Thread-Level Parallelism

15-213: Introduction to Computer Systems
26th Lecture, Nov. 30, 2010

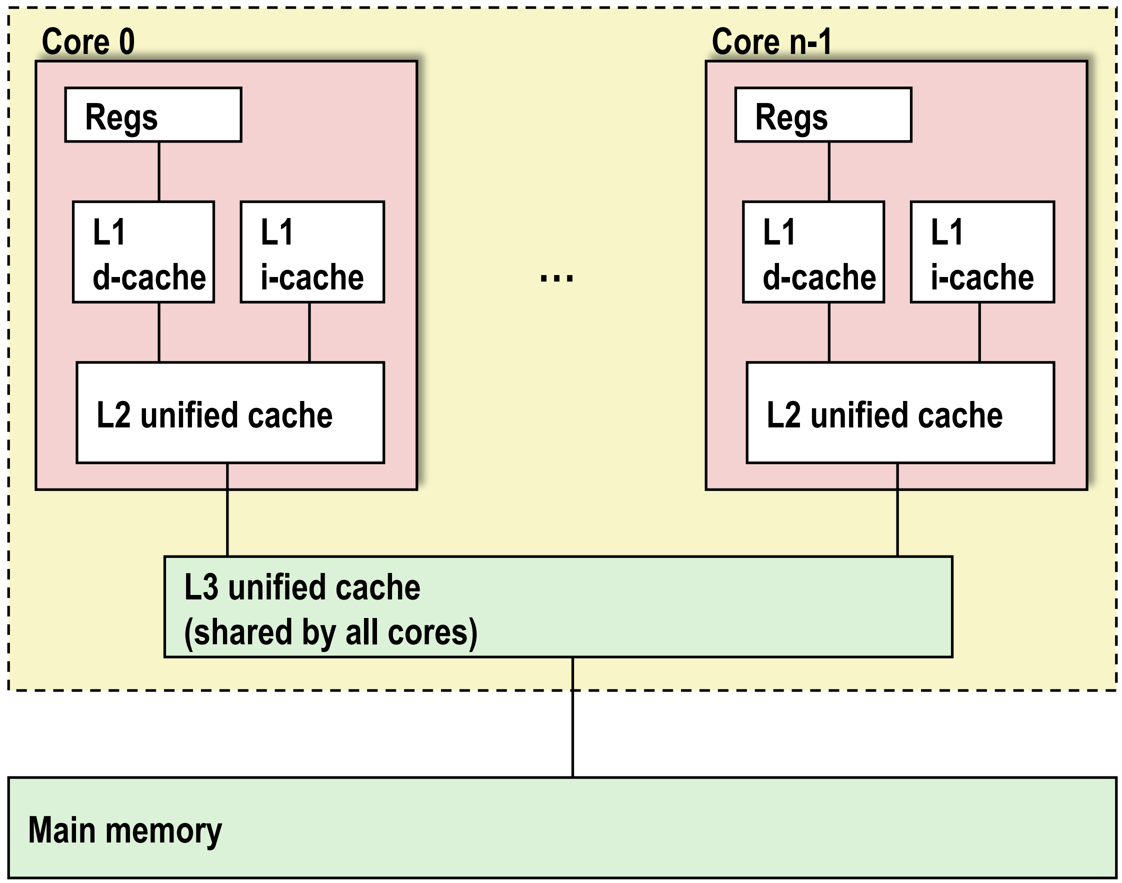
Instructors:

Randy Bryant and Dave O'Hallaron

Today

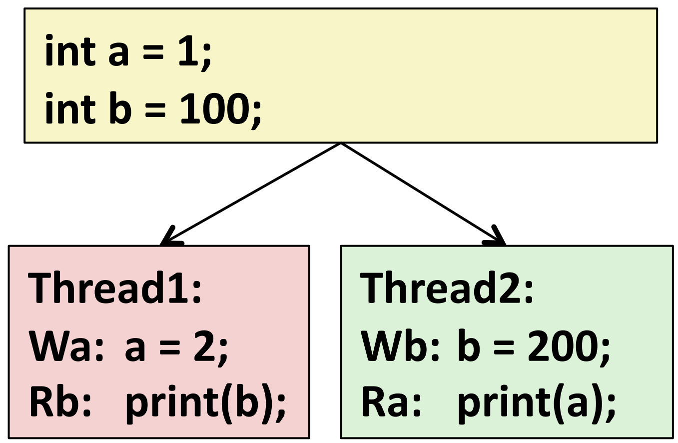
- **Parallel Computing Hardware**
  - Multicore
    - Multiple separate processors on single chip
  - Hyperthreading
    - Replicated instruction execution hardware in each processor
  - Maintaining cache consistency
- **Thread Level Parallelism**
  - Splitting program into independent tasks
    - Example: Parallel summation
    - Some performance artifacts
  - Divide-and conquer parallelism
    - Example: Parallel quicksort

Multicore Processor

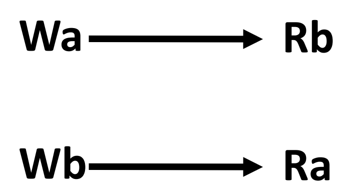


- **Intel Nehalem Processor**
  - E.g., Shark machines
  - Multiple processors operating with coherent view of memory

