Parallel & Distributed Computing

Lecture 5. Race Conditions and Synchronization in OpenMP

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Outline

- Correctness issues in parallel programming (in OpenMP)
  - Barriers
  - Examples of race conditions
  - Mutual Exclusion
  - Memory fence

Concept: Synchronization

- **Synchronization**
  - The process of managing shared resources so that reads and writes occur in the correct order regardless of how the threads are scheduled
- **Synchronization methods**
  - Barriers
  - Mutual Exclusion
  - …

Barriers in OpenMP

- **Barrier**
  - **A synchronization point at which every member in a team of threads must arrive before any member can proceed**
- **Syntax**

  #pragma omp barrier

  - **Automatically inserted at the end of worksharing constructs**
    - **e.g.,** *for* **pragma,** *single* **pragma, …**
  - **Can be disabled by using the** *nowait* **clause**

Example: Use of Barrier

```
#pragma omp parallel shared(numt)
{
  int numt = omp_get_num_threads();
  int tid = omp_get_thread_num();
  printf("hi, from %d\n", tid);
  if (tid == 0) {
    printf("%d threads say hi!\n", numt);
  }
}
```

Output using 4 threads

hi, from 3
hi, from 0
hi, from 2
4 threads say hi!
hi, from 1

- **Question:**
  - **What's the expected output?**
  - **How can we let the last printf appear last?**

Barbara Chapman, "A Guide to OpenMP," 2010.

Example: an Explicit Barrier

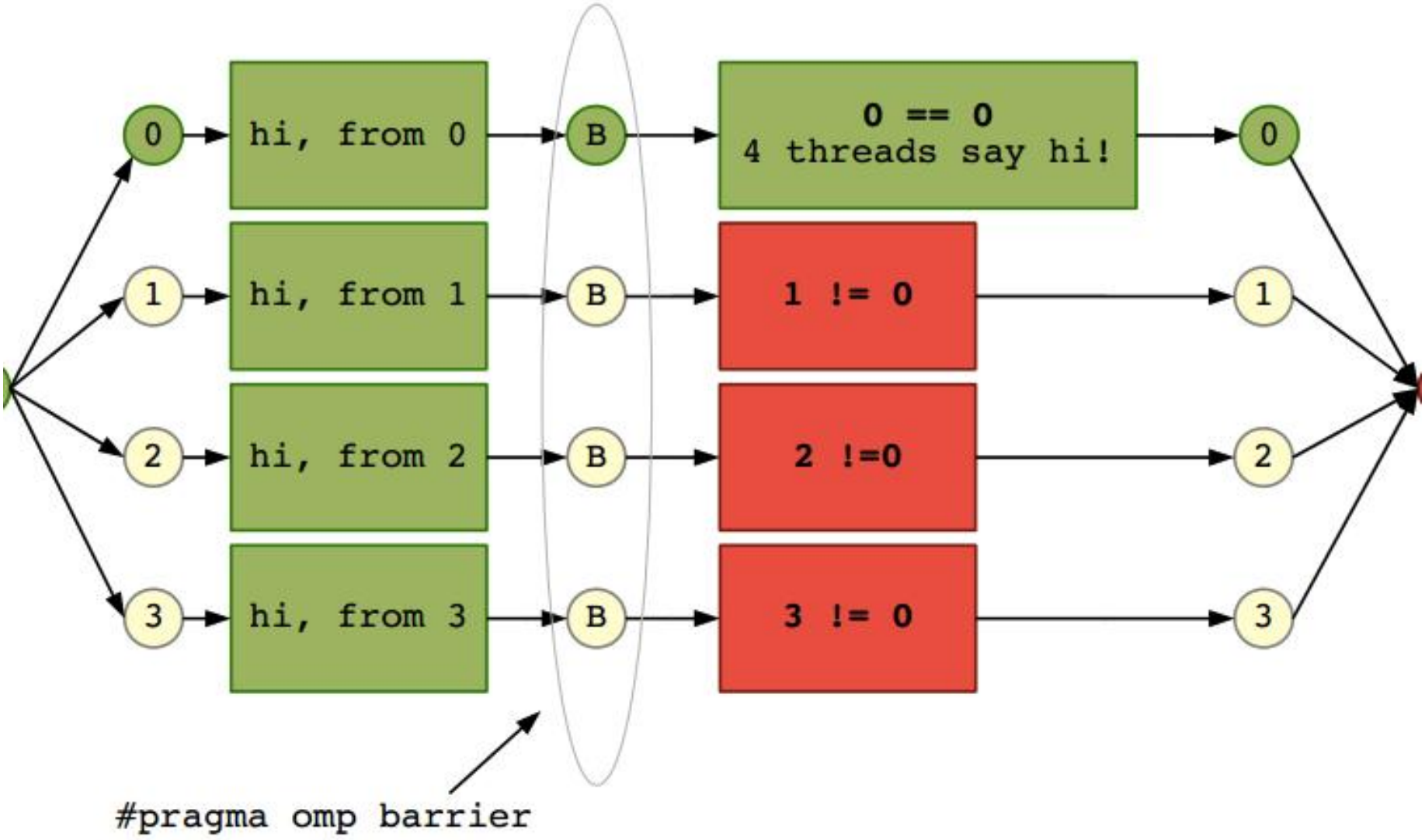
```
#pragma omp parallel shared(numt)
{
  int numt = omp_get_num_threads();
  int tid = omp_get_thread_num();
  printf("hi, from %d\n", tid);
#pragma omp barrier
  if (tid == 0) {
    printf("%d threads say hi!\n", numt);
  }
}
```

Output using 4 threads

hi, from 3
hi, from 0
hi, from 2
hi, from 1
4 threads say hi!

Barbara Chapman, "A Guide to OpenMP," 2010.

Example: an Explicit Barrier



Barbara Chapman, "A Guide to OpenMP," 2010.

Clause: *nowait*

- **The *nowait* clause tells the compiler that there is no need for a barrier synchronization at the end of a parallel *for* loop or *single* block of code**

Case: *parallel, for, single* Pragmas

```
for (i = 0; i < N; i++)
    a[i] = alpha(i);

if (gamma < 0.0)
    printf("gamma < 0.0\n");

for (i = 0; i < N; i++)
    b[i] = beta(i, gamma);
```

Solution: parallel, for, single Pragmas

```
#pragma omp parallel
{
    #pragma omp for nowait
    for (i = 0; i < N; i++)
        a[i] = alpha(i);
    #pragma omp single nowait
    if (gamma < 0.0)
        printf("gamma < 0.0\n");
    #pragma omp for
    for (i = 0; i < N; i++)
        b[i] = beta(i, gamma);
}
```

Mutual Exclusion

- **Mutual exclusion**
  - A kind of synchronization
  - Allows only a single thread or process at a time to have access to shared resource
  - Implemented using some form of locking
- **Critical section (a high-level synchronization)**
  - Only one thread at a time will execute the structured block within a critical section
- **Lock (a low-level synchronization)**

