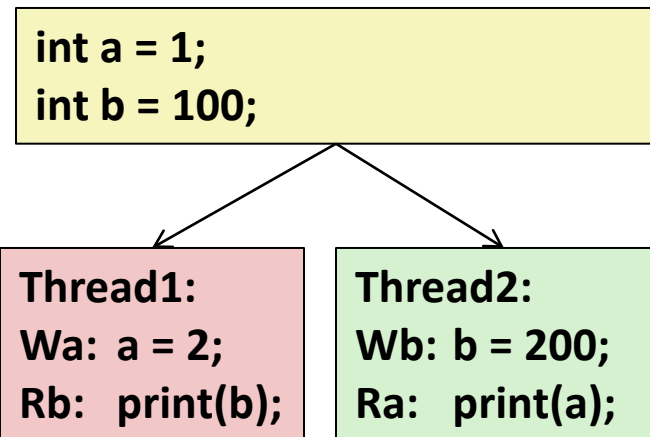
Thread1:
Wa: a = 2;
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Thread2:
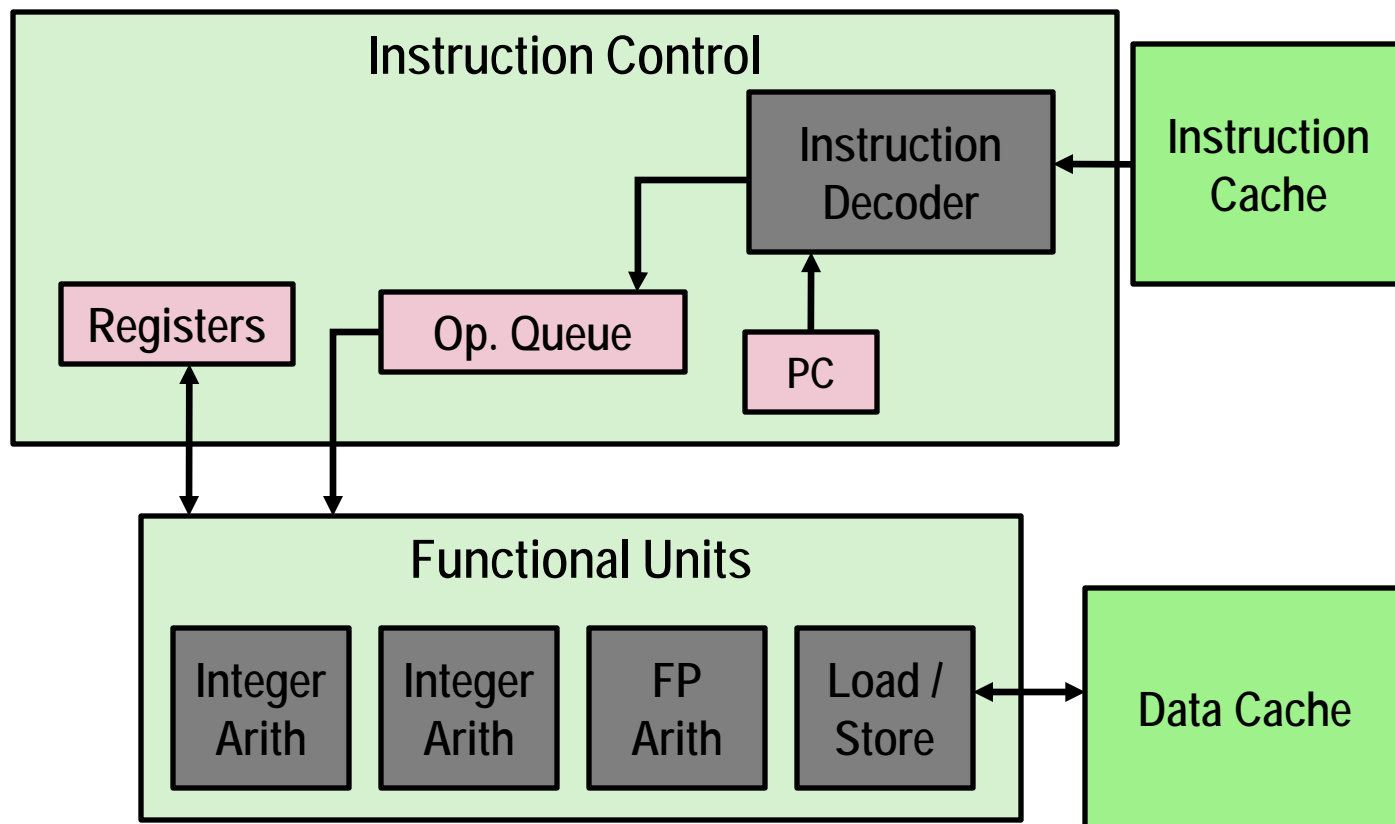**Wb: b = 200;**
Ra: print(a);
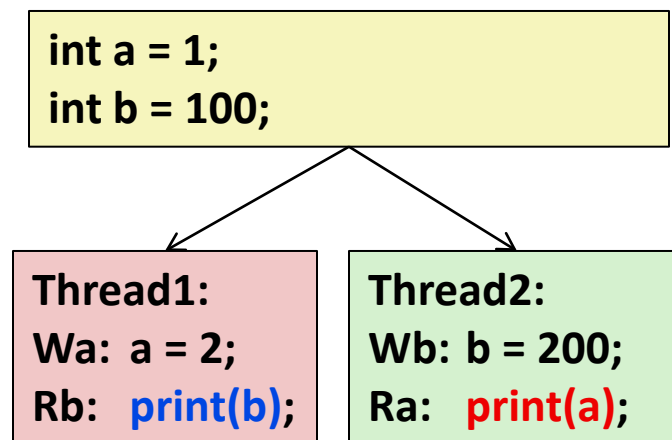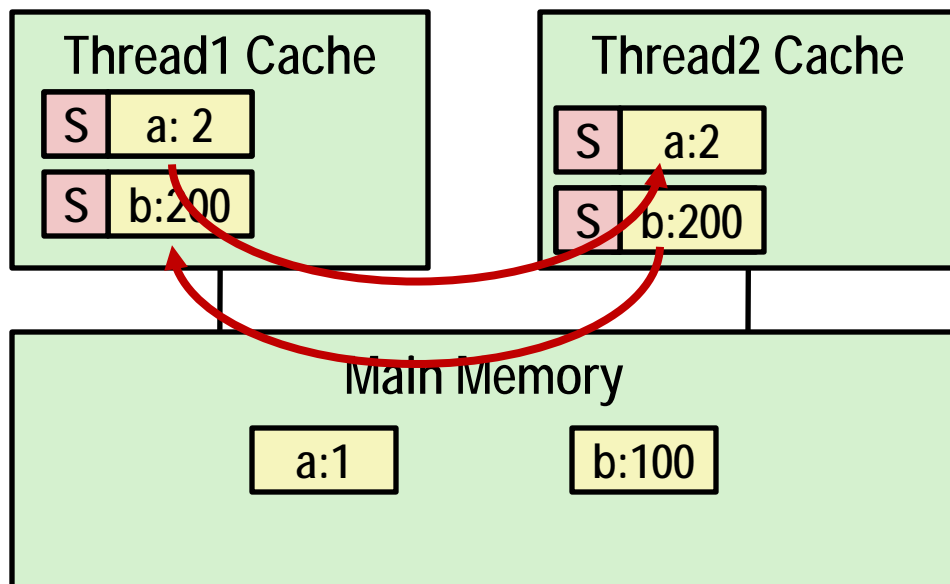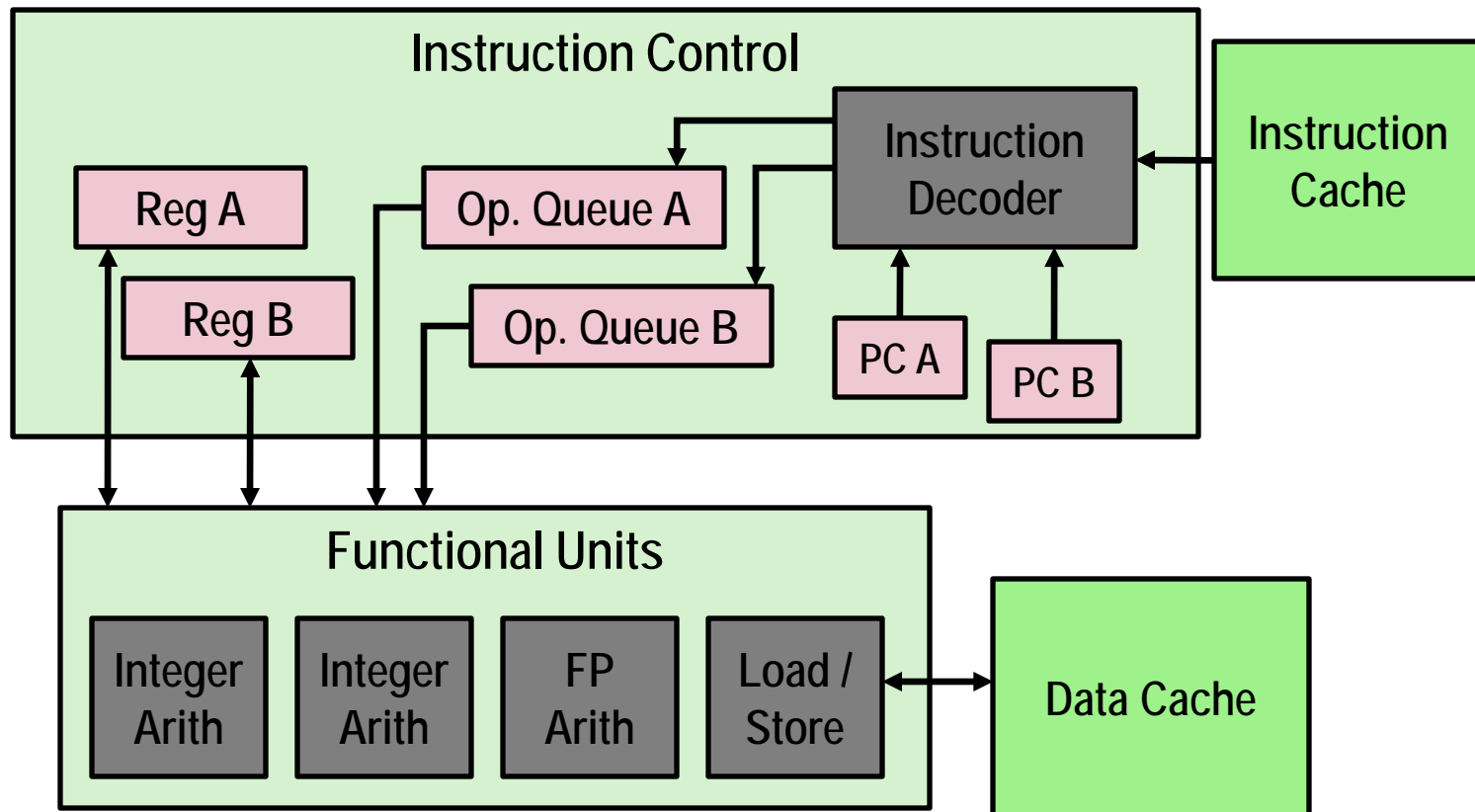