Memory Consistency

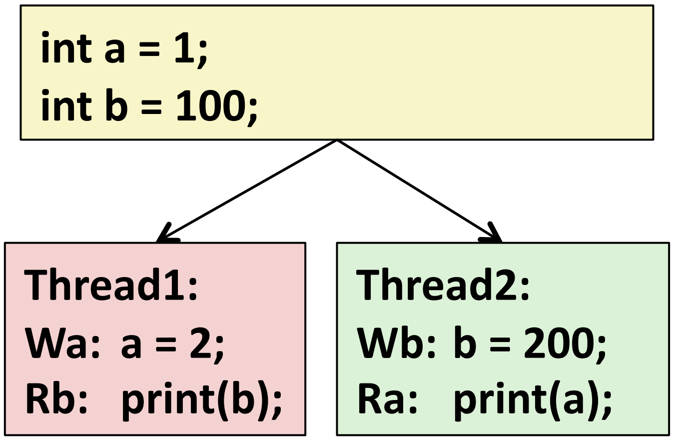


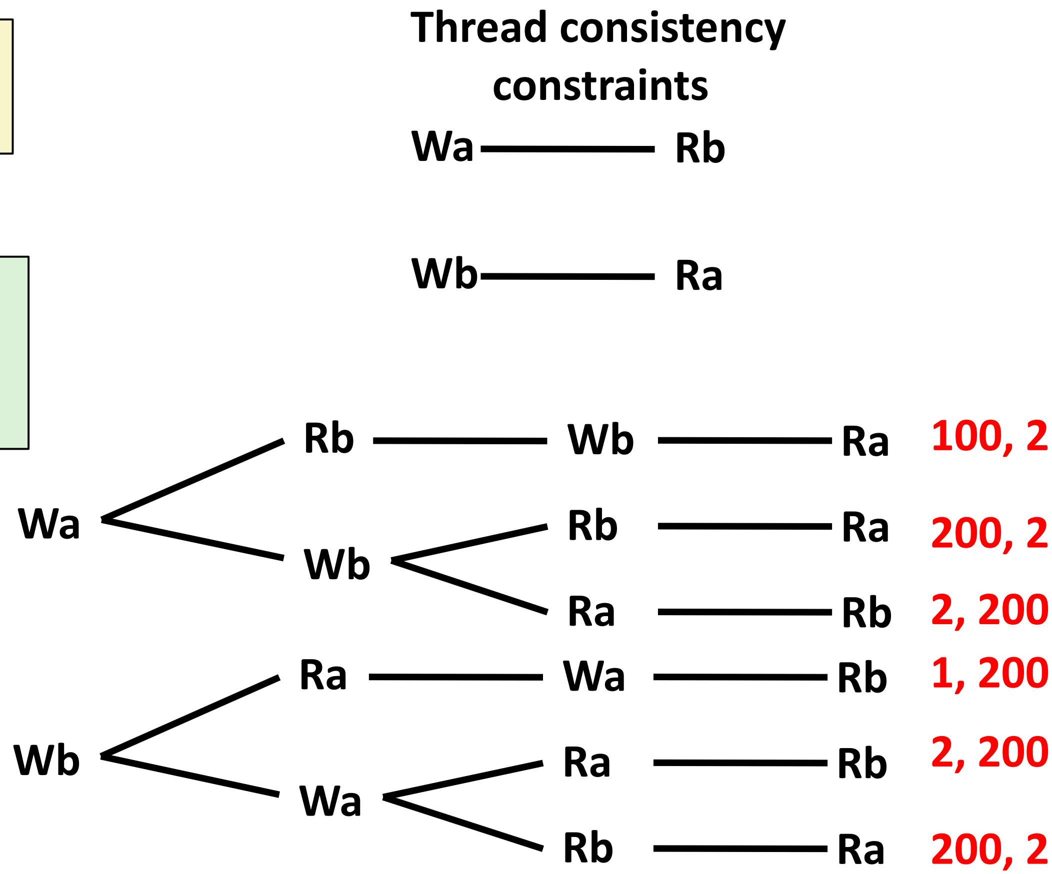
Thread consistency constraints



- **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





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

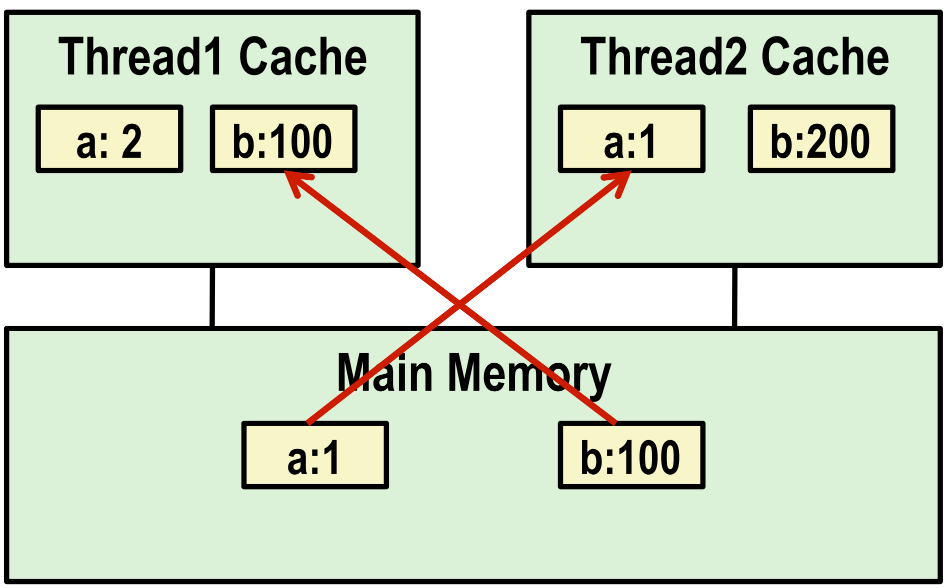
Non-Coherent Cache Scenario

- 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);
```



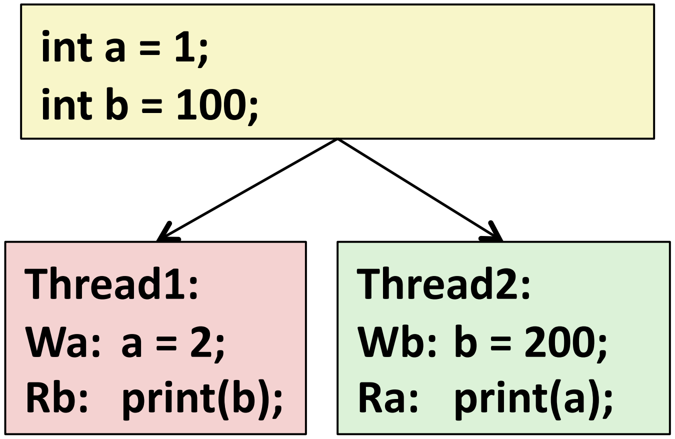
print 1

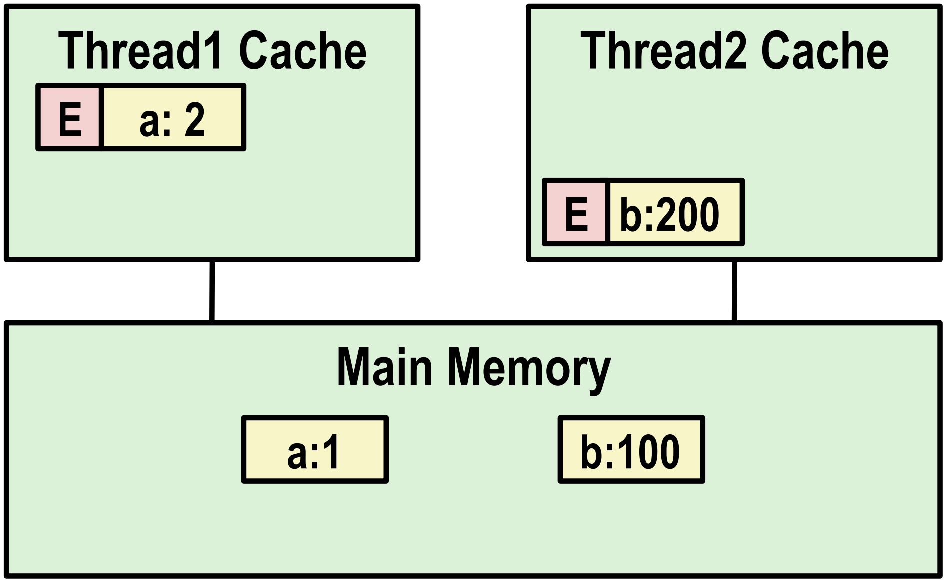
print 100

Snoopy Caches

- **Tag each cache block with state**

Invalid	Cannot use value
Shared	Readable copy
Exclusive	Writeable copy





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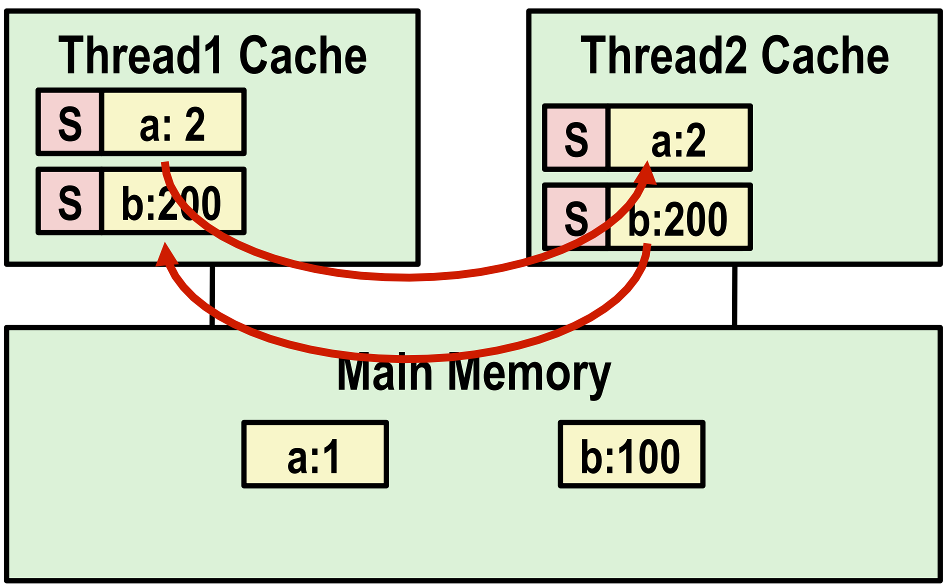
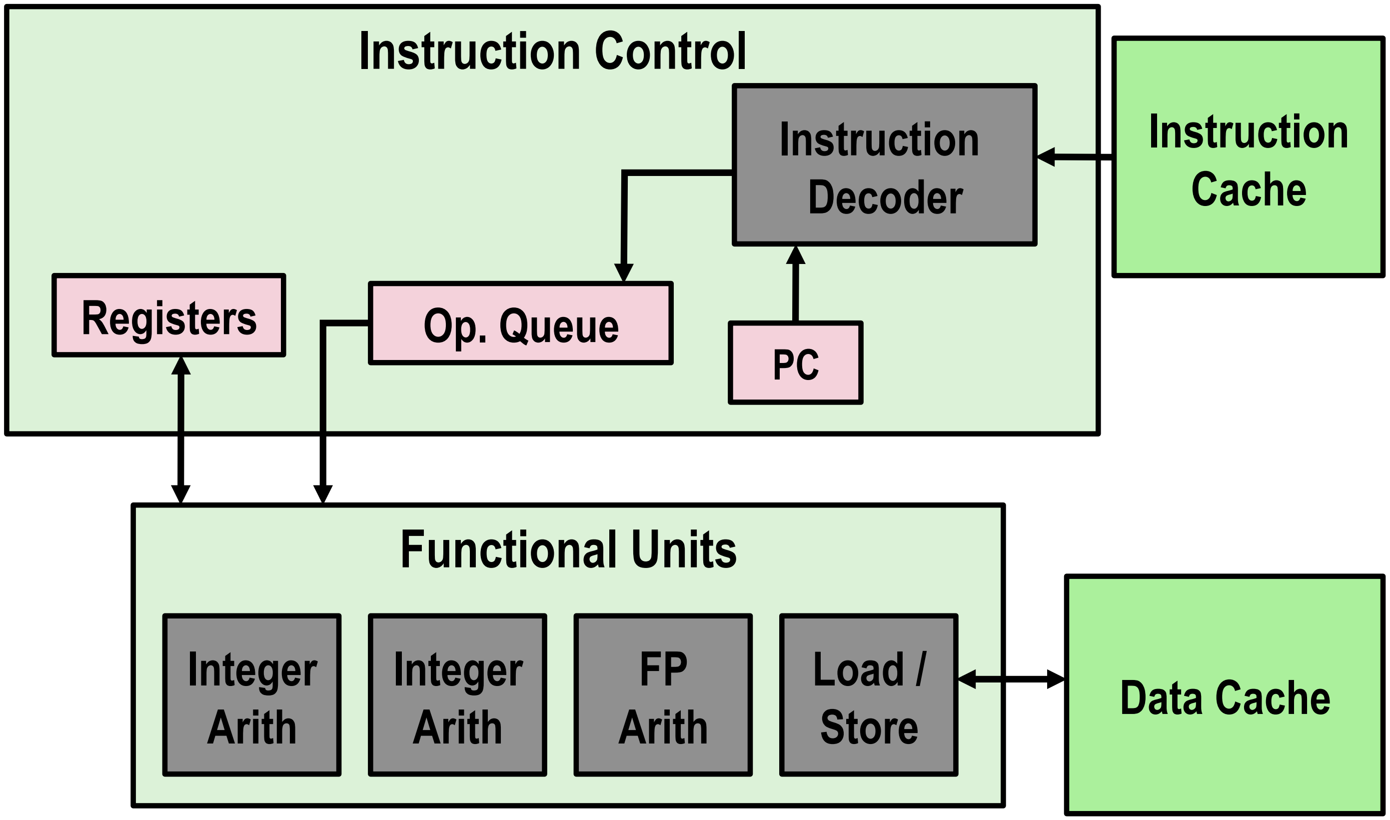


print 2

print 200