An Example of Race Condition

```
double area, pi, x;
int i, n;
...
area = 0.0;
for (i = 0; i < n; i++) {
   x = (i + 0.5)/n;
   area += 4.0/(1.0 + x*x);
}
pi = area / n;
```

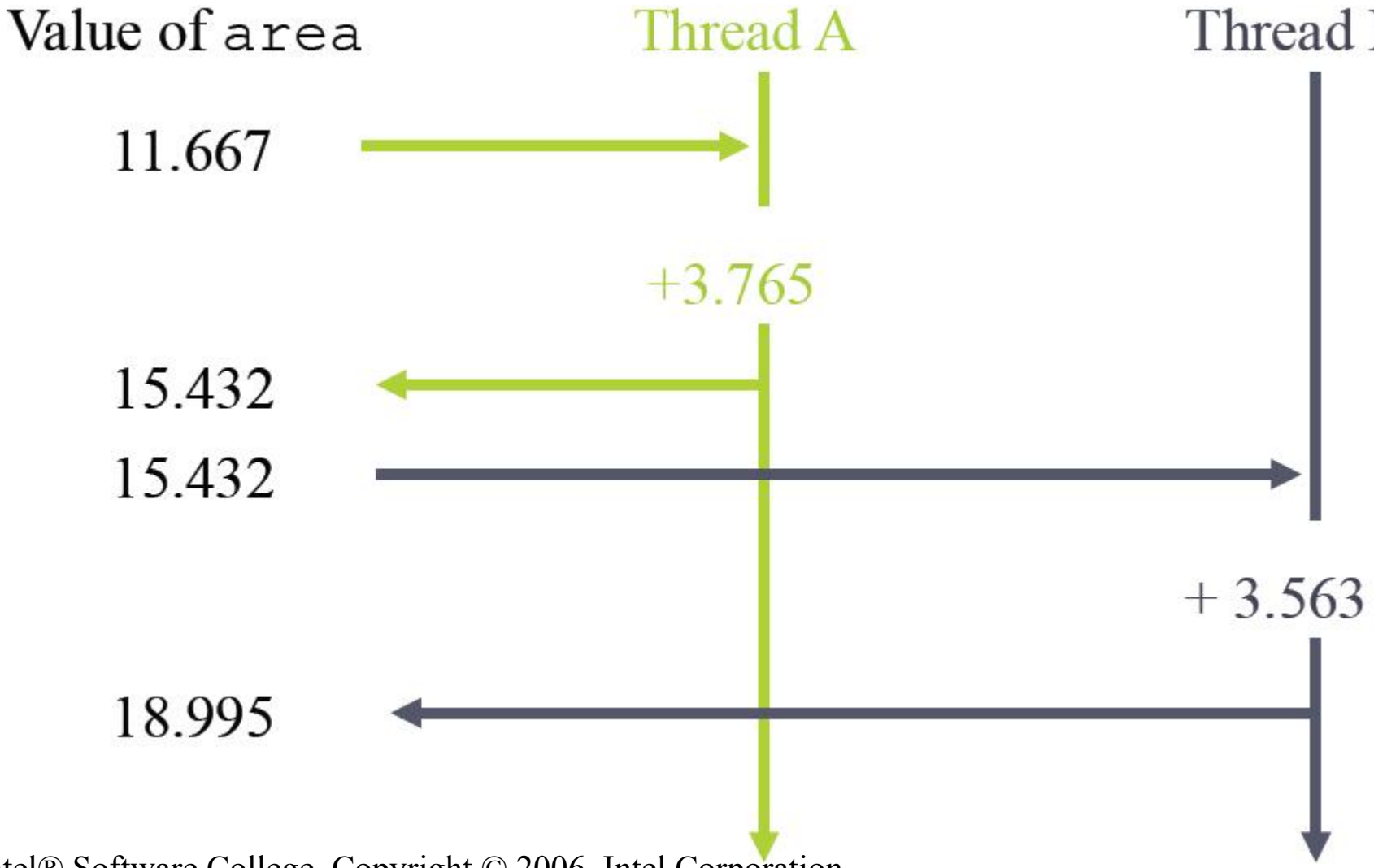
- **What happens when we make the `for` loop parallel?**

Race Condition

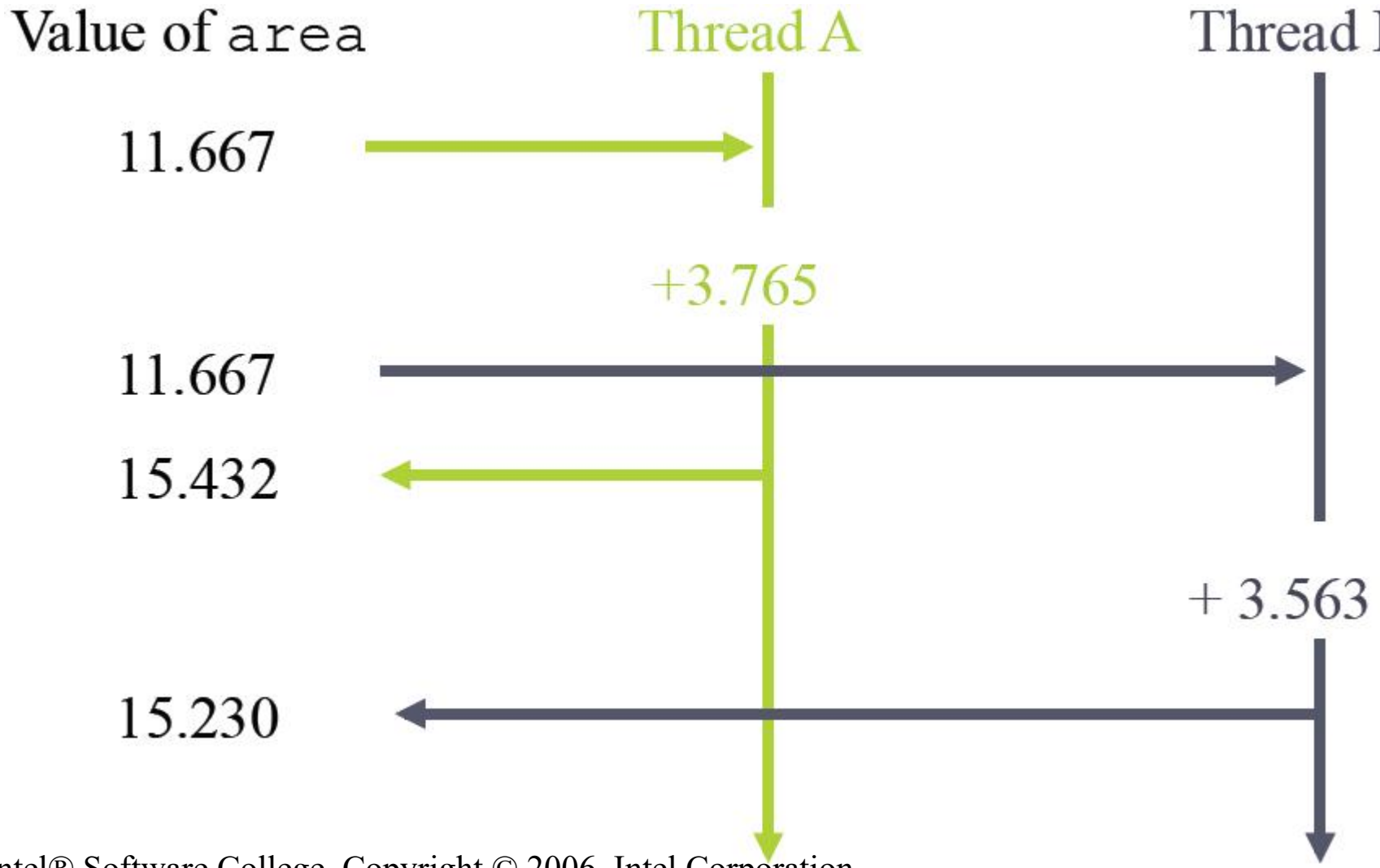
- **A *race condition* is nondeterministic behavior caused by the times at which two or more threads access a shared variable**
- **For example, suppose both Thread A and Thread B are executing the statement…**

```
area += 4.0 / (1.0 + x*x);
```