print 2

print 200

- When cache sees request for one of its E-tagged blocks
    - Supply value from cache
    - Set tag to S

Hyperthreading: 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 enough instruction control to process K instruction streams**
- **K copies of all registers**
- **Share functional units**

Some Machines

- **Shark Machines**
    - Intel Nehalem processors
    - 8 cores, each with 2-way hyperthreading
    - 2.2 GHz clock rate

- **GHC Cluster Machines**
    - Intel Westmere processors
    - 6 cores, each with 2-way hypertheading
    - 3.2 GHz clock rate

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

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
  - 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;
```
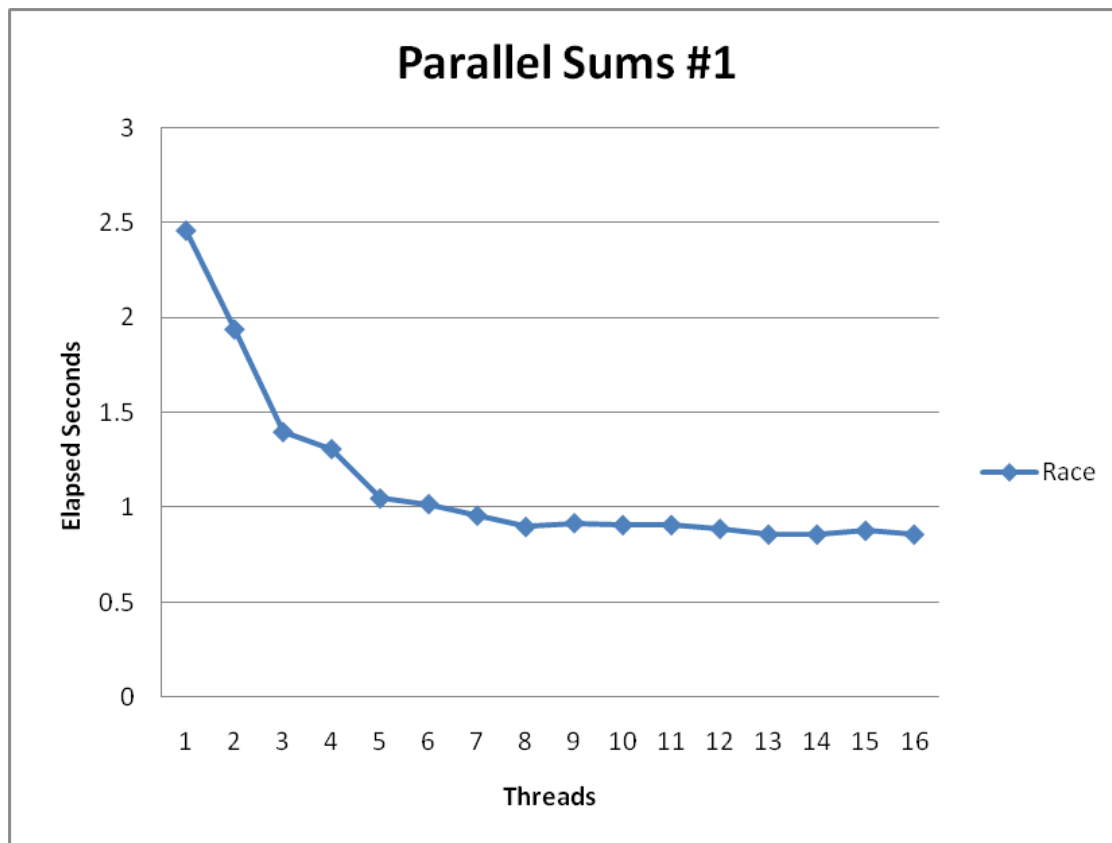
Thread Function: No Synchronization