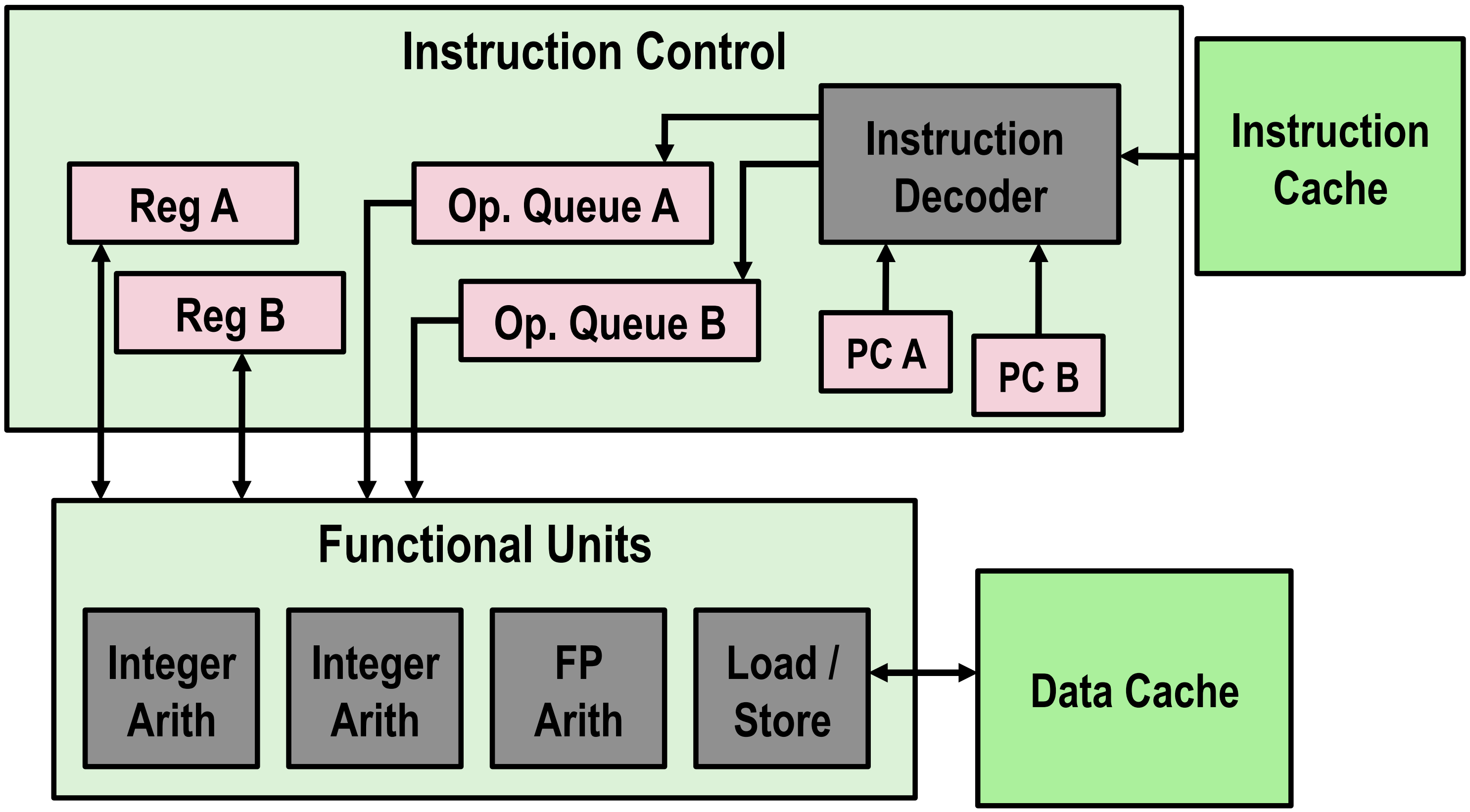
- When cache sees request for one of its E-tagged blocks
  - Supply value from cache
  - Set tag to S

Out-of-Order Processor Structure



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

Hyperthreading



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

Summary: Creating Parallel Machines

- **Multicore**
  - Separate instruction logic and functional units
  - Some shared, some private caches
  - Must implement cache coherency
- **Hyperthreading**
  - Also called “simultaneous multithreading”
  - Separate program state
  - Shared functional units & caches
  - No special control needed for coherency
- **Combining**
  - Shark machines: 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;

/* 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];
```