One Timing ⇒ Correct Sum



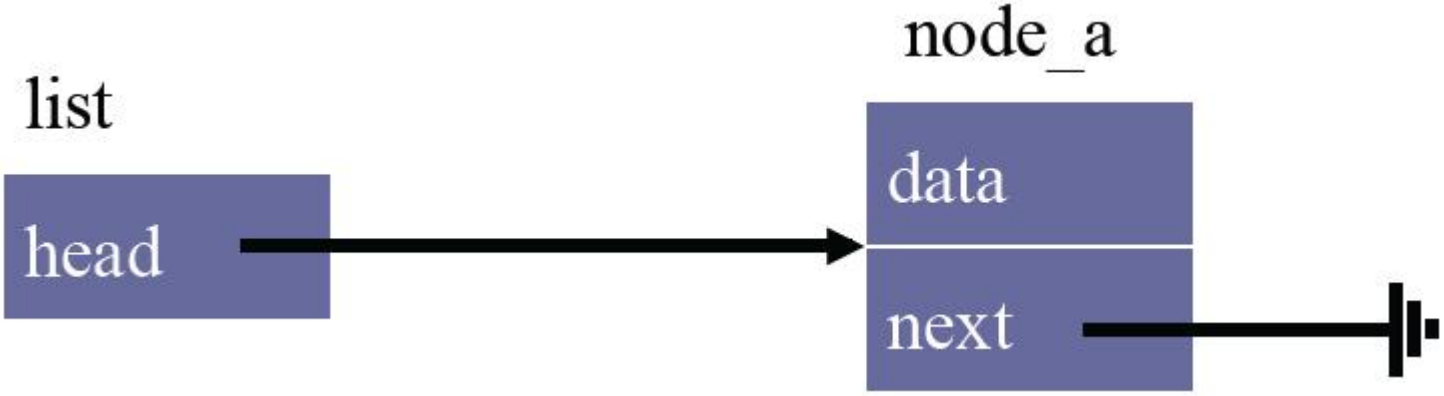
Another Timing ⇒ Incorrect Sum



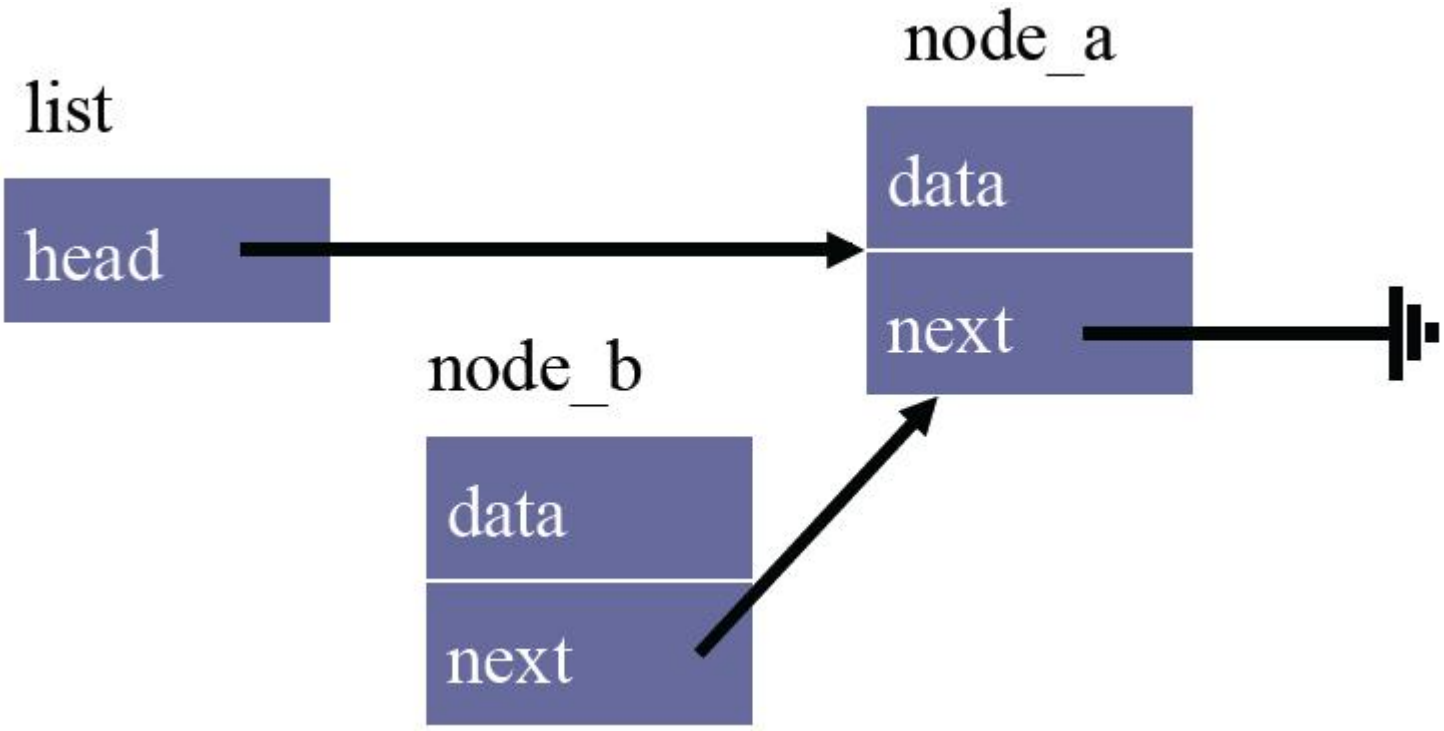
Another Race Condition Example

```
struct Node {
    struct Node* next;
    int data;
}
struct List {
    struct Node* head;
};
void AddHead (struct List* list, struct Node* node) {
    node->next = list->head;
    list->head = node;
}
```

