Thread-Level Parallelism

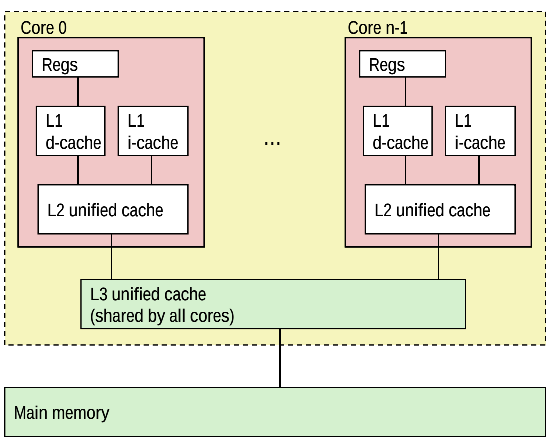
15-213 / 18-213: Introduction to Computer Systems
26th Lecture, April 25, 2013

Instructors:
Seth Copen Goldstein, Anthony Rowe, and Greg Kesden

Today

- **Parallel Computing Hardware**
  - Multicore
    - Multiple separate processors on single chip
  - Others
- **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

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 (not covered)
  - 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**
  - ⌊N/K⌋ 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];
```

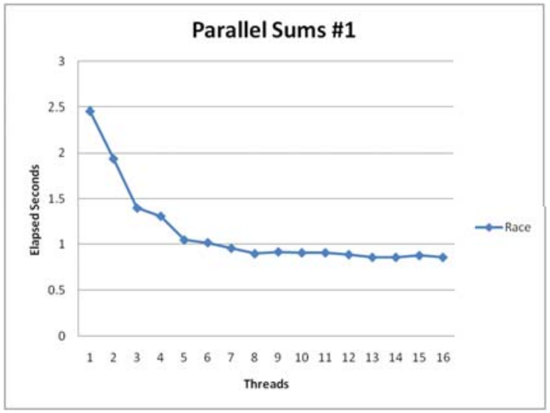

Accumulating in Single Global Variable: Operation

```
    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

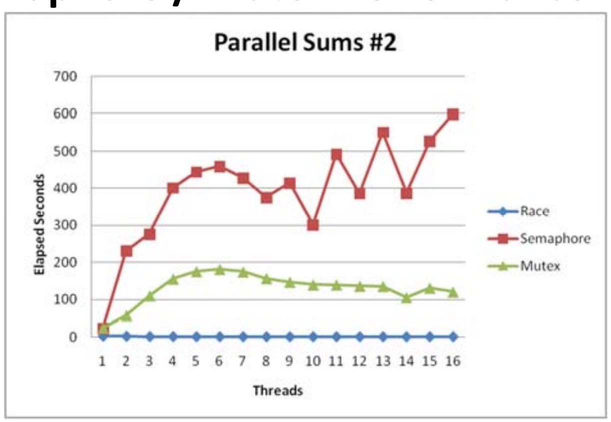
Semaphore

```
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;
```

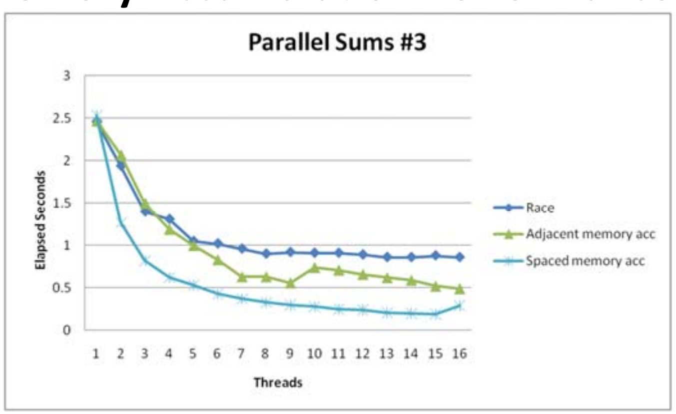
Separate Accumulation: Operation

```
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

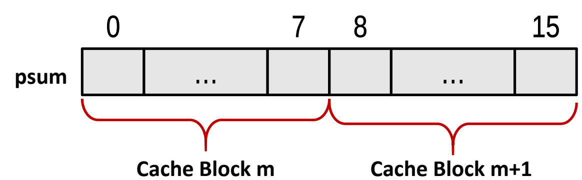
```
void *sum_global(void *vargp)
{
    int myid = *((int *)vargp);
    size_t start = myid * nelems_per_thread;
    size_t end = start + nelems_per_thread;
    size_t i;