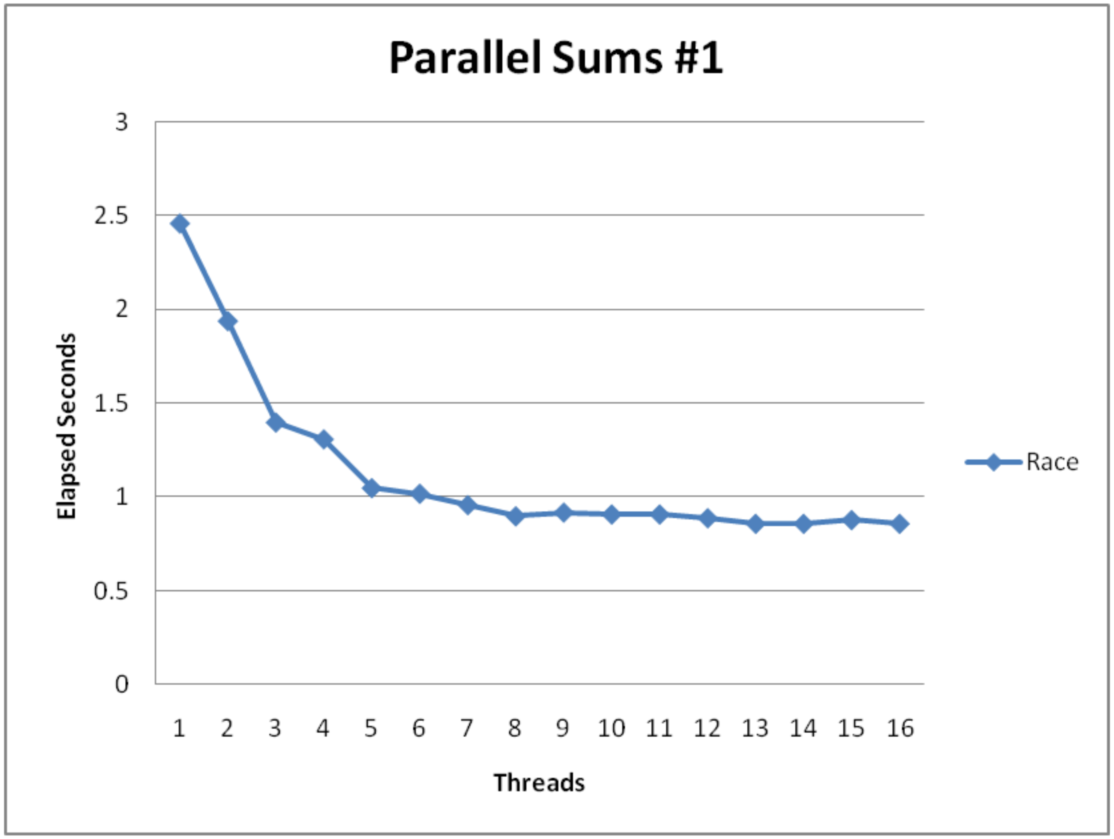
Accumulating in Single Global Variable: Operation

```
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

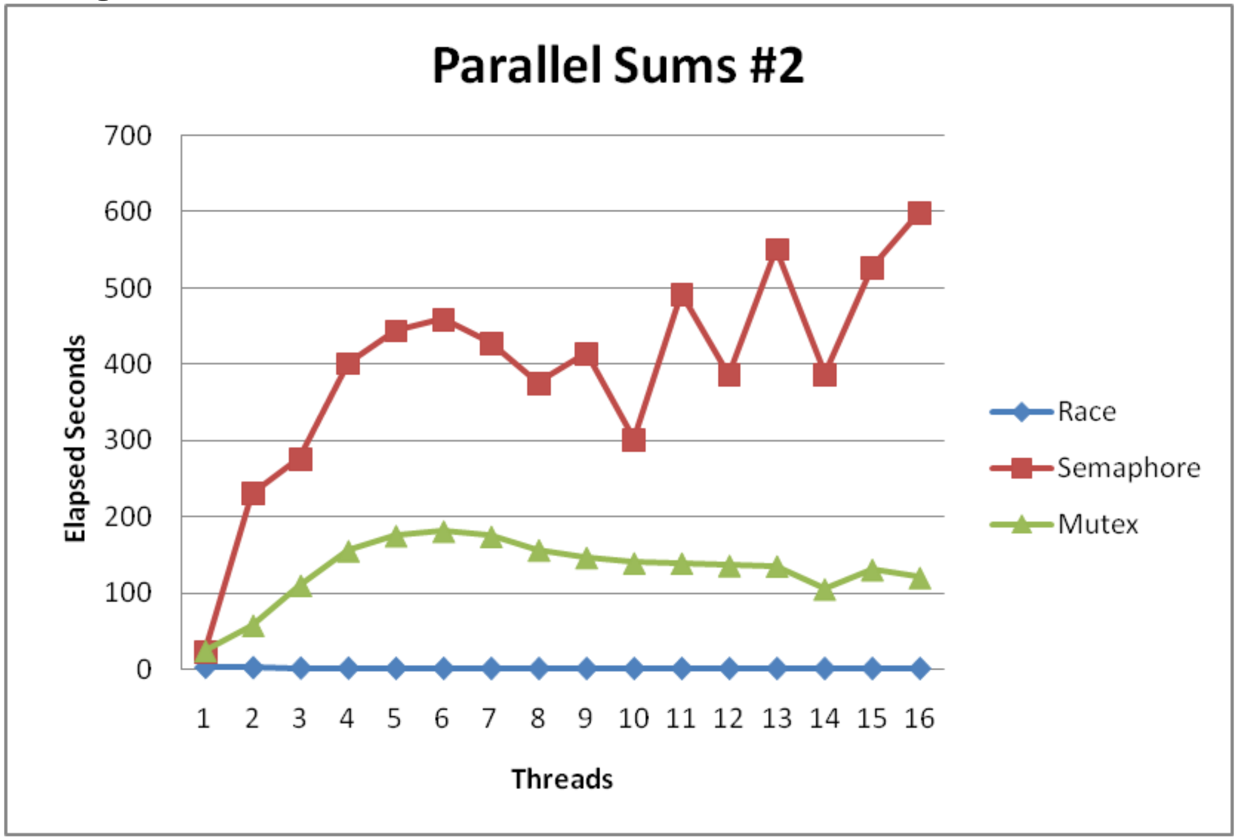
Semaphore

```
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;
```

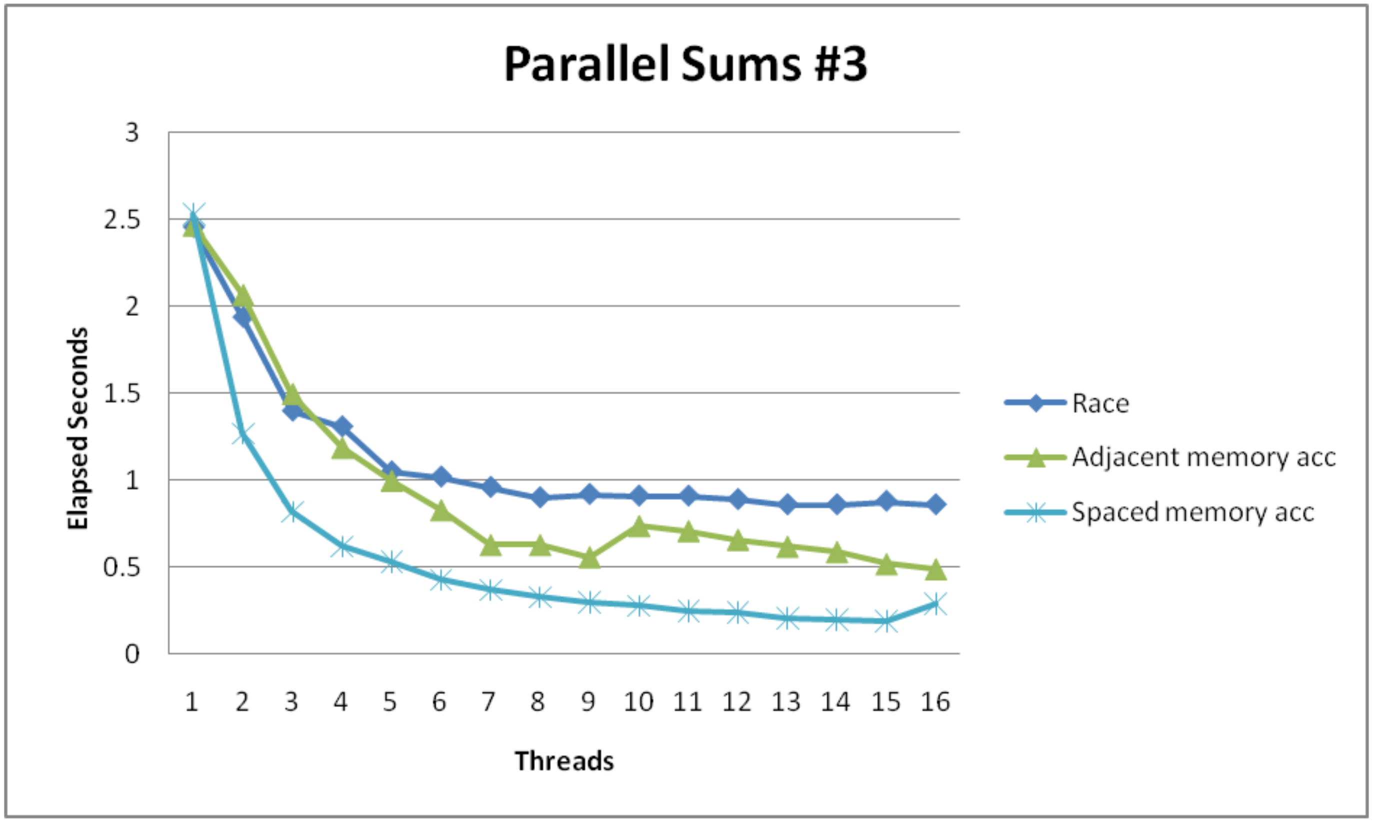
Separate Accumulation: Operation