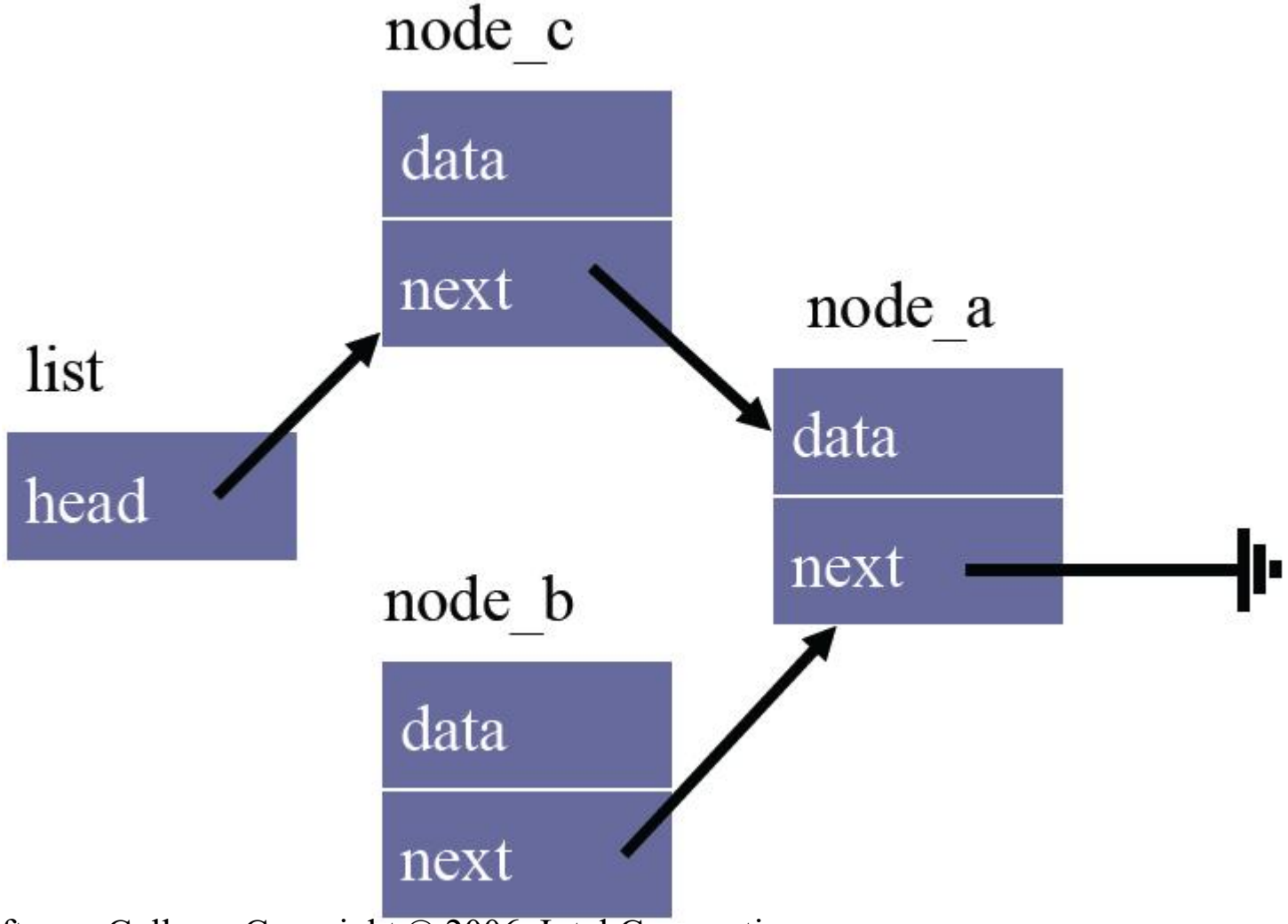
Original Singly-Linked List



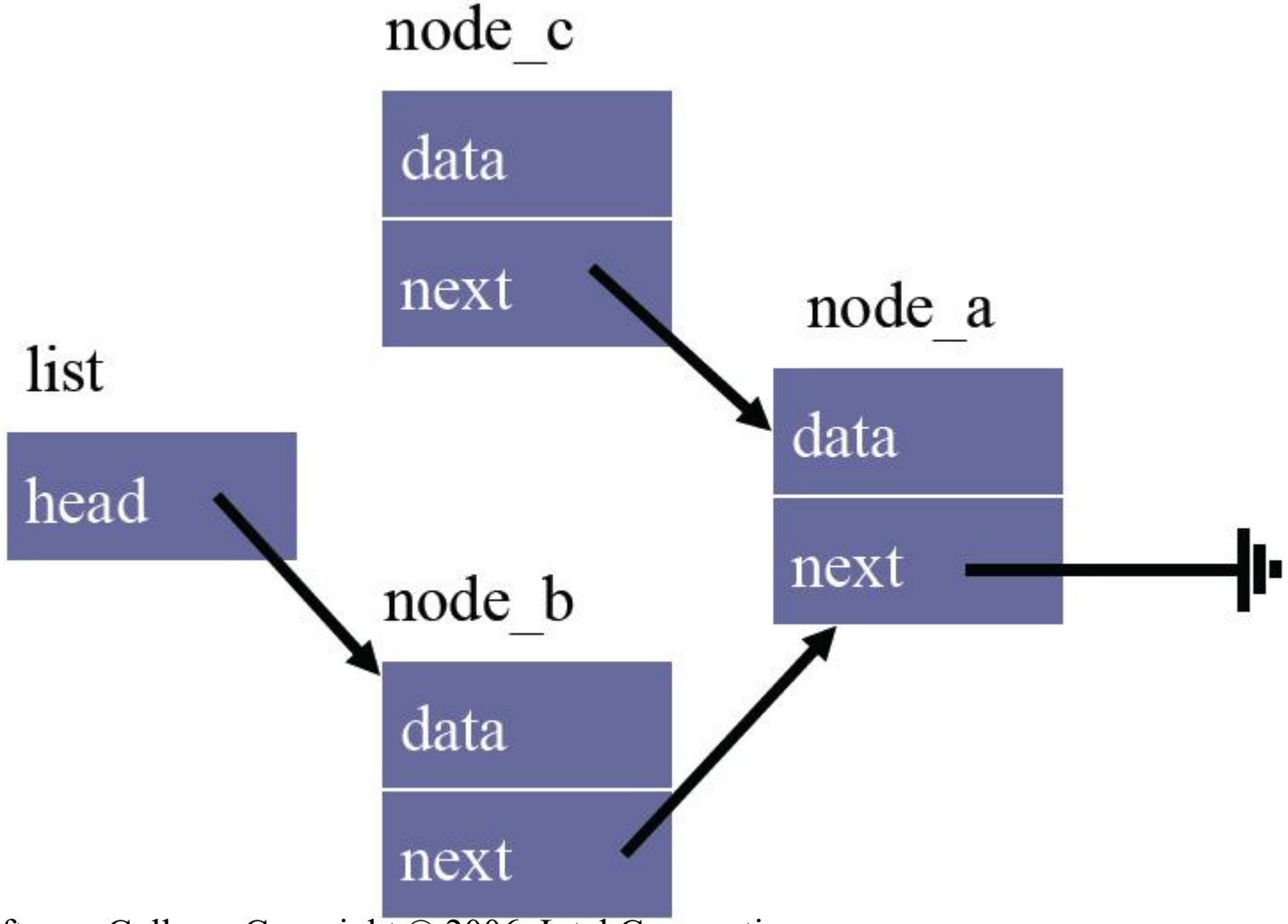
Thread 1 after Stmt. 1 of AddHead



Thread 2 Executes AddHead



Thread 1 after Stmt. 2 of AddHead



Why Race Conditions Are Nasty

- Programs with race conditions exhibit nondeterministic behavior
  - Sometimes give correct result
  - Sometimes give erroneous result
- Programs often work correctly on trivial data sets and small number of threads
- Errors more likely to occur when number of threads and/or execution time increases
- Hence debugging race conditions can be difficult