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


Memory Accumulation Performance



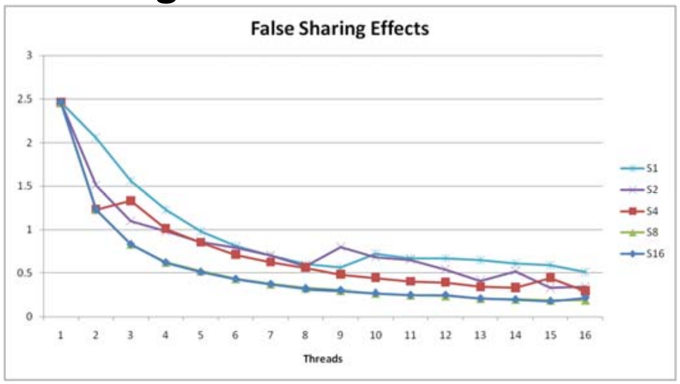
- **Clear threading advantage**
  - Adjacent speedup: 5 X
  - Spaced-apart speedup: 13.3 X (Only observed speedup > 8)
- **Why does spacing the accumulators apart matter?**

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

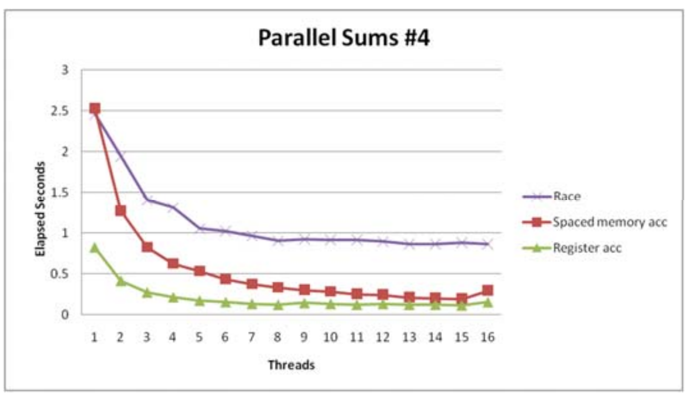


- Best spaced-apart performance 2.8 X better than best adjacent
- **Demonstrates cache block size = 64**
  - 8-byte values
  - No benefit increasing spacing beyond 8

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**

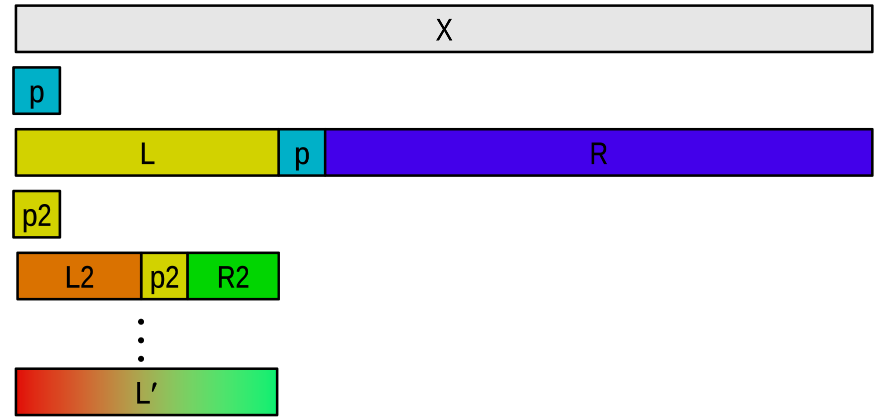
Summary of Summation

Method	Seq time	Max Speedup	Speedup on 8
Race	2.5	2.9	2.9
Semaphore	2.5	1.0	0.0
Mutex	2.5	1.0	0.0
Adj Mem Accum	2.5	5.0	4.2
Spaced Mem Accum	2.5	13.3	6.2
Register Accum	0.8	7.5	7.5