```
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

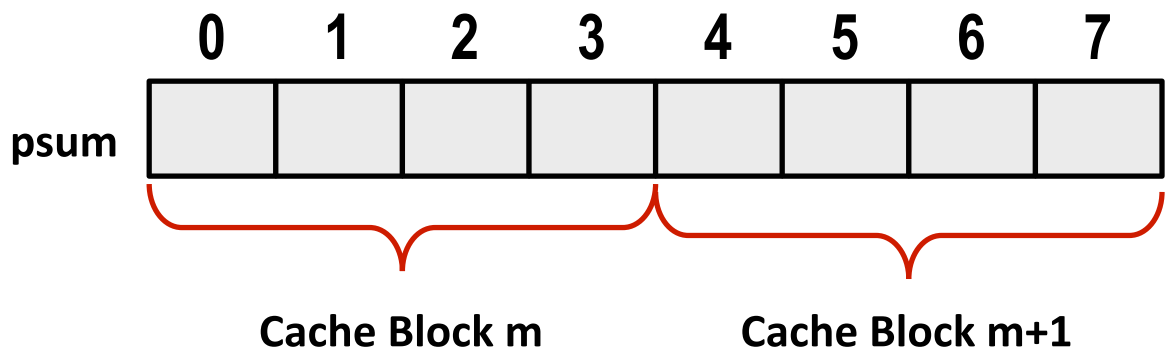
```
void *sum_global(void *vargp)
{
    int myid = *((int *)vargp);
    size_t start = myid * nelems_per_thread;
    size_t end = start + nelems_per_thread;
    size_t i;

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

Memory Accumulation Performance



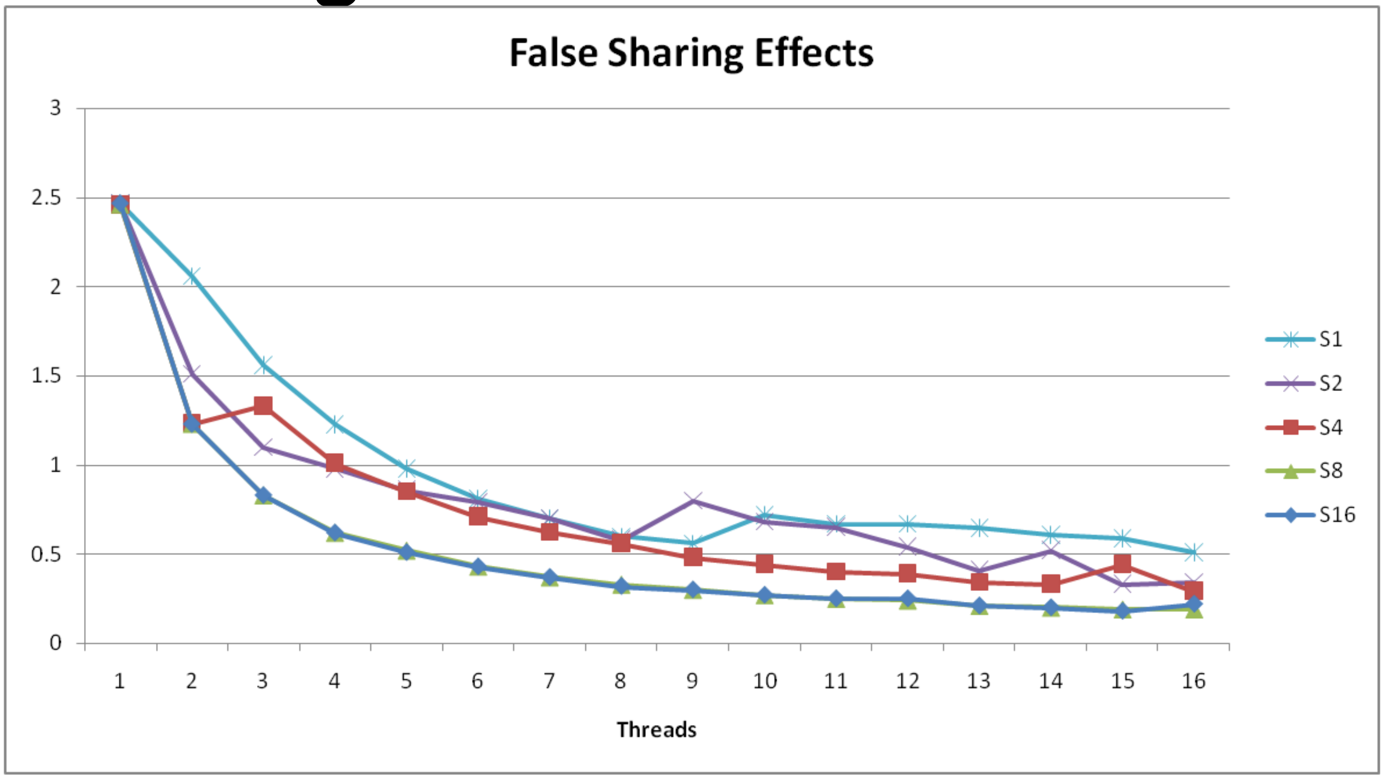
- **Clear threading advantage**
  - Adjacent speedup: 5 X
  - Spaced-apart speedup: 13.3 X (Only observed speedup > 8)
- **Why does spacing the accumulators apart matter?**

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



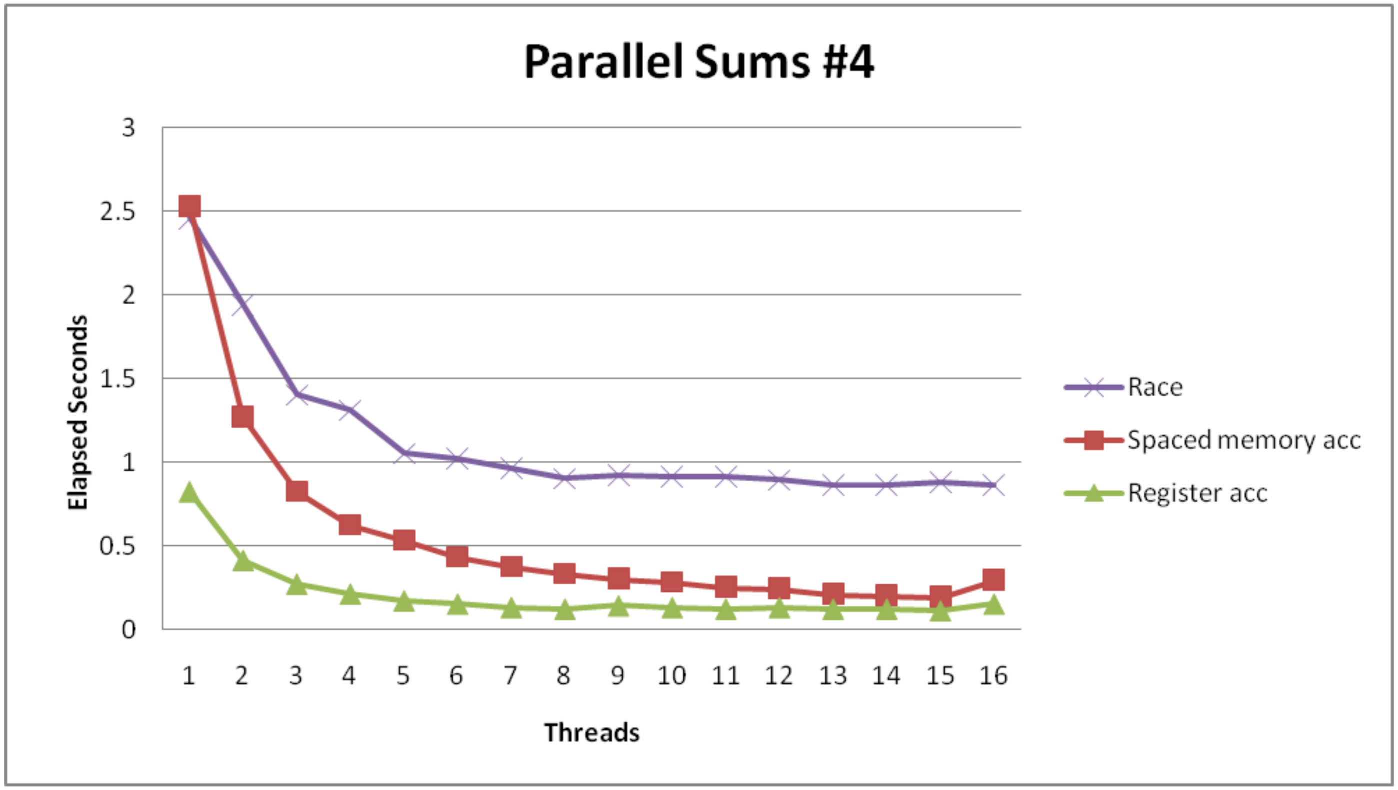
- Best spaced-apart performance 2.8 X better than best adjacent

- **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

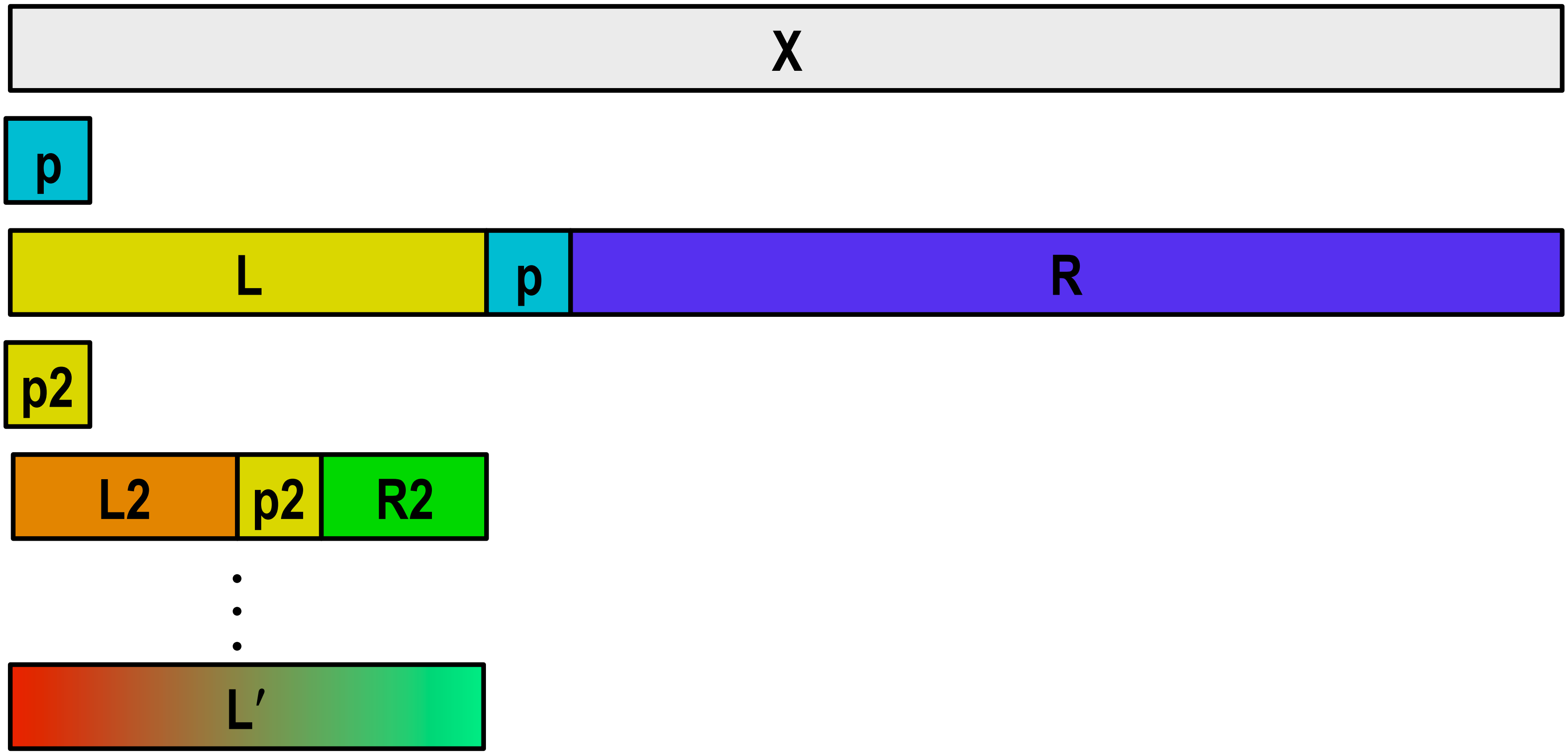


- **Clear threading advantage**
  - Speedup = 7.5 X
- **2X better than fastest memory accumulation**