How to Avoid Race Conditions

- **Scope variables to be private to threads**
  - **Use OpenMP *private* clause**
  - **Variables declared within threaded functions**
  - **Allocate on thread's stack (pass as parameter)**
- **Control shared access with critical region**
  - **Mutual exclusion and synchronization**

Mutual Exclusion

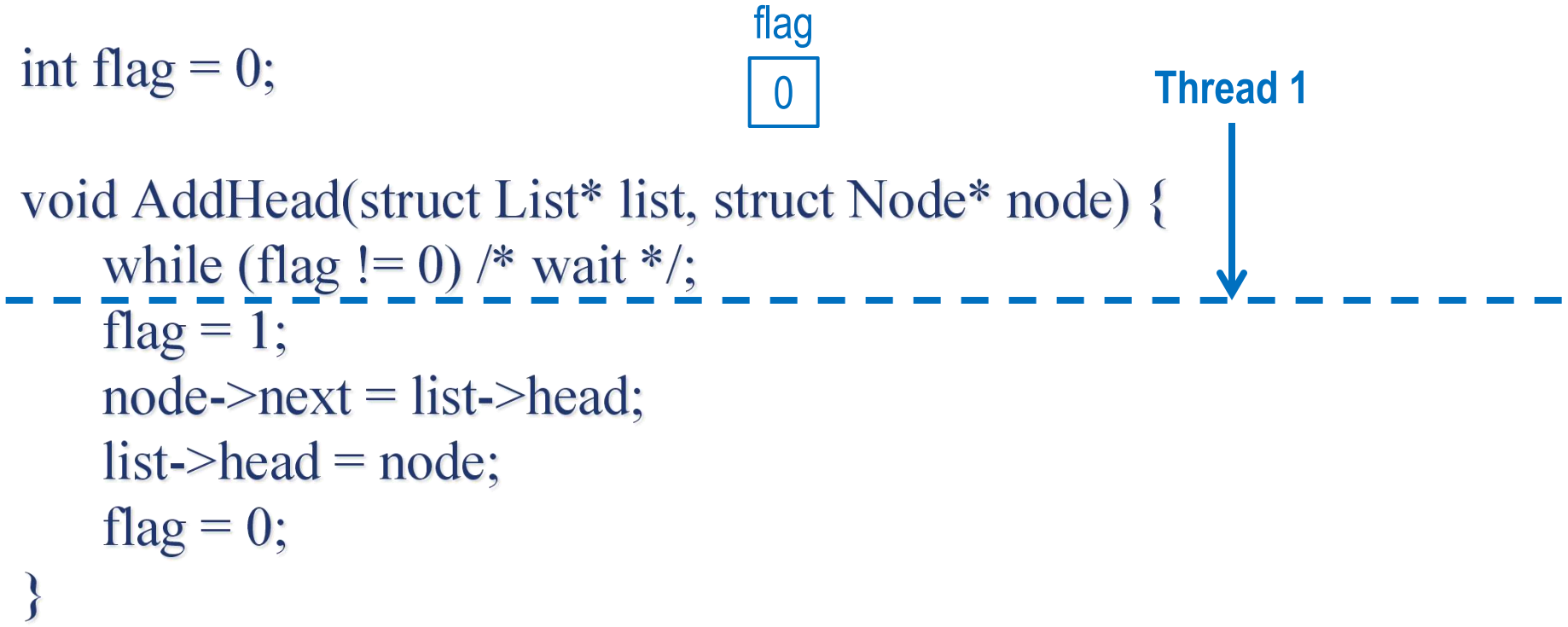
- We can prevent the race conditions described earlier…
  - Ensure that only one thread at a time references or updates shared variables
- Mutual exclusion
  - A kind of synchronization
  - Allows only a single thread or process at a time to have access to shared resource
  - Implemented using some form of locking

Do Flags Guarantee Mutual Exclusion?

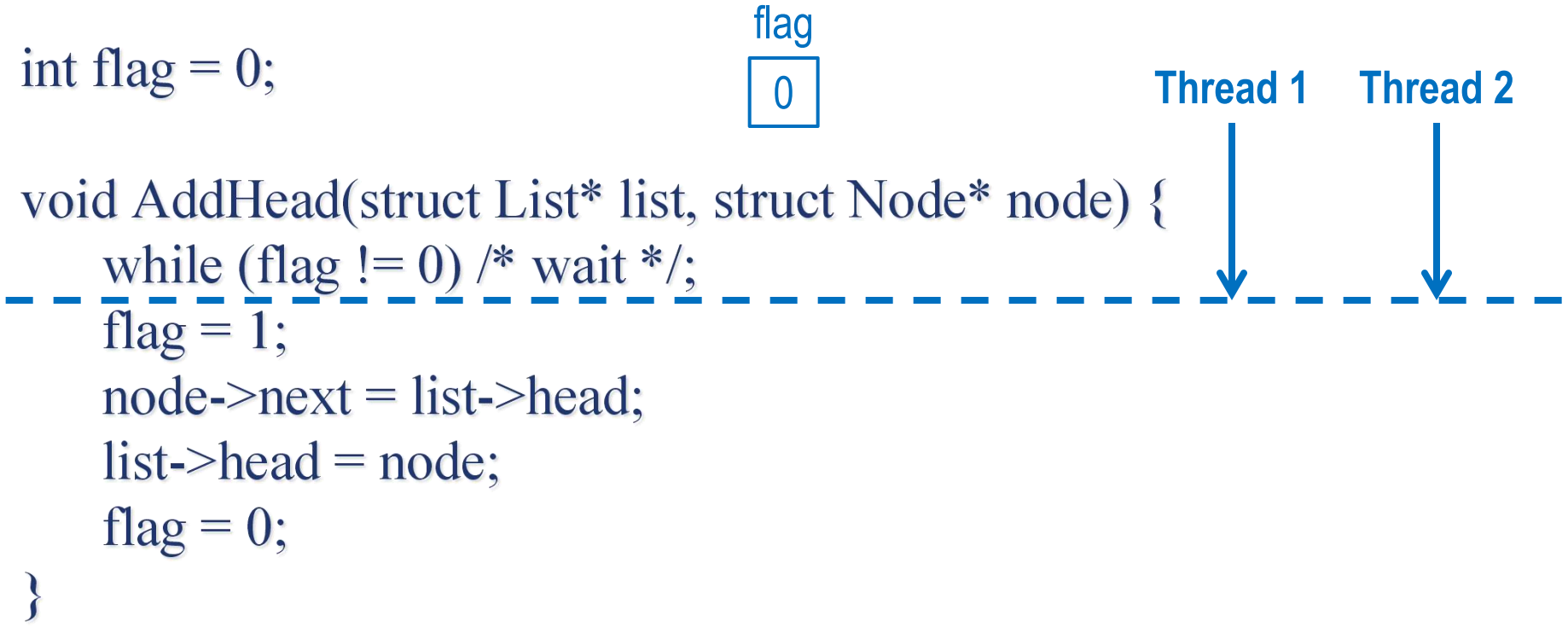
```
int flag = 0;

void AddHead(struct List* list, struct Node* node) {
    while (flag != 0) /* wait */;
    flag = 1;
    node->next = list->head;
    list->head = node;
    flag = 0;
}
```