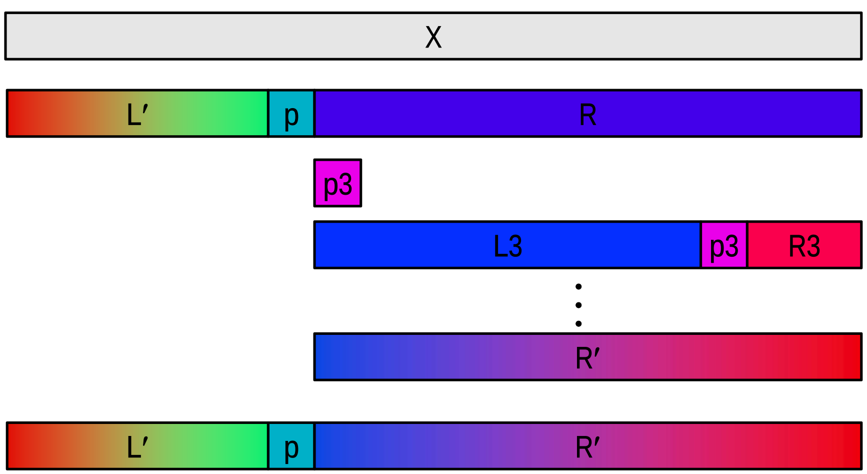
A More Substantial Example: Sort

- **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 ≤ 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

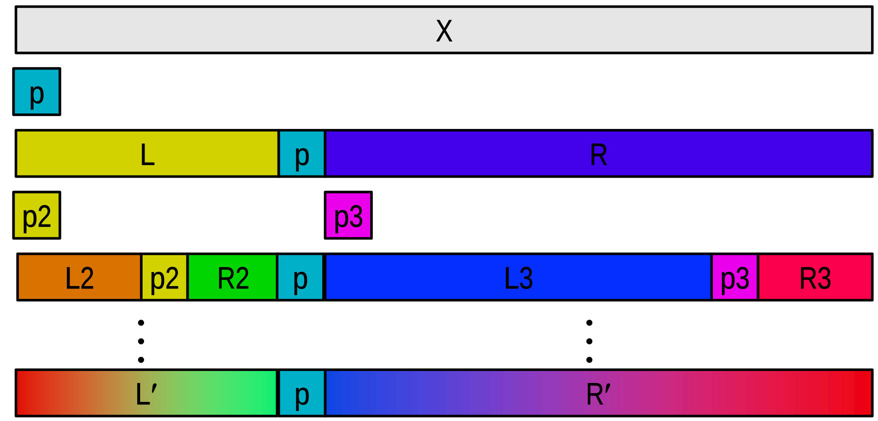
```
void qsort_serial(data_t *base, size_t nele) {
  if (nele <= 1)
    return;
  if (nele == 2) {
    if (base[0] > base[1])
      swap(base, base+1);
    return;
  }

  /* 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′

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);
}
```

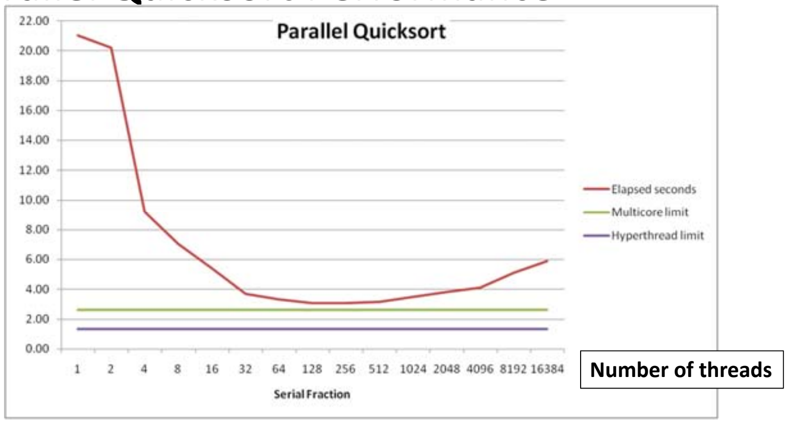
- **If below Nthresh, call sequential quicksort**
- **Otherwise create sorting task**