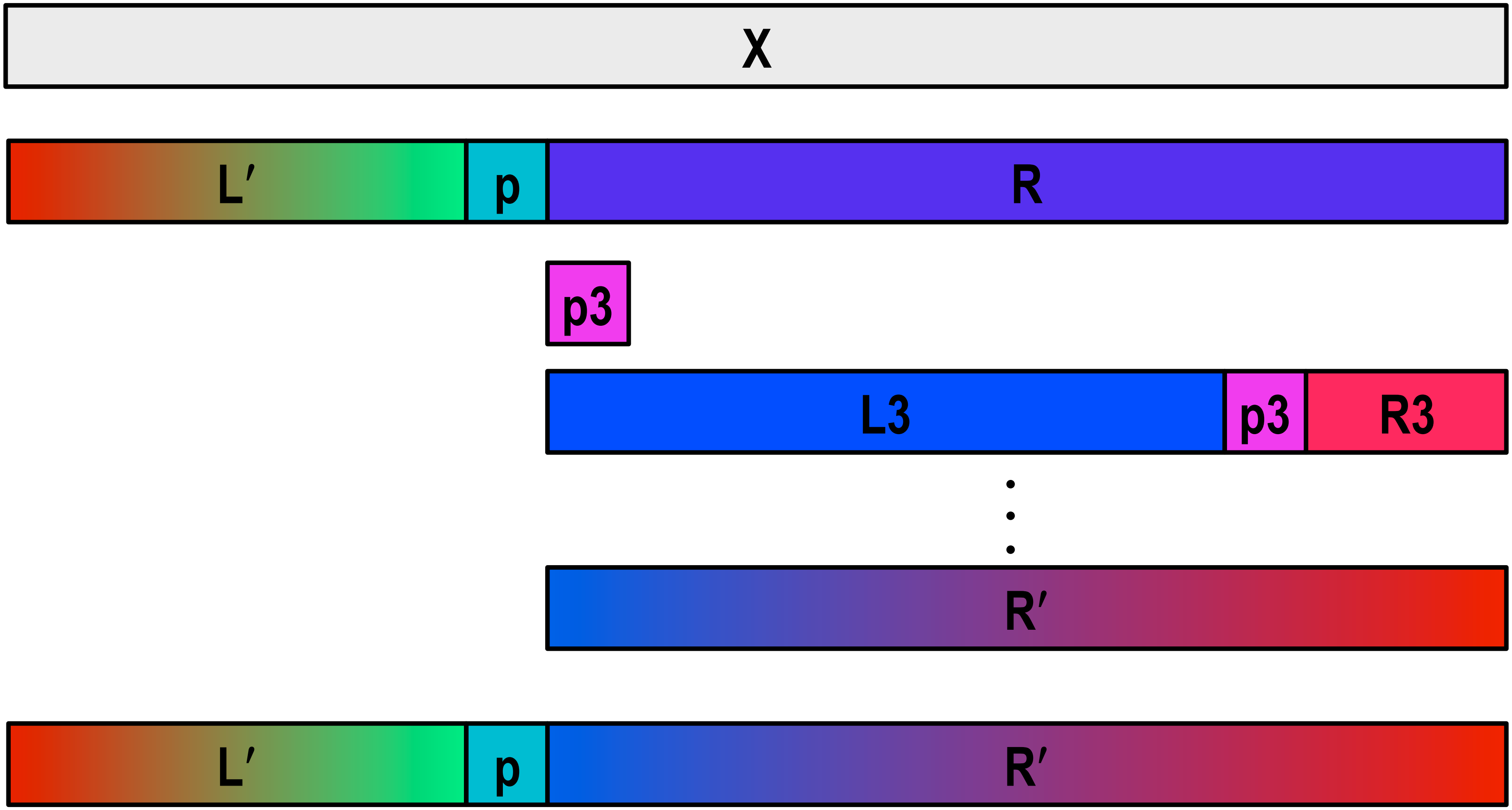
A More Interesting Example

- **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 ≤ p
    - R: Values ≥ 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

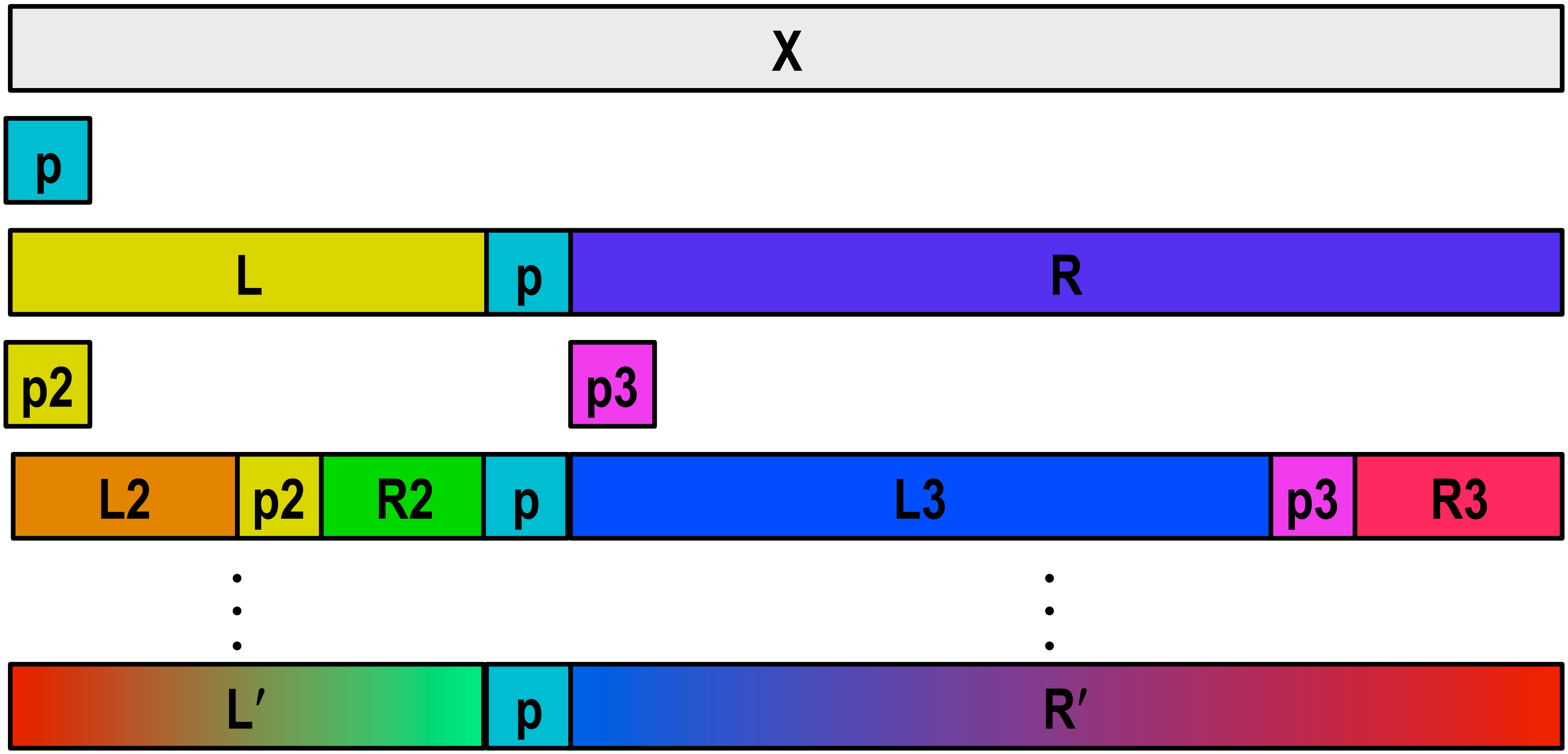
```
void qsort_serial(data_t *base, size_t nele) {
  if (nele <= 1)
    return;
  if (nele == 2) {
    if (base[0] > base[1])
      swap(base, base+1);
    return;
  }
  /* Partition returns index of pivot */
  size_t m = partition(base, nele);
  if (m > 1)
    qsort_serial(base, m);
  if (nele-1 > m+1)
    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 ≤ Nthresh, do sequential quicksort
  - Else
    - Choose "pivot" p from X
    - Rearrange X into
      - L: Values ≤ p
      - R: Values ≥ p
    - Recursively spawn separate threads
      - Sort L to get L′
      - Sort R to get R′
    - Return L′ : p : R′
- **Degree of parallelism**
  - Top-level partition: none
  - Second-level partition: 2X
  - …