Flags Don't Guarantee Mutual Exclusion



Flags Don't Guarantee Mutual Exclusion



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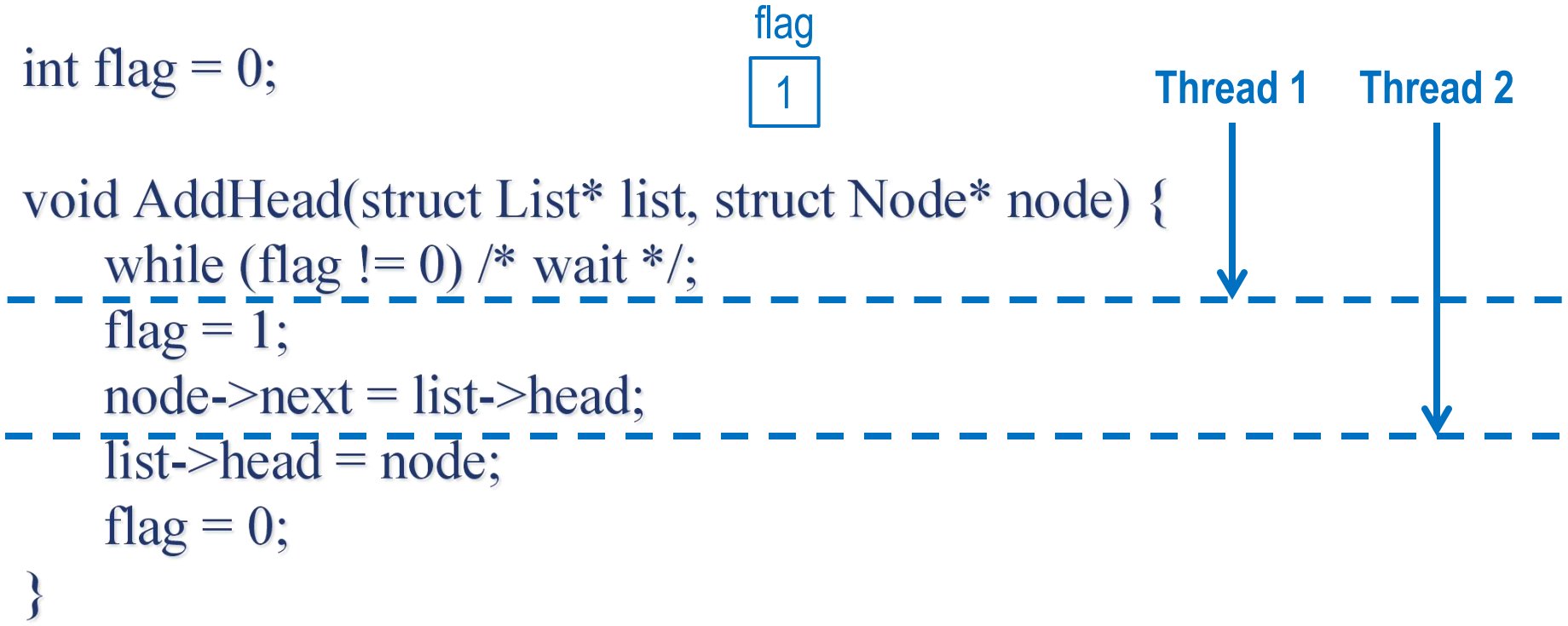
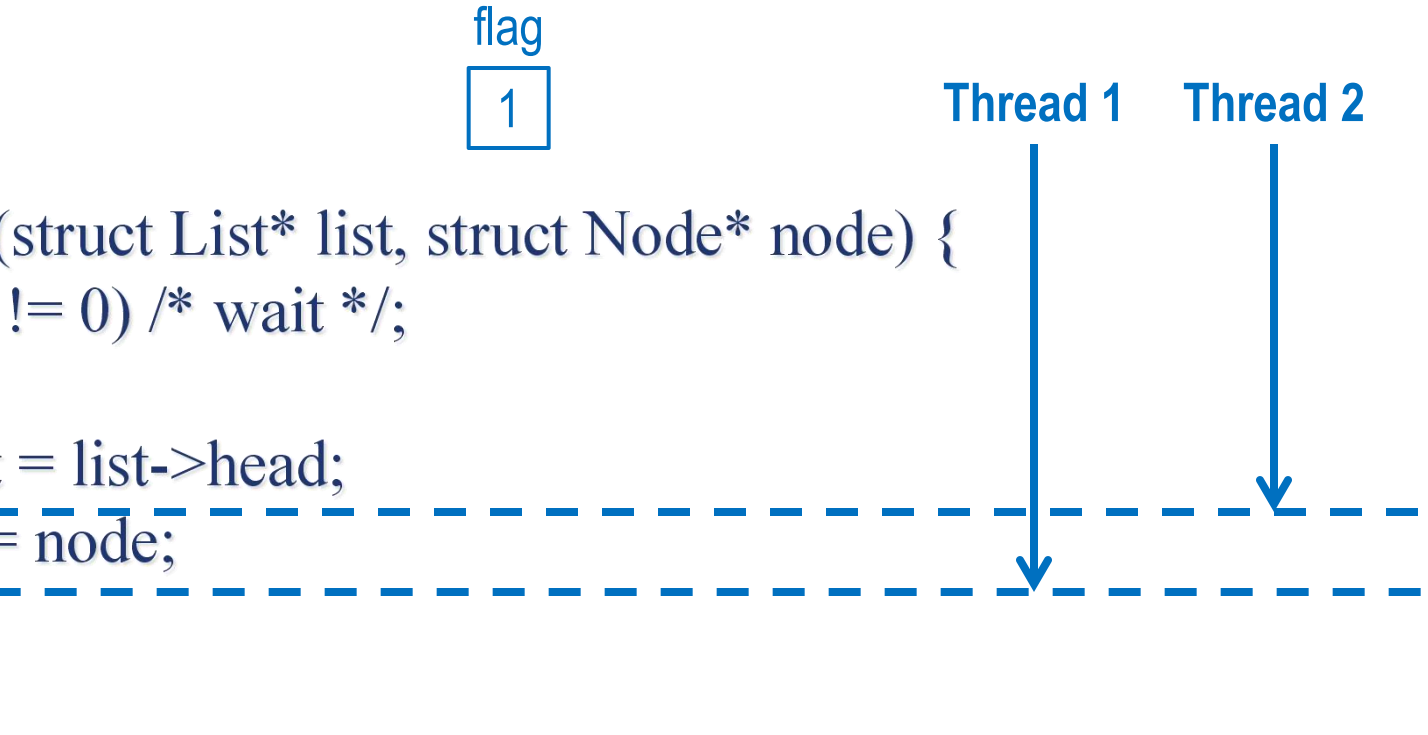
    node->next = list->head;
    list->head = node;
    flag = 0;
}
```



Flags Don't Guarantee Mutual Exclusion