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;
}
```

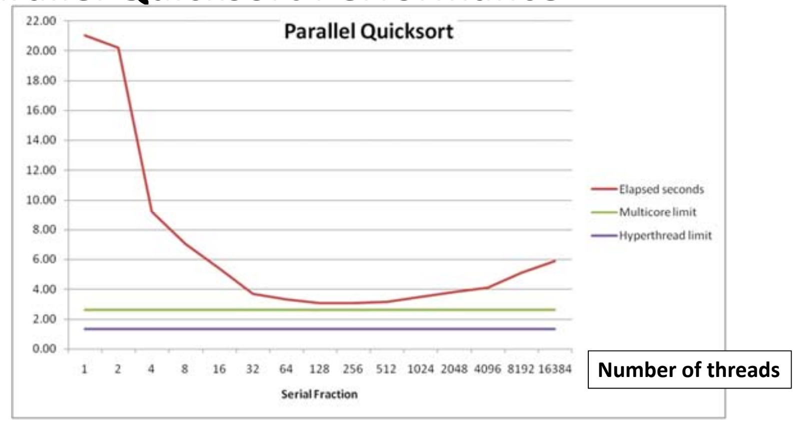
- **Same idea as sequential quicksort**

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

Amdahl's Law

- **Overall problem**
  - T Total sequential 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

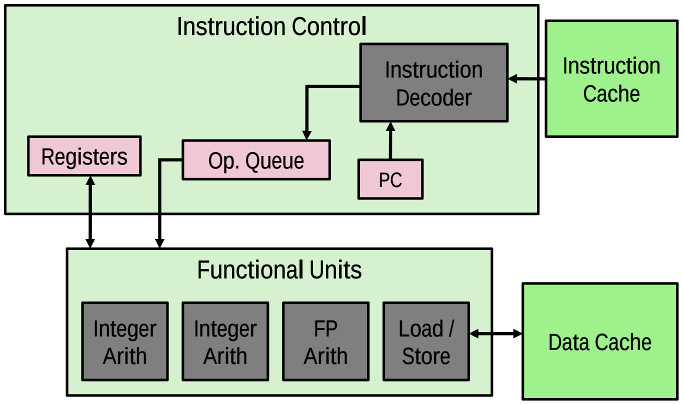
- **Sequential bottleneck**
  - Top-level partition: No speedup
  - Second level: ≤ 2X speedup
  - k^{th} level: $\leq 2^{k-1}$X speedup
- **Implications**
  - Good performance for small-scale parallelism
  - Would need to parallelize partitioning step to get large-scale parallelism
    - Parallel Sorting by Regular Sampling
      - H. Shi & J. Schaeffer, J. Parallel & Distributed Computing, 1992

Lessons Learned

- **Must have 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

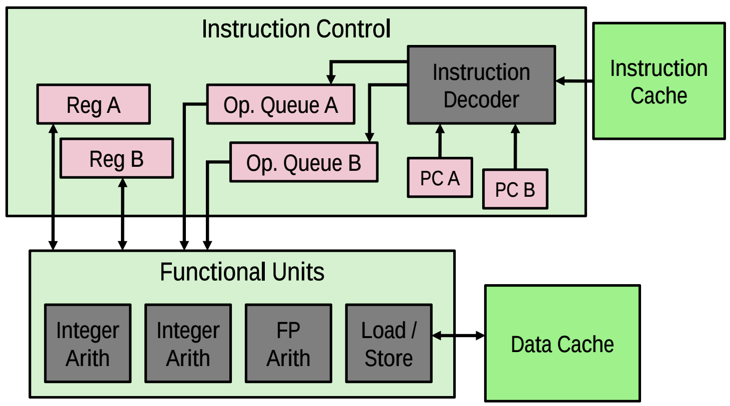
Extra slides

Out-of-Order Processor Structure



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

Hyperthreading

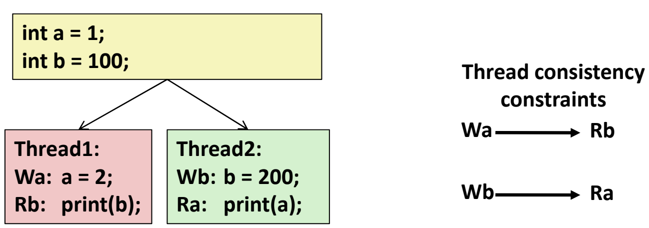


- **Replicate enough instruction control to process K instruction streams**
- **K copies of all registers**
- **Share functional units**

Summary: Creating Parallel Machines

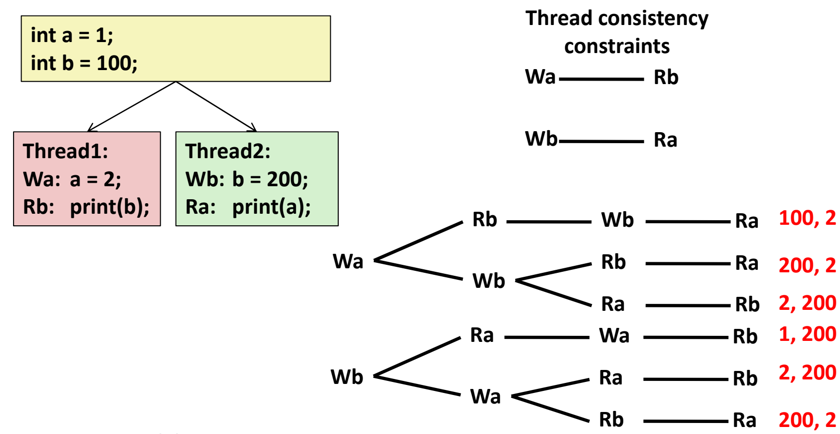
- **Multicore**
  - Separate instruction logic and functional units
  - Some shared, some private caches
  - Must implement cache coherency
- **Hyperthreading**
  - Also called “simultaneous multithreading”
  - Separate program state
  - Shared functional units & caches
  - No special control needed for coherency
- **Combining**
  - Shark machines: 8 cores, each with 2-way hyperthreading
  - Theoretical speedup of 16X
    - Never achieved in our benchmarks

Memory Consistency