```
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!**

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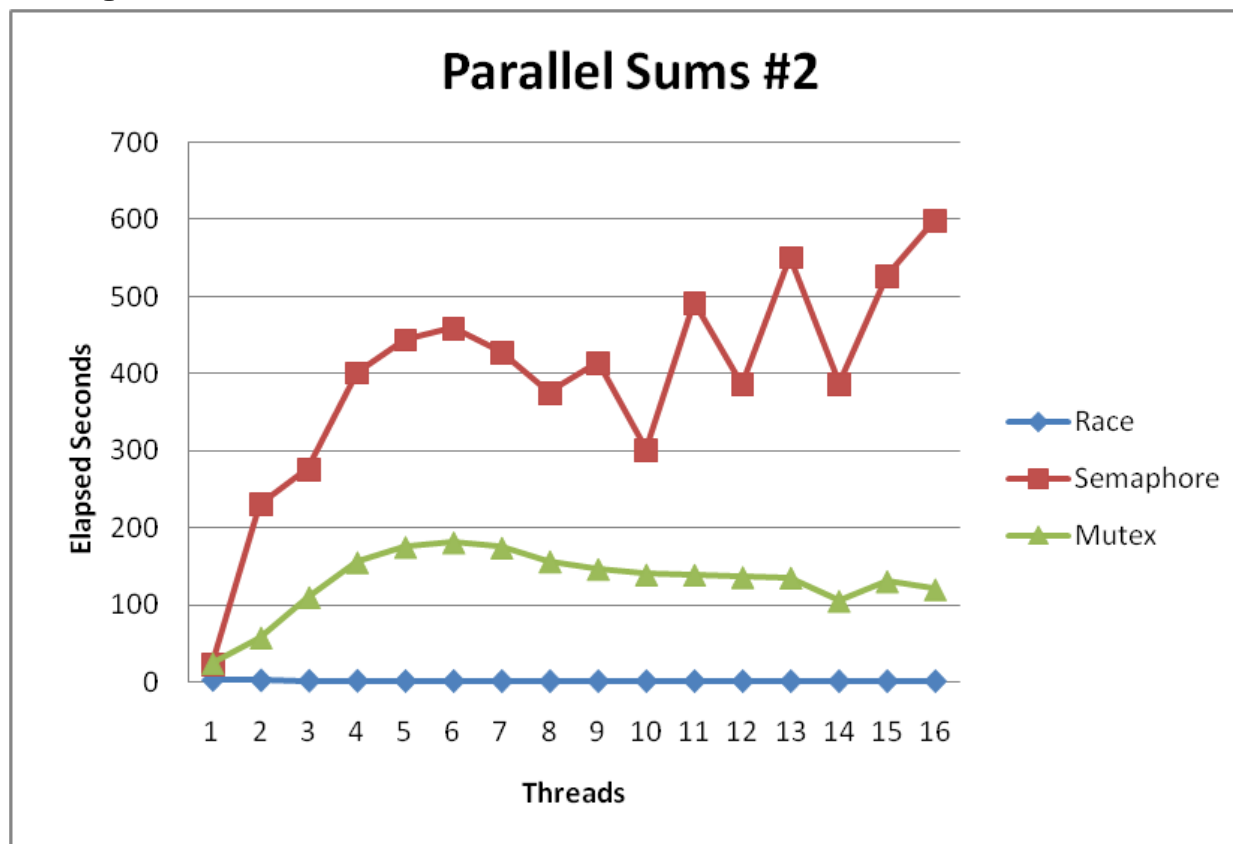
- **Terrible Performance**
  - 2.5 seconds ➔ ~10 minutes
- **Mutex 3X faster than semaphore**
- **Clearly, neither is successful**

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;
```
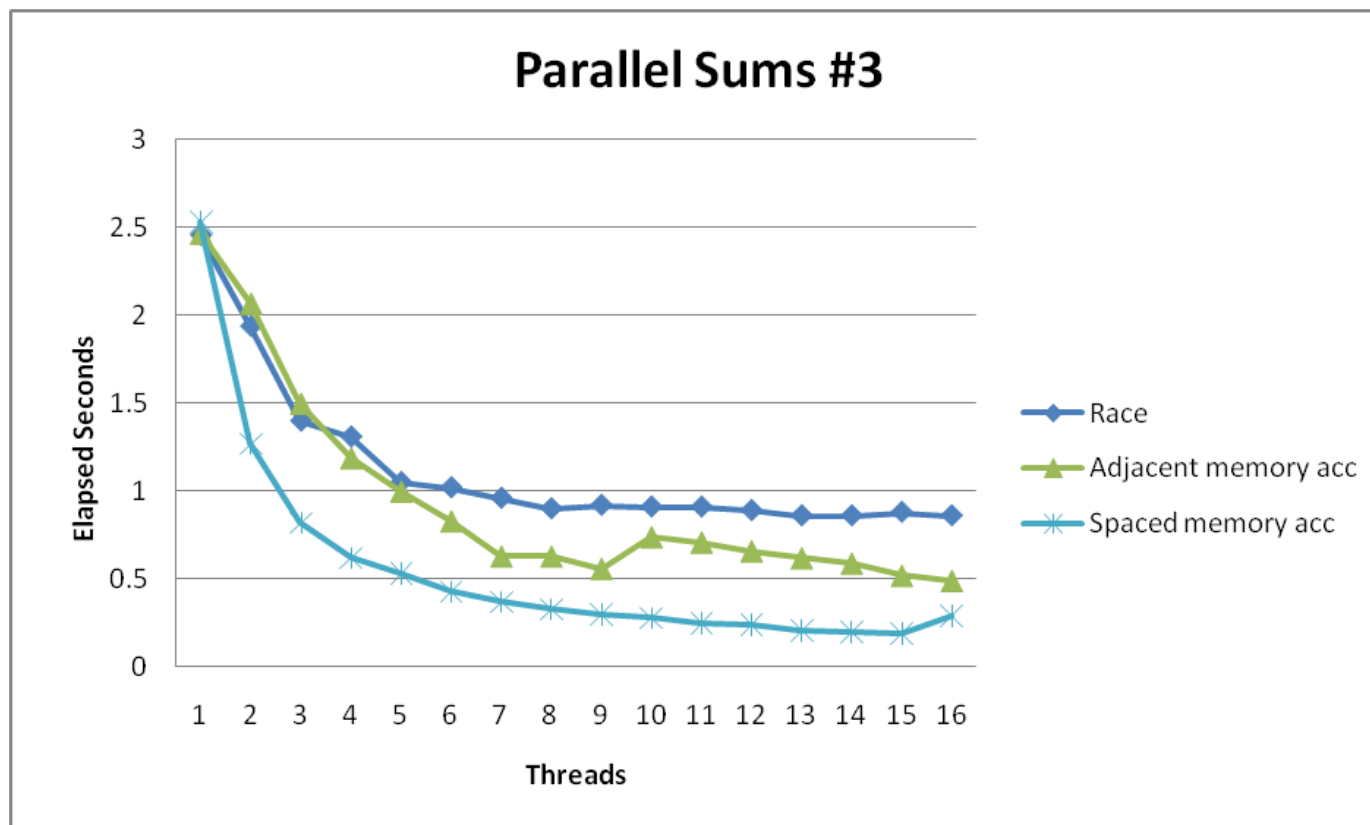
Thread Function: Memory Accumulation