```
int flag = 0;

void AddHead(struct List* list, struct Node* node) {
    while (flag != 0) /* wait */;
    flag = 1;
    node->next = list->head;
    list->head = node;
    flag = 0;
}
```



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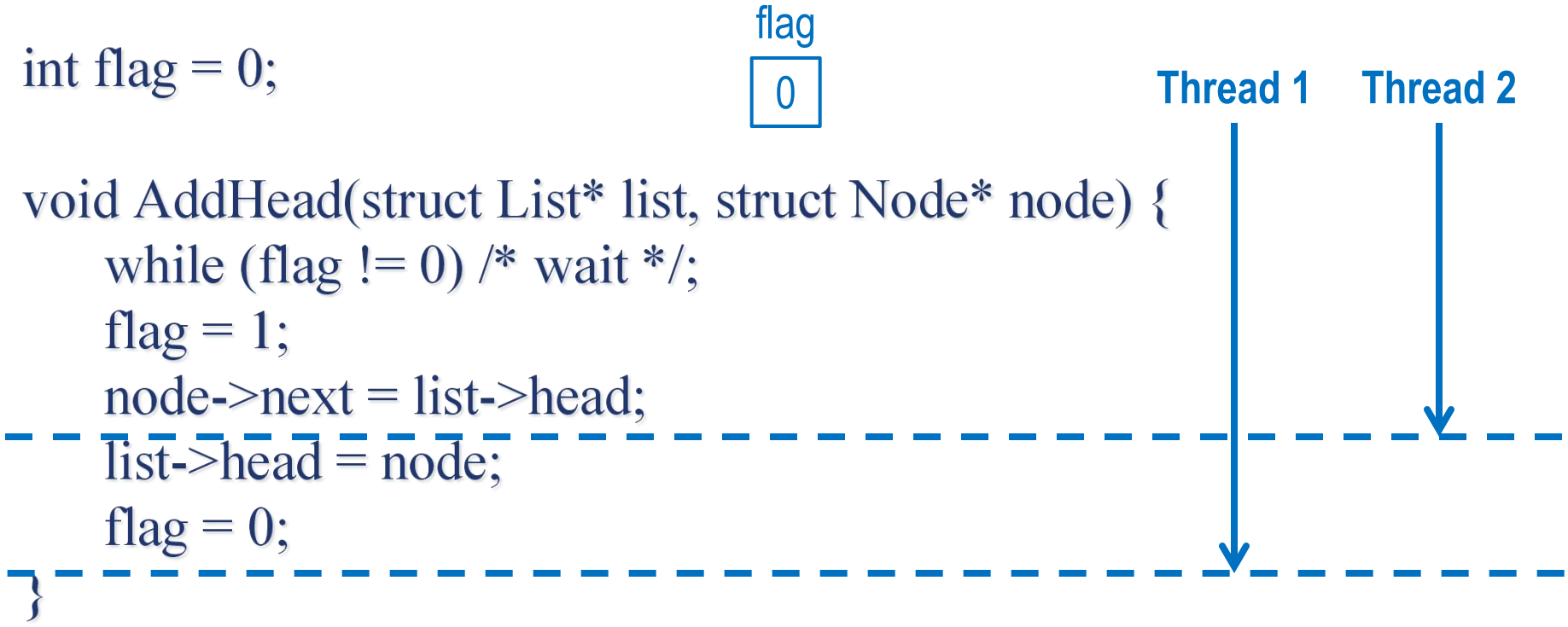
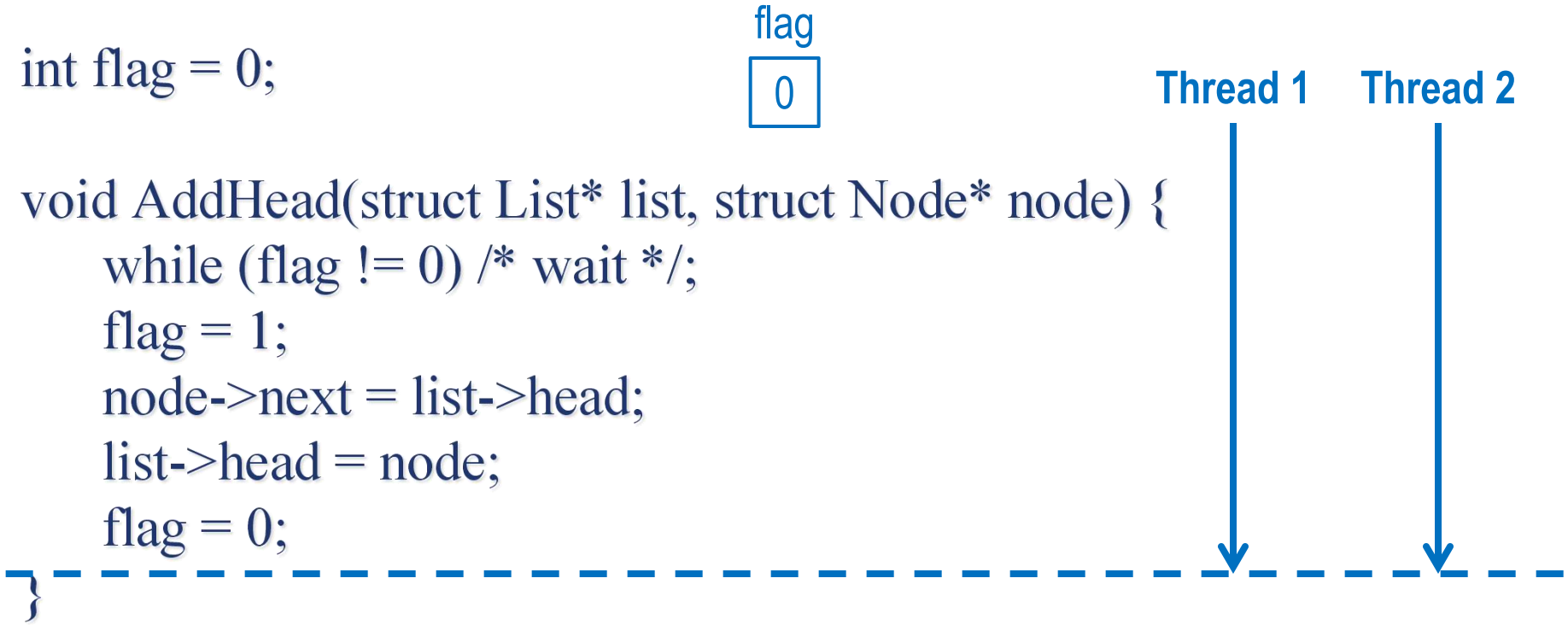


Flags Don't Guarantee Mutual Exclusion