Parallel Quicksort Visualized



Parallel Quicksort Data Structures

```
/* Structure that defines sorting task */
typedef struct {
  data_t *base;
  size_t nele;
  pthread_t tid;
} sort_task_t;

volatile int ntasks = 0;
volatile int ctasks = 0;
sort_task_t **tasks = NULL;
sem_t tmutex;
```

- **Data associated with each sorting task**
  - base: Array start
  - nele: Number of elements
  - tid: Thread ID
- **Generate list of tasks**
  - Must protect by mutex

Parallel Quicksort Initialization

```
static void init_task(size_t nele) {
  ctasks = 64;
  tasks = (sort_task_t **) Calloc(ctasks, sizeof(sort_task_t *));
  ntasks = 0;
  Sem_init(&tmutex, 0, 1);
  nele_max_serial = nele / serial_fraction;
}
```

- **Task queue dynamically allocated**
- **Set Nthresh = N/F:**
  - N Total number of elements
  - F Serial fraction
    - Fraction of total size at which shift to sequential quicksort

Parallel Quicksort: Accessing Task Queue

```
static sort_task_t *new_task(data_t *base, size_t nele) {
  P(&tmutex);
  if (ntasks == ctasks) {
    ctasks *= 2;
    tasks = (sort_task_t **)
          Realloc(tasks, ctasks * sizeof(sort_task_t *));
  }
  int idx = ntasks++;
  sort_task_t *t = (sort_task_t *) Malloc(sizeof(sort_task_t));
  tasks[idx] = t;
  V(&tmutex);
  t->base = base;
  t->nele = nele;
  t->tid = (pthread_t) 0;
  return t;
}
```

- **Dynamically expand by doubling queue length**
  - Generate task structure dynamically (consumed when reap thread)
- **Must protect all accesses to queue & ntasks by mutex**

Parallel Quicksort: Top-Level Function

```
void tqsort(data_t *base, size_t nele) {
  int i;
  init_task(nele);
  tqsort_helper(base, nele);
  for (i = 0; i < get_ntasks(); i++) {
    P(&tmutex);
    sort_task_t *t = tasks[i];
    V(&tmutex);
    Pthread_join(t->tid, NULL);
    free((void *) t);
  }
}
```

- **Actual sorting done by tqsort_helper**
- **Must reap all of the spawned threads**
  - All accesses to task queue & ntasks guarded by mutex

Parallel Quicksort: Recursive function

```
void tqsort_helper(data_t *base, size_t nele) {
  if (nele <= nele_max_serial) {
    /* Use sequential sort */
    qsort_serial(base, nele);
    return;
  }
  sort_task_t *t = new_task(base, nele);
  Pthread_create(&t->tid, NULL, sort_thread, (void *) t);
}
```