```
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;
}
```
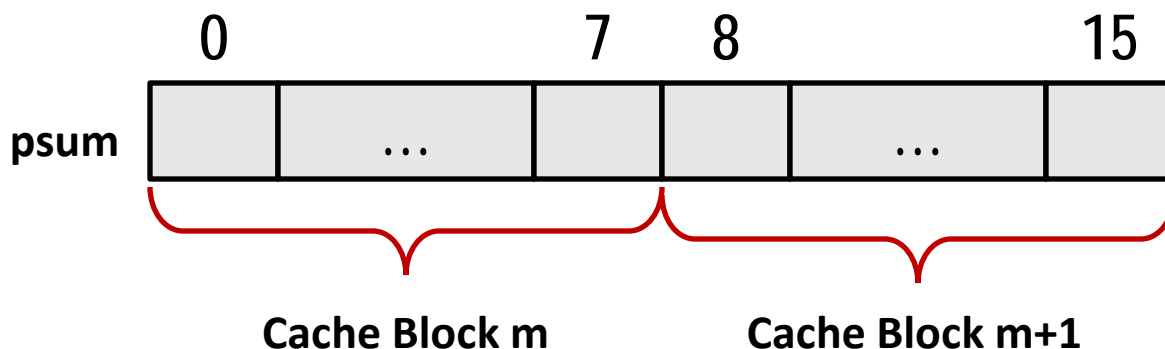
Memory Accumulation Performance

Parallel Sums #3

- **Clear threading advantage**
  - Adjacent speedup: 5 X
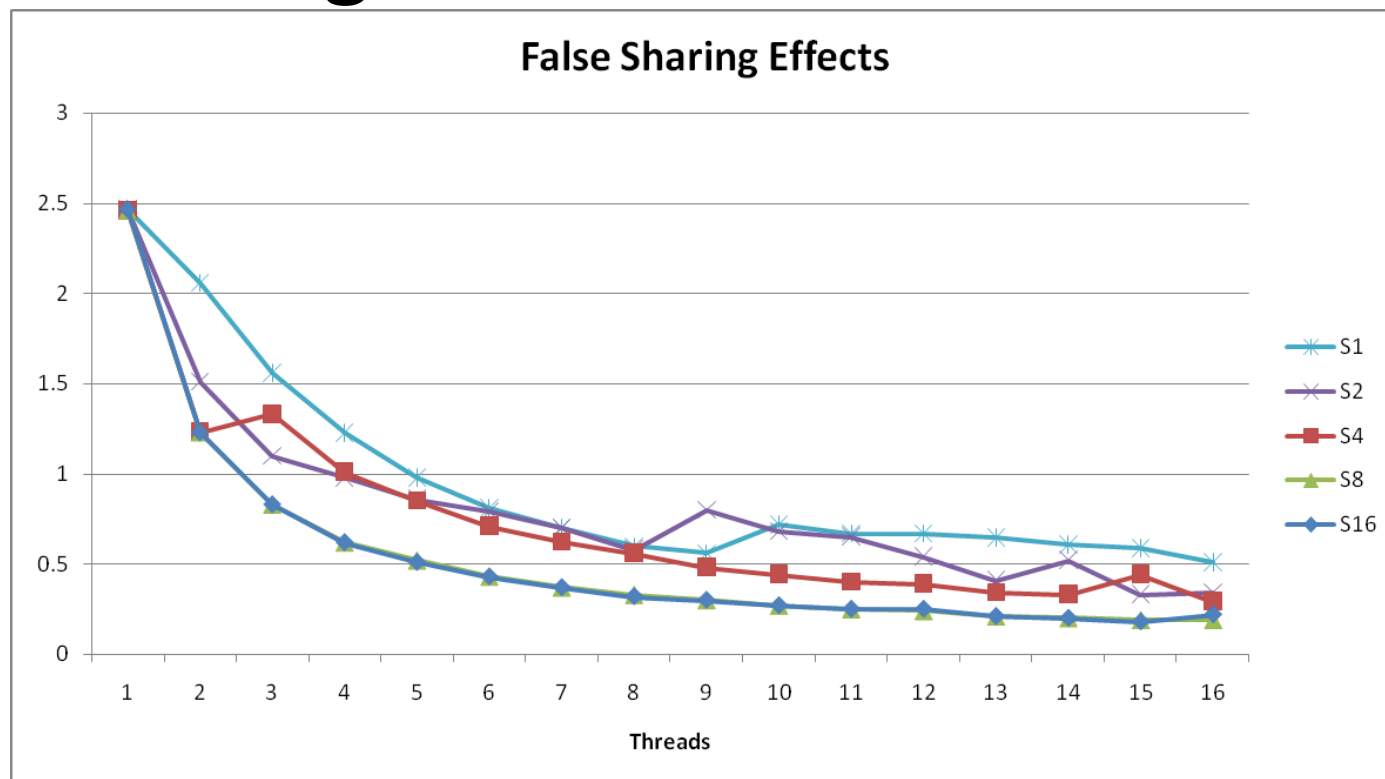 - Spaced-apart speedup: 13.3 X (Only observed speedup > 8)
- **Why does spacing the accumulators apart matter?**

False Sharing

- **Coherency 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


False Sharing Effects

- 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

Parallel Sums #4
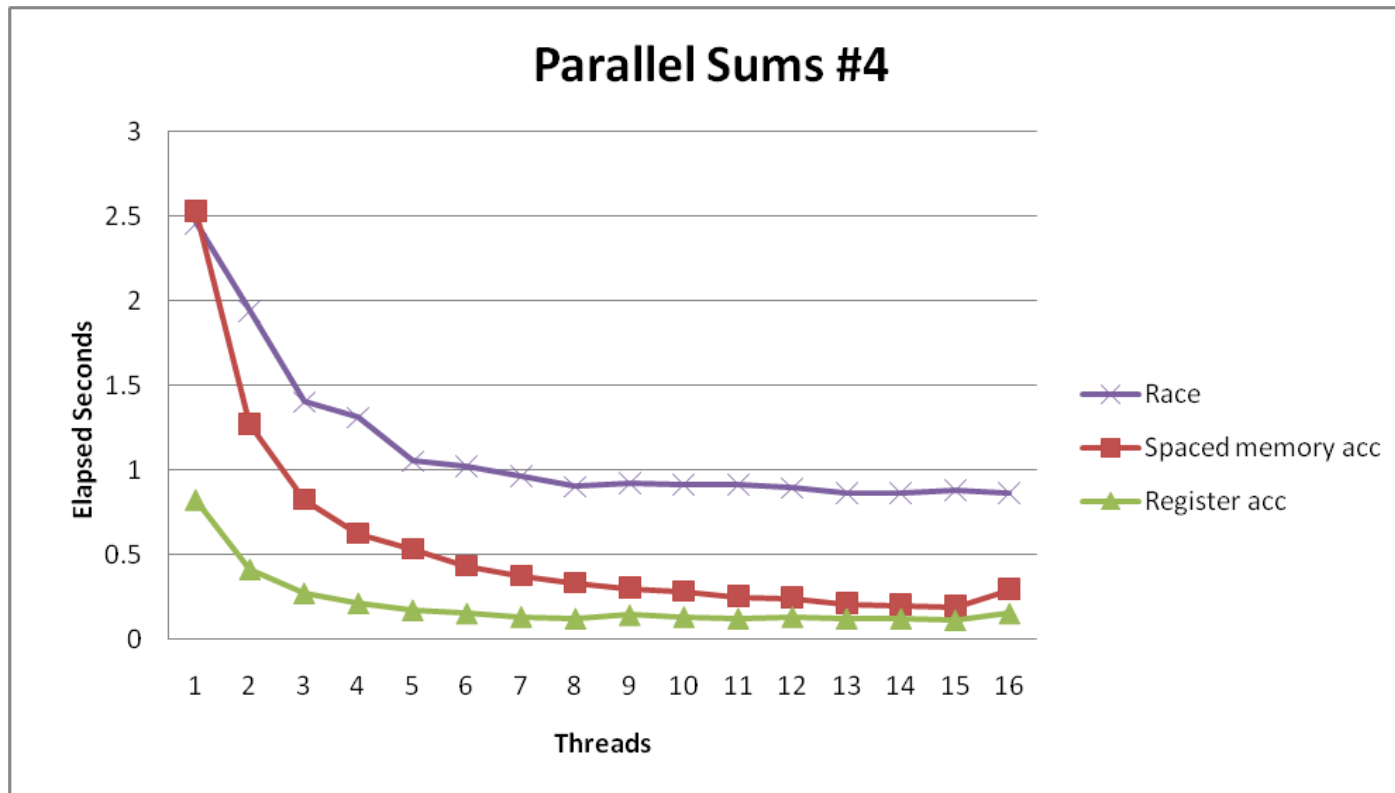
- ■ **Clear threading advantage**
  - ▪ Speedup = 7.5 X
- ■ **2X better than fastest memory accumulation**

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**

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
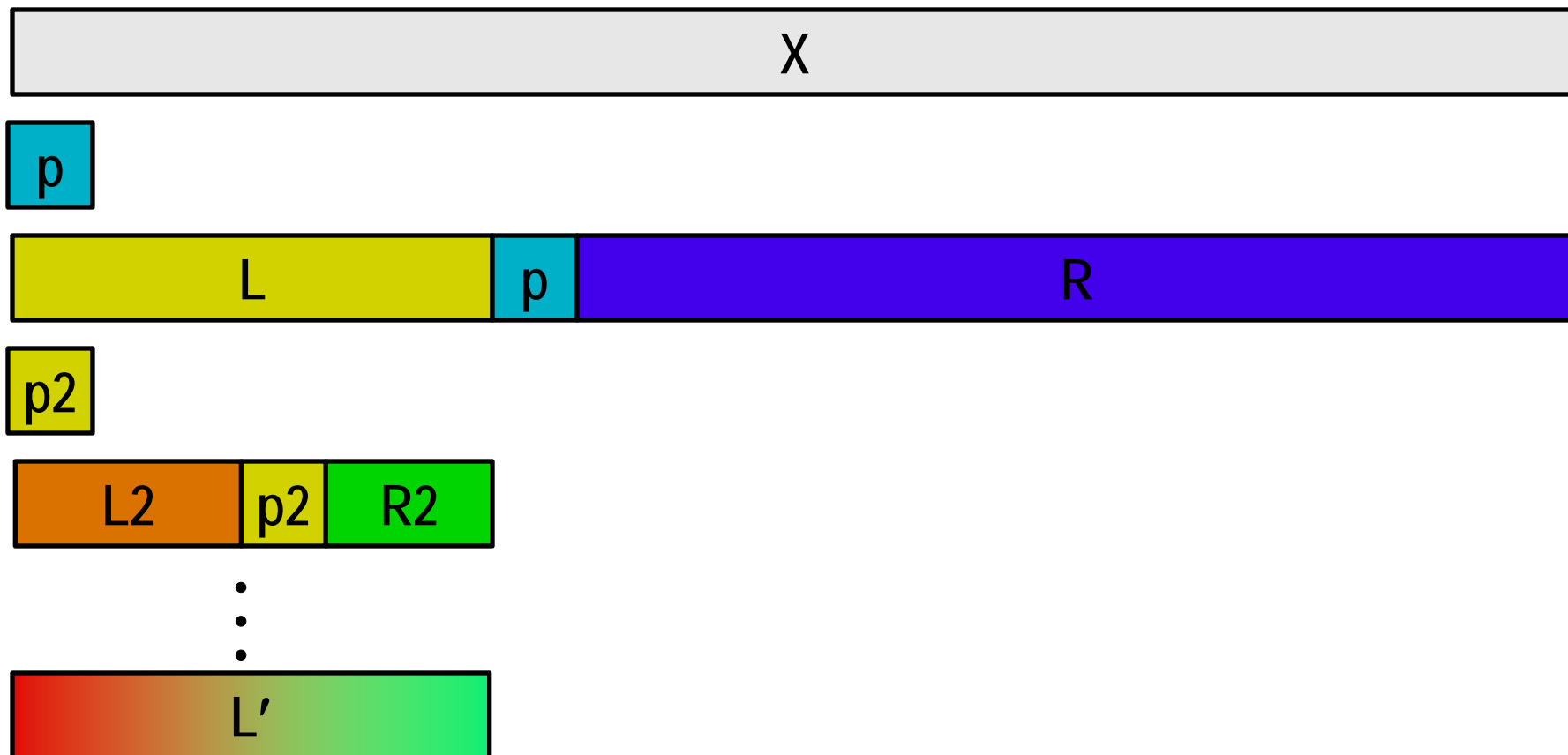
Sequential Quicksort Visualized
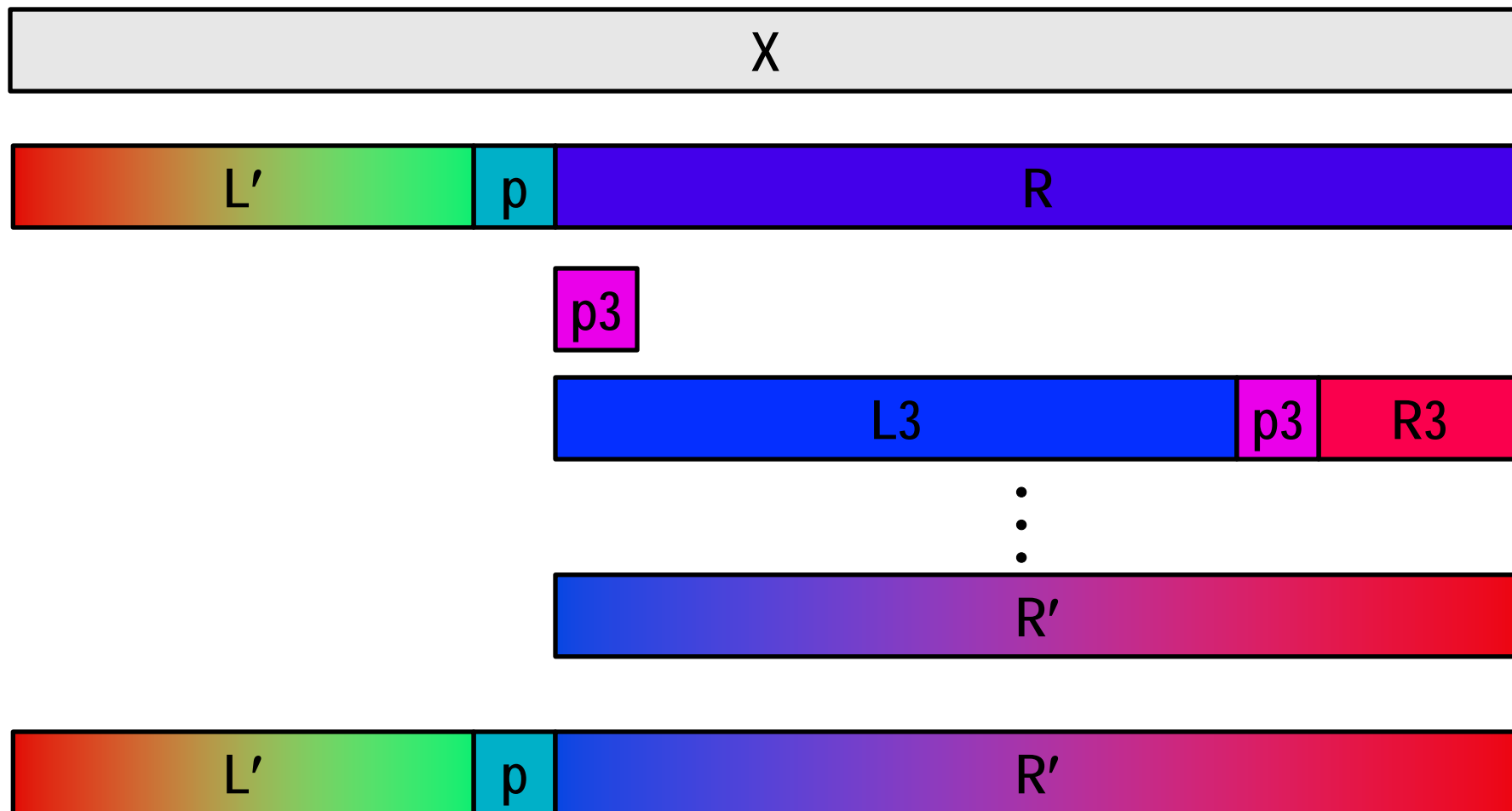
Sequential Quicksort Code