- **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

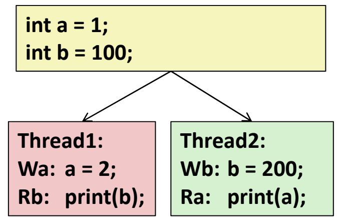
Sequential Consistency Example

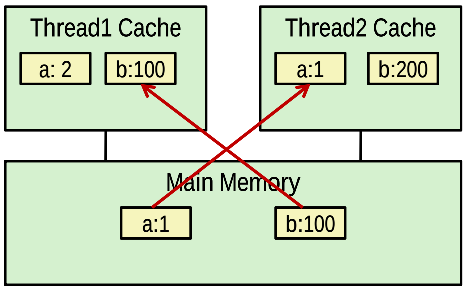


- **Impossible outputs**
  - 100, 1 and 1, 100
  - Would require reaching both Ra and Rb before Wa and Wb

Non-Coherent Cache Scenario

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





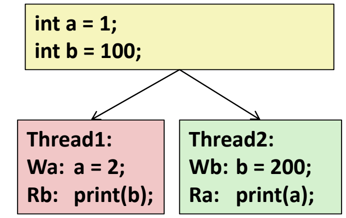
print 1

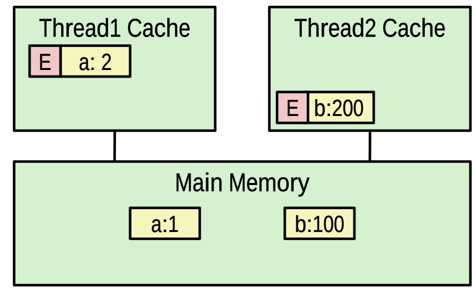
print 100

Snoopy Caches

- **Tag each cache block with state**

Invalid	Cannot use value
Shared	Readable copy
Exclusive	Writeable copy

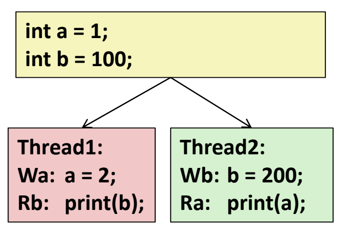


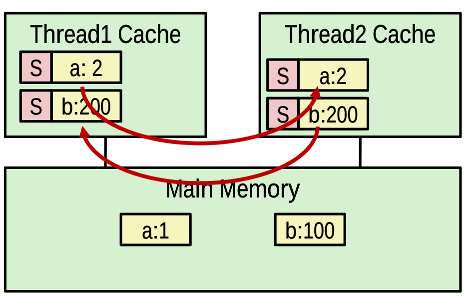


Snoopy Caches

- **Tag each cache block with state**

Invalid	Cannot use value
Shared	Readable copy
Exclusive	Writeable copy





print 2

print 200

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

Crucial concept: Thread Safety

- **Functions called from a thread must be *thread-safe***
- ***Def:* A function is *thread-safe* iff it will always produce correct results when called repeatedly from multiple concurrent threads.**
- **Classes of thread-unsafe functions:**
  - Class 1: Functions that do not protect shared variables
  - Class 2: Functions that keep state across multiple invocations
  - Class 3: Functions that return a pointer to a static variable
  - Class 4: Functions that call thread-unsafe functions

Thread-Unsafe Functions (Class 1)

- **Failing to protect shared variables**
  - Fix: Use *P* and *V* semaphore operations
  - Example: **`goodcnt.c`**
  - Issue: Synchronization operations will slow down code

Thread-Unsafe Functions (Class 2)

- **Relying on persistent state across multiple function invocations**
  - Example: Random number generator that relies on static state