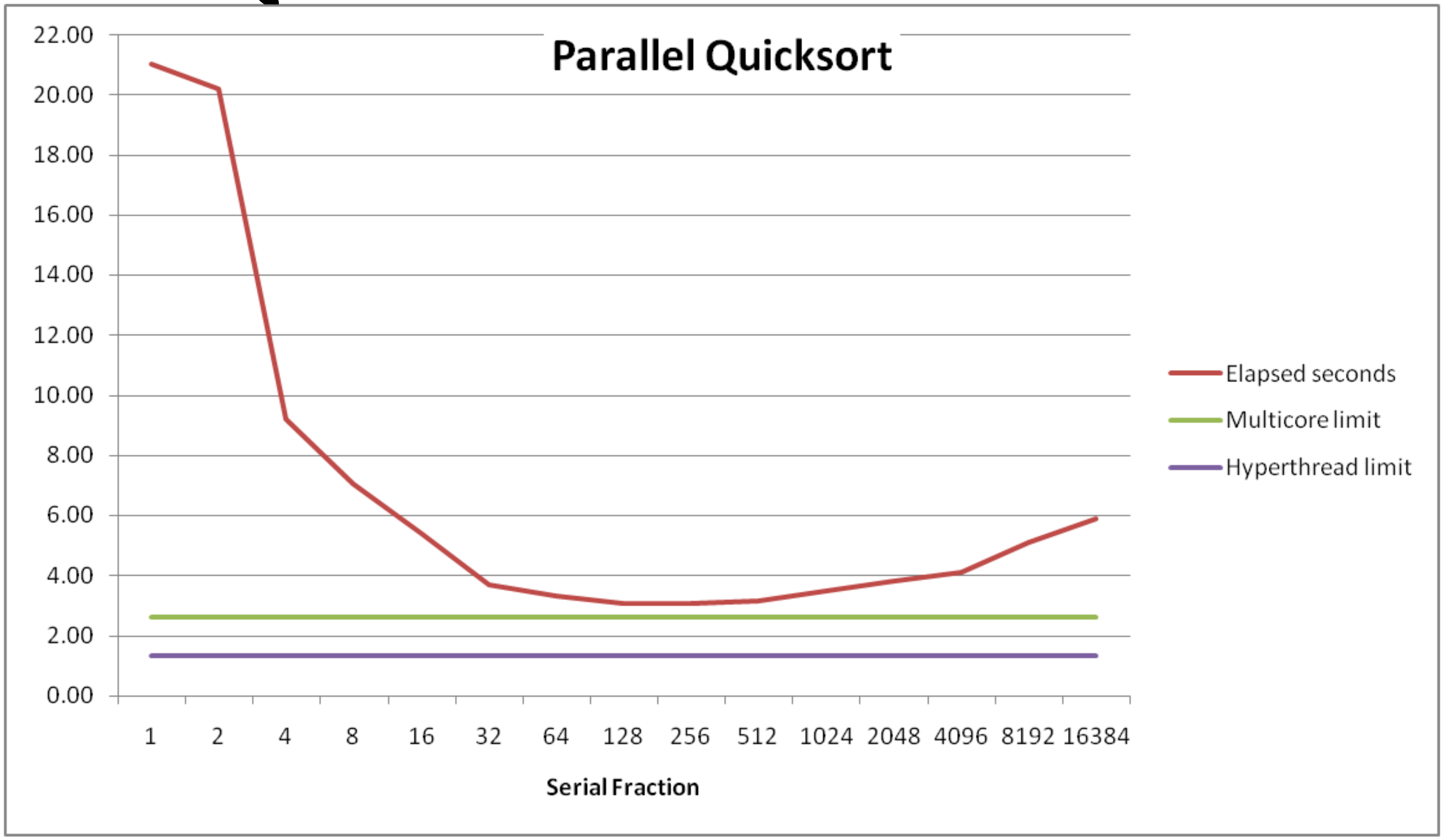
- If below Nthresh, call sequential quicksort
- Otherwise create sorting task

Parallel Quicksort: Sorting Task Function

```
static void *sort_thread(void *vargp) {
  sort_task_t *t = (sort_task_t *) vargp;
  data_t *base = t->base;
  size_t nele = t->nele;
  size_t m = partition(base, nele);
  if (m > 1)
    tqsort_helper(base, m);
  if (nele-1 > m+1)
    tqsort_helper(base+m+1, nele-m-1);
  return NULL;
}
```

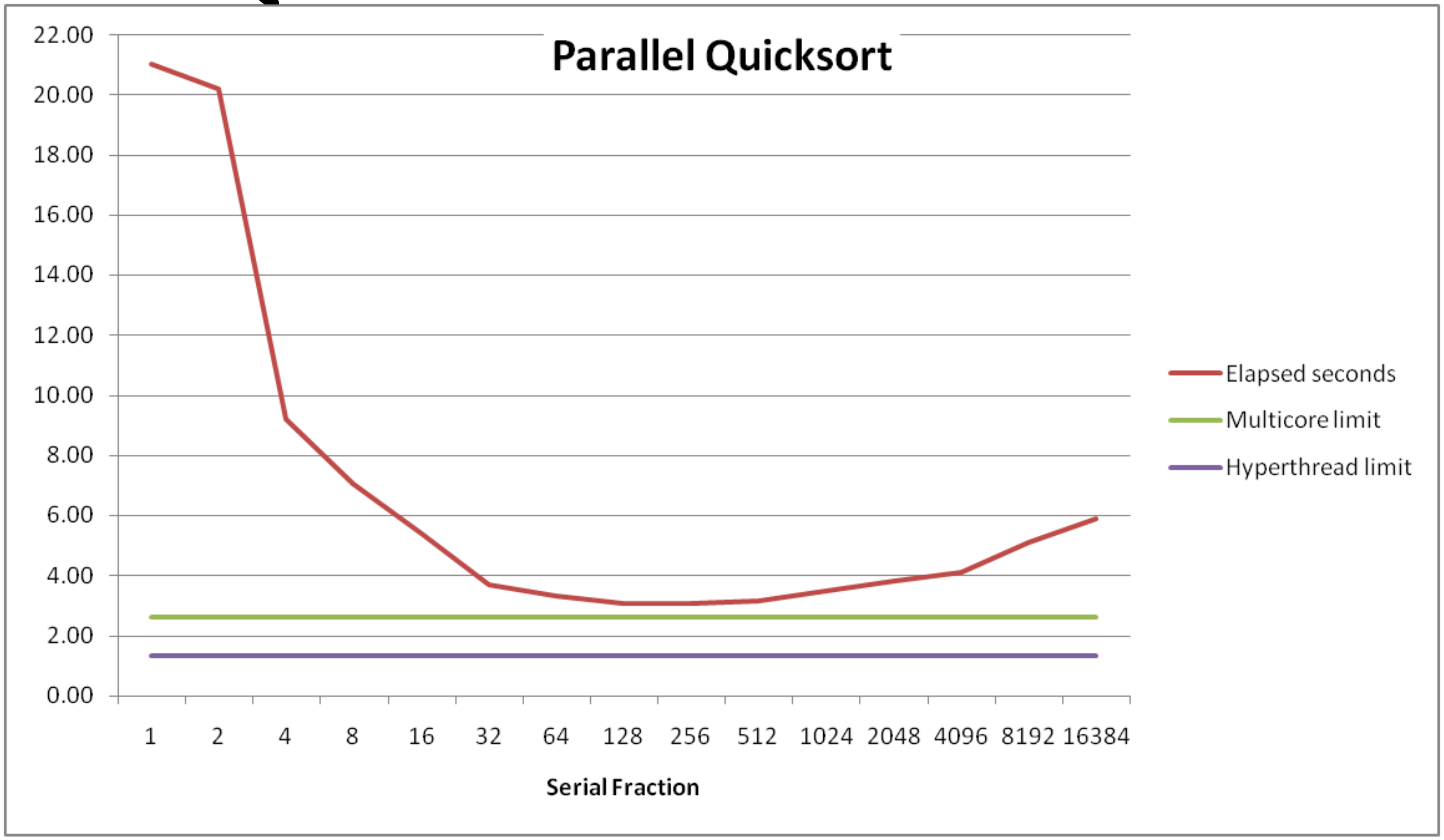
- Same idea as sequential quicksort

Parallel Quicksort Performance



- 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

Implementation Subtleties

- **Task set data structure**
  - Array of structs

    ```
    sort_task_t *tasks;
    ```

    - new_task returns pointer or integer index
  - Array of pointers to structs

    ```
    sort_task_t **tasks;
    ```

    - new_task dynamically allocates struct and returns pointer
- **Reaping threads**
  - Can we be sure the program won't terminate prematurely?

Amdahl's Law

- **Overall problem**
  - T Total time required
  - p Fraction of total that can be sped up ($0 \le p \le 1$)
  - 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 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: ≤ 2X speedup
  - k^{th} level: ≤ 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 strategy**
  - Partition into K independent parts
  - Divide-and-conquer
- **Inner loops must be synchronization free**
  - Synchronization operations very expensive
- **Watch out for hardware artifacts**
  - Sharing and false sharing of global data
- **You can do it!**
  - Achieving modest levels of parallelism is not difficult