```
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);
}
```
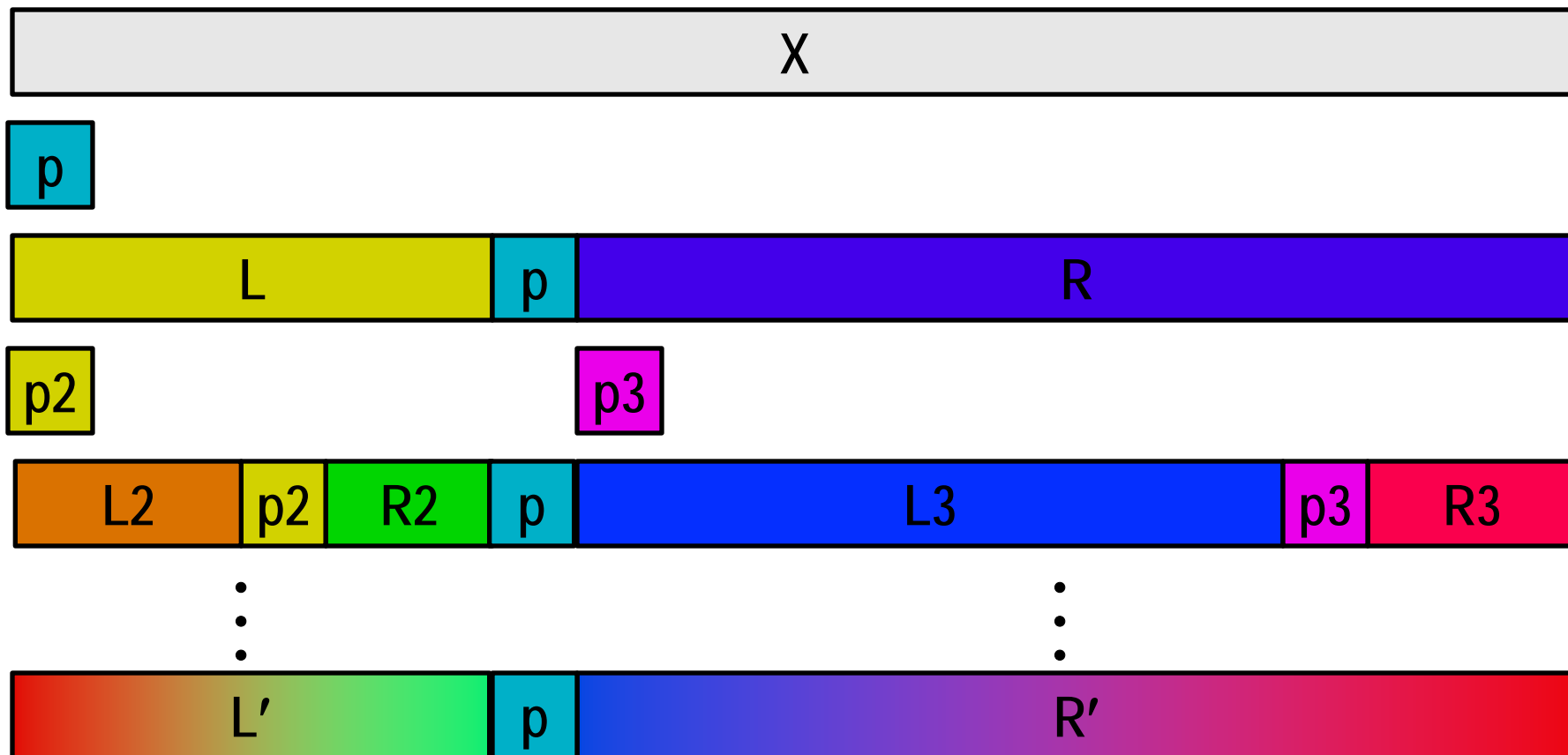
- **Sort nele elements starting at base**
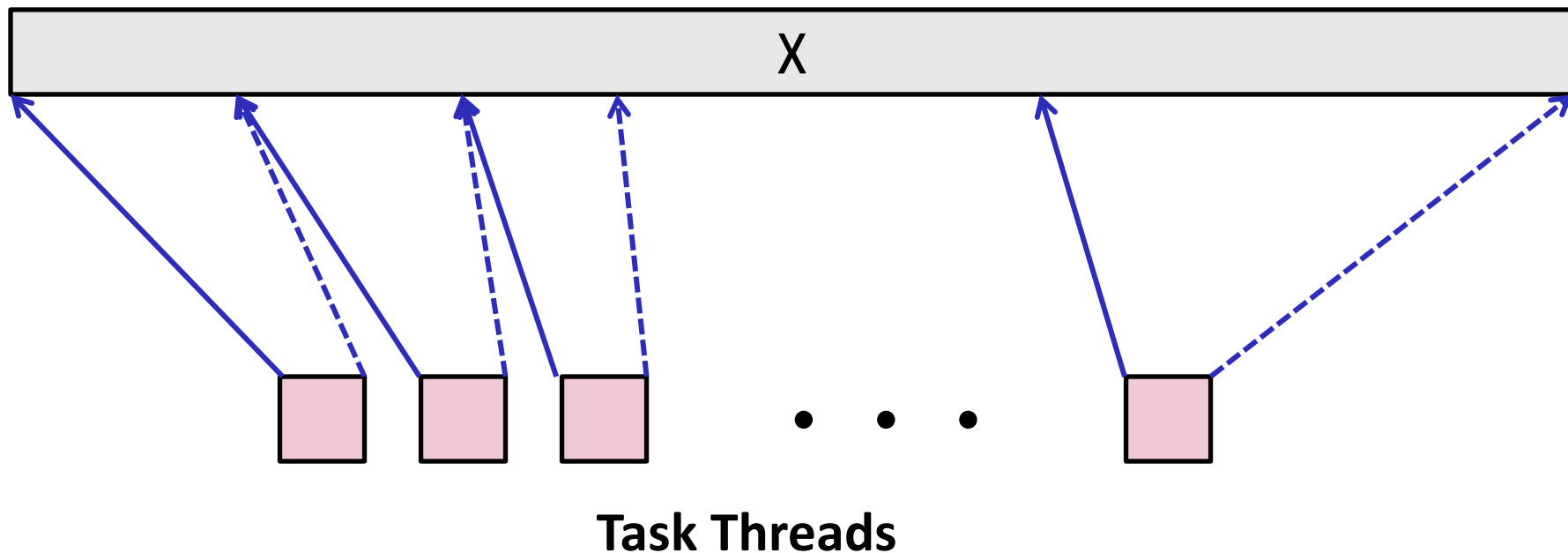 - Recursively sort L or R if has more than one element

Parallel Quicksort

- **Parallel quicksort of set of values X**
  - If $N \leq$ Nthresh, 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'

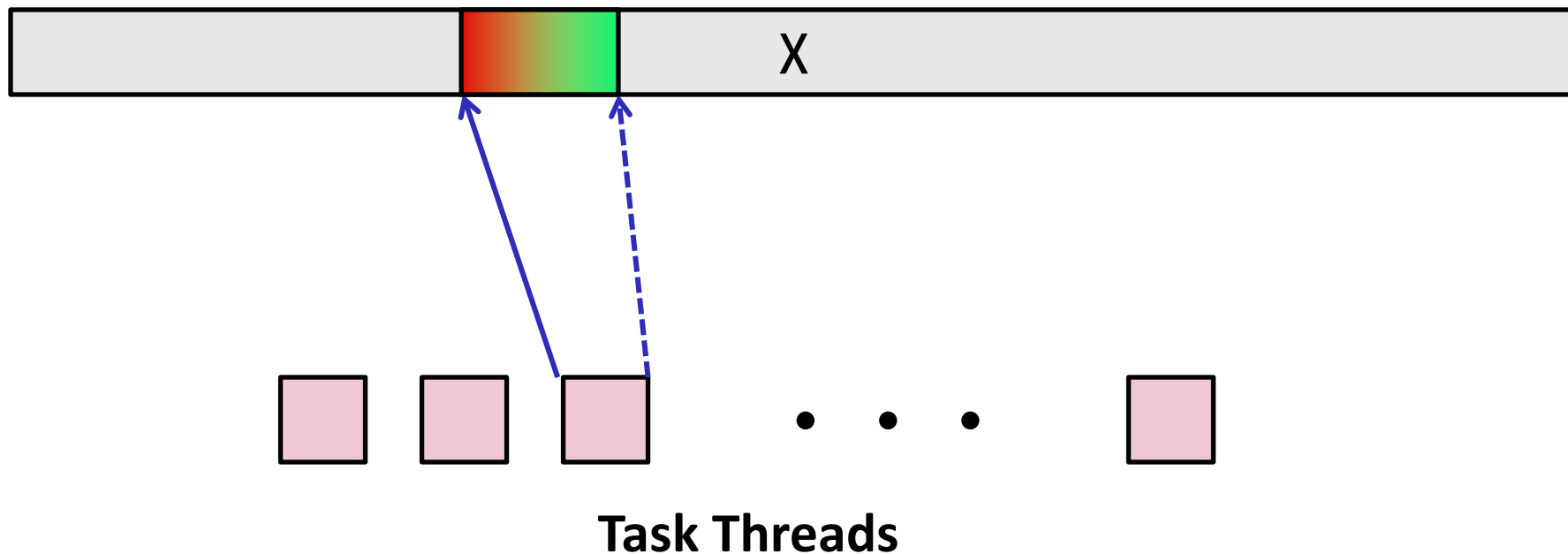# Parallel Quicksort Visualized