```
static unsigned int next = 1;

/* rand: return pseudo-random integer on 0..32767 */
int rand(void)
{
    next = next*1103515245 + 12345;
    return (unsigned int)(next/65536) % 32768;
}

/* srand: set seed for rand() */
void srand(unsigned int seed)
{
    next = seed;
}
```


Thread-Safe Random Number Generator

- **Pass state as part of argument**
  - and, thereby, eliminate static state

```
/* rand_r - return pseudo-random integer on 0..32767 */

int rand_r(int *nextp)
{
    *nextp = *nextp*1103515245 + 12345;
    return (unsigned int)(*nextp/65536) % 32768;
}
```

- **Consequence: programmer using `rand_r` must maintain seed**

Thread-Unsafe Functions (Class 3)

- **Returning a pointer to a static variable**
- **Fix 1. Rewrite function so caller passes address of variable to store result**
  - Requires changes in caller and callee
- **Fix 2. Lock-and-copy**
  - Requires simple changes in caller (and none in callee)
  - However, caller must free memory.

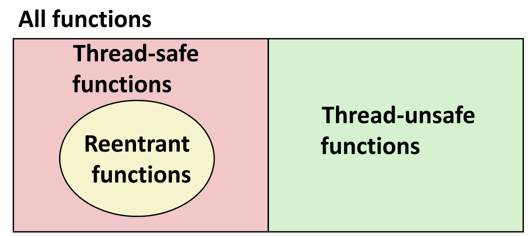
```
/* lock-and-copy version */
char *ctime_ts(const time_t *timep,
               char *privatep)
{
    char *sharedp;

    P(&mutex);
    sharedp = ctime(timep);
    strcpy(privatep, sharedp);
    V(&mutex);
    return privatep;
}
```

Thread-Unsafe Functions (Class 4)

- **Calling thread-unsafe functions**
  - Calling one thread-unsafe function makes the entire function that calls it thread-unsafe
  - Fix: Modify the function so it calls only thread-safe functions ☺

Reentrant Functions

- **Def: A function is *reentrant* iff it accesses no shared variables when called by multiple threads.**
  - Important subset of thread-safe functions
    - Require no synchronization operations
    - Only way to make a Class 2 function thread-safe is to make it reentrant (e.g., `rand_r`)



Thread-Safe Library Functions

- **All functions in the Standard C Library (at the back of your K&R text) are thread-safe**
  - Examples: `malloc`, `free`, `printf`, `scanf`
- **Most Unix system calls are thread-safe, with a few exceptions:**

Thread-unsafe function	Class	Reentrant version
`asctime`	3	`asctime_r`
`ctime`	3	`ctime_r`
`gethostbyaddr`	3	`gethostbyaddr_r`
`gethostbyname`	3	`gethostbyname_r`
`inet_ntoa`	3	`(none)`
`localtime`	3	`localtime_r`
`rand`	2	`rand_r`

Today

- **Thread safety**
- **Parallel Computing Hardware**
  - Multicore
    - Multiple separate processors on single chip
  - Hyperthreading
    - Multiple threads executed on a given processor at once
- **Thread-Level Parallelism**
  - Splitting program into independent tasks
    - Example: Parallel summation
    - Some performance artifacts
  - Divide-and conquer parallelism
    - Example: Parallel quicksort