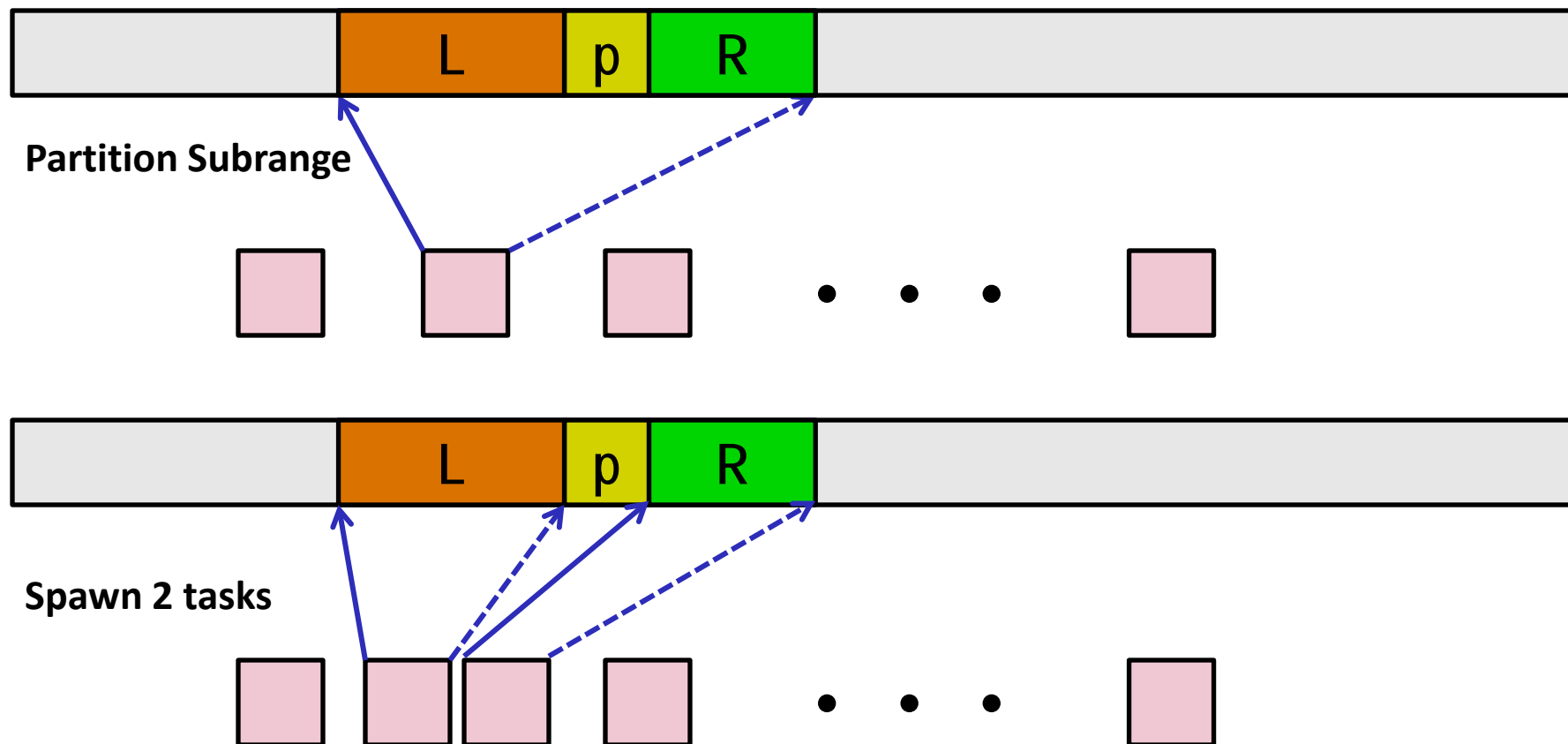# Thread Structure: Sorting Tasks

Task Threads

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

Small Sort Task Operation

Task Threads

■ **Sort subrange using serial quicksort**

Large Sort Task Operation

Partition Subrange

Spawn 2 tasks

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;
}
```
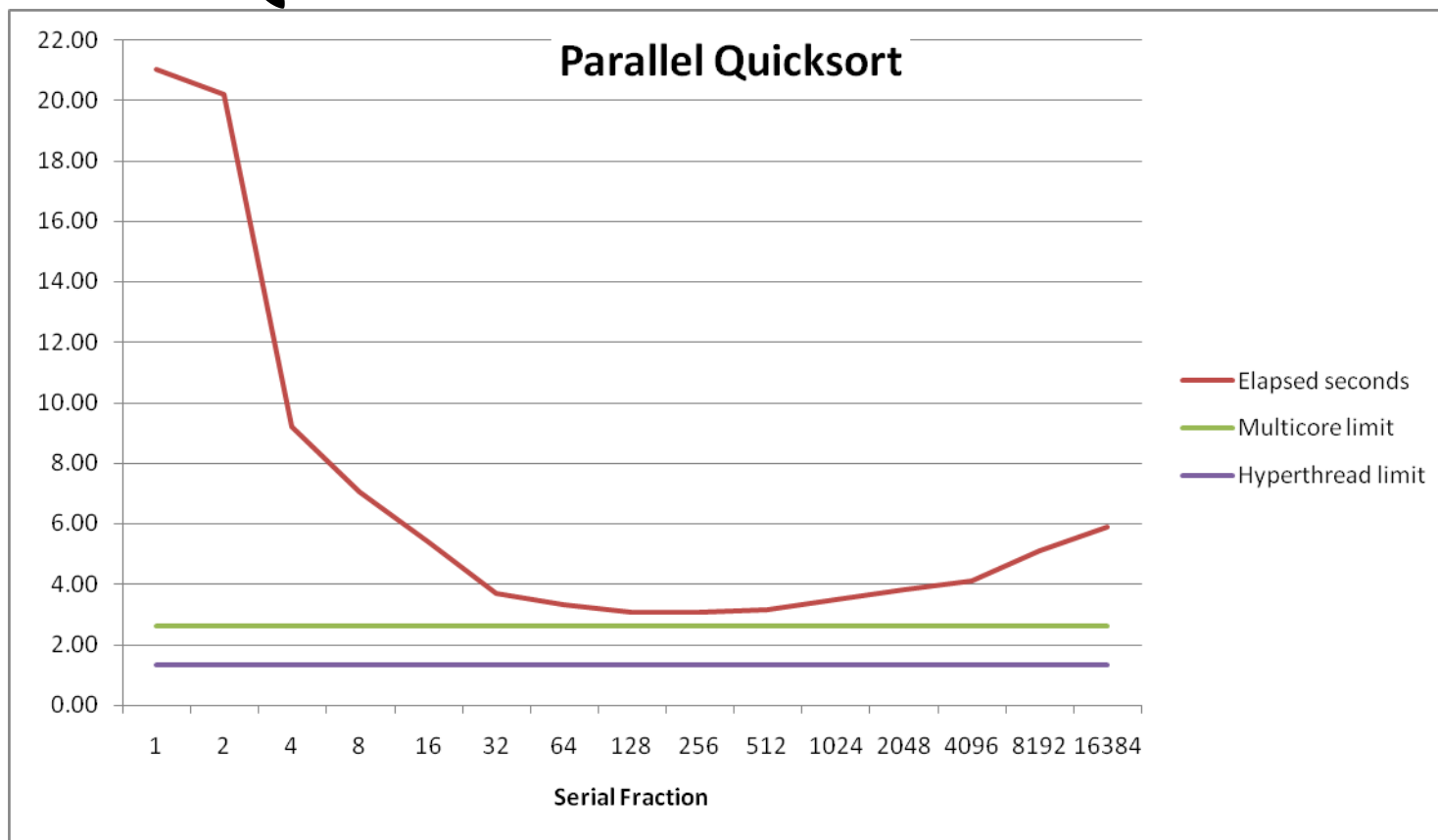
- **Get task parameters**
- **Perform partitioning step**
- **Call recursive sort routine on each partition**

Parallel Quicksort Performance
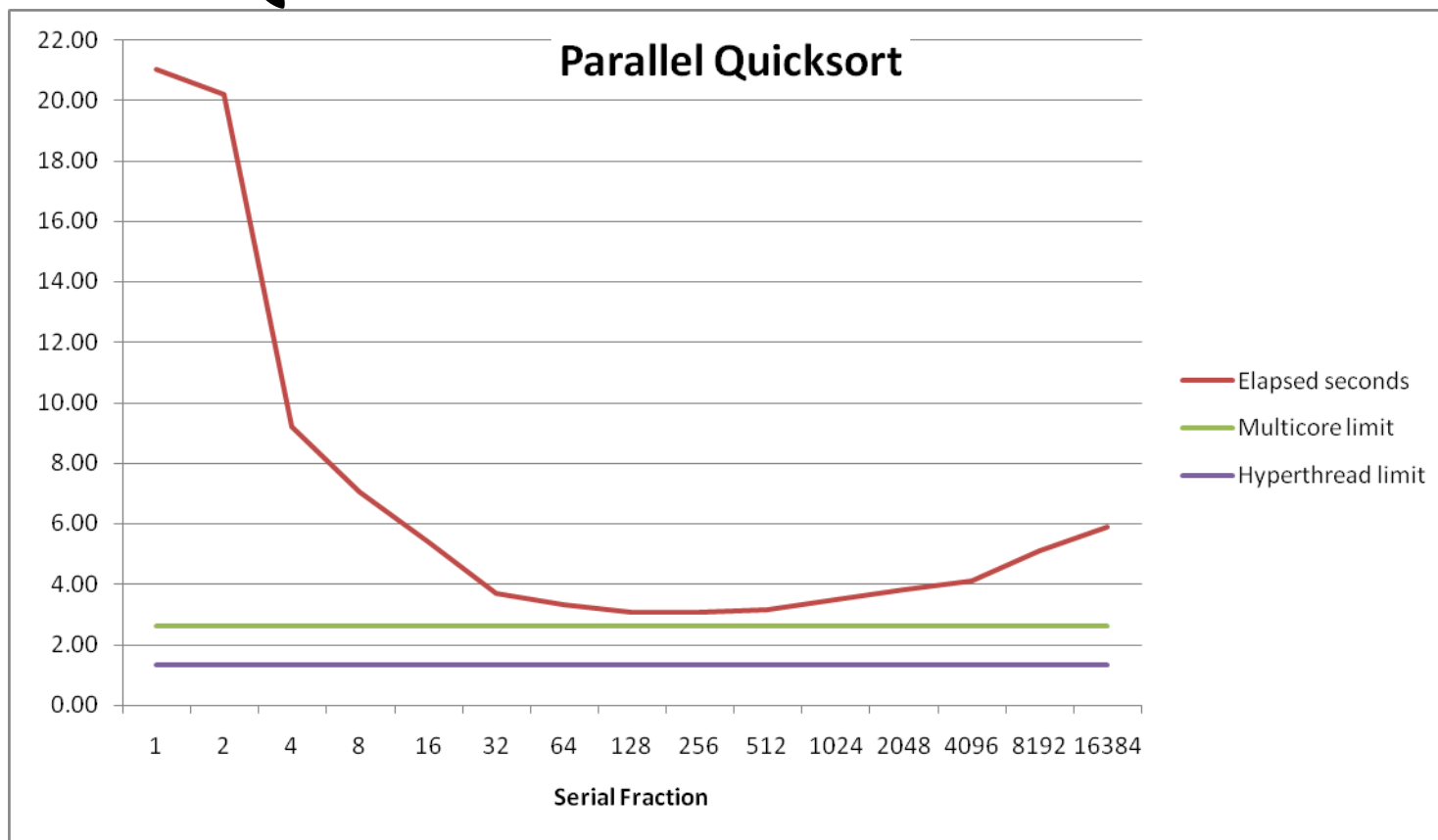
- **Serial fraction: Fraction of input at which do serial sort**
- **Sort 2^{37} (134,217,728) random values**
- **Best speedup = 6.84X**

Parallel Quicksort Performance

- ■ **Good performance over wide range of fraction values**
  - ▪ F too small: Not enough parallelism
  - ▪ F too large: Thread overhead + run out of thread memory

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 = ∞
    - T_∞ = (1-p)T

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**

- $T_9 = 0.9 * 10/9 + 0.1 * 10 = 1.0 + 1.0 = 2.0$
- Maximum possible speedup
  - $T_\infty = 0.1 * 10.0 = 1.0$

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
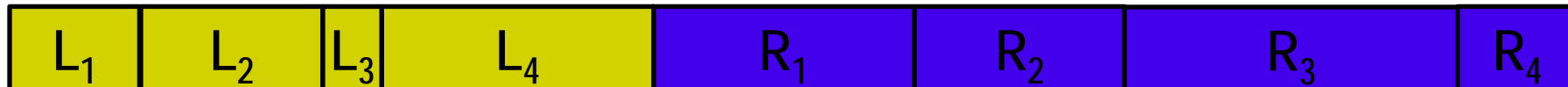
Parallelizing Partitioning Step

X_1	X_2	X_3	X_4

p

Parallel partitioning based on global p

| L_1 | R_1 | | L_2 | R_2 | | L_3 | R_3 | | L_4 | R_4 |

Reassemble into partitions

| L_1 | L_2 | L_3 | L_4 | R_1 | R_2 | R_3 | R_4 |

Experience with Parallel Partitioning

- **Could not obtain speedup**

- **Speculate: Too much data copying**
  - Could not do everything within source array
  - Set up temporary space for reassembling partition

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