```
int flag = 0;

void AddHead(struct List* list, struct Node* node) {
    while (flag != 0) /* wait */;
    flag = 1;
    node->next = list->head;
    list->head = node;
    flag = 0;
}
```



Locking Mechanism

- **The previous method fails because…**
  - **(i) Checking the value of *flag* and (ii) setting its value are two distinct operations**
- **We need some sort of *atomic* test-and-set**
  - **Operating systems provide functions to do this**
- **Lock**
  - **Synchronization mechanism used to control access to shared resources**
  - **(A generic term)**

Pragma: critical

- **Critical section**
  - **A portion of code that only thread at a time may execute (mutually exclusive)**
- **Syntax in OpenMP**

  #pragma omp critical
- **Good news! (^_^)**
  - **Critical sections eliminate race conditions**
- **Bad news! (@_@)**
  - **Critical sections are executed sequentially**
- **More bad news! (@_@)**
  - **You have to identify critical sections yourself**

Is the AddHead() Function Correct Now?

```
void AddHead(struct List* list, struct Node* node) {
    node->next = list->head;
#pragma omp critical
    list->head = node;
}
```

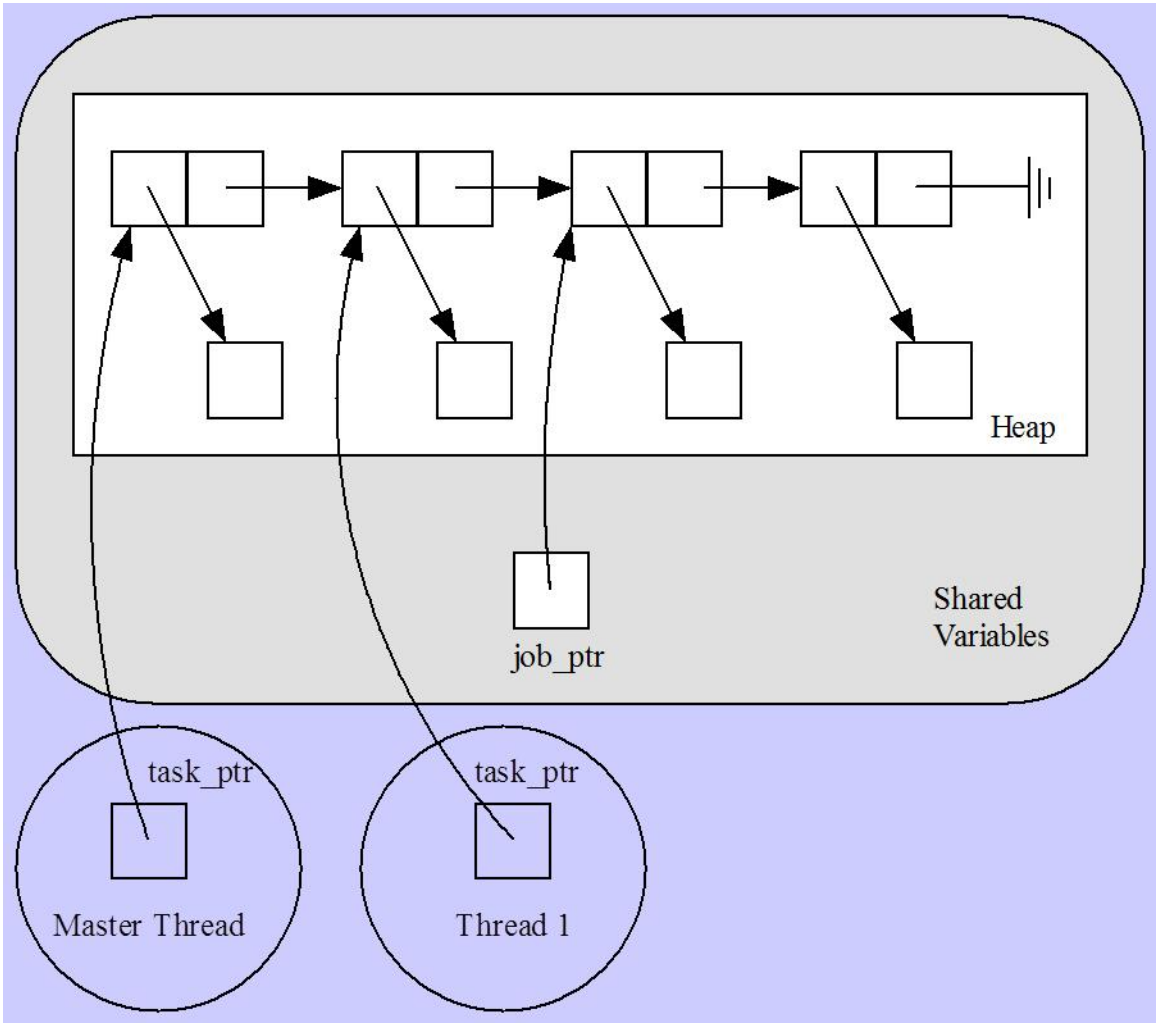
Protect All References to Shared Data

- You must protect both read and write access to any shared data
- For the AddHead() function, both lines need to be protected

Corrected AddHead() Function

```
void AddHead(struct List* list, struct Node* node) {
#pragma omp critical
    {
        node->next = list->head;
        list->head = node;
    }
}
```

Example: Processing a “To-Do” List



Michael J.Quinn, "Parallel Programming in C with MPI and OpenMP," 2003.

"To-Do" List: Sequential Code (1/2)

```
int main(int argc, char* argv[]) {
    struct task_struct* job_ptr;
    struct task_struct* task_ptr;
    …
    task_ptr = get_next_task(&job_ptr);
    while (task_ptr != NULL) {
        complete_task(task_ptr);
        task_ptr = get_next_task(&job_ptr);
    }
}
```

"To-Do" List: Sequential Code (2/2)

```
struct task_struct* get_next_task(struct task_struct** job_ptr) {
    struct task_struct* answer;
    if (*job_ptr == NULL) answer = NULL;
    else {
        answer = (*job_ptr)->task;
        *job_ptr = (*job_ptr)->next;
    }
    return answer;
}
```

Parallelization Strategy

- Every thread should repeatedly take next task from list and complete it, until there are no more tasks
- We must ensure no two threads take the same task from the list; i.e., must declare a critical section

"To-Do" List: Use of *parallel* Pragma

```
#pragma omp parallel private(task_ptr)
{
    task_ptr = get_next_task(&job_ptr);
    while (task_ptr != NULL) {
        complete_task(task_ptr);
        task_ptr = get_next_task(&job_ptr);
    }
}
```

- **Almost correct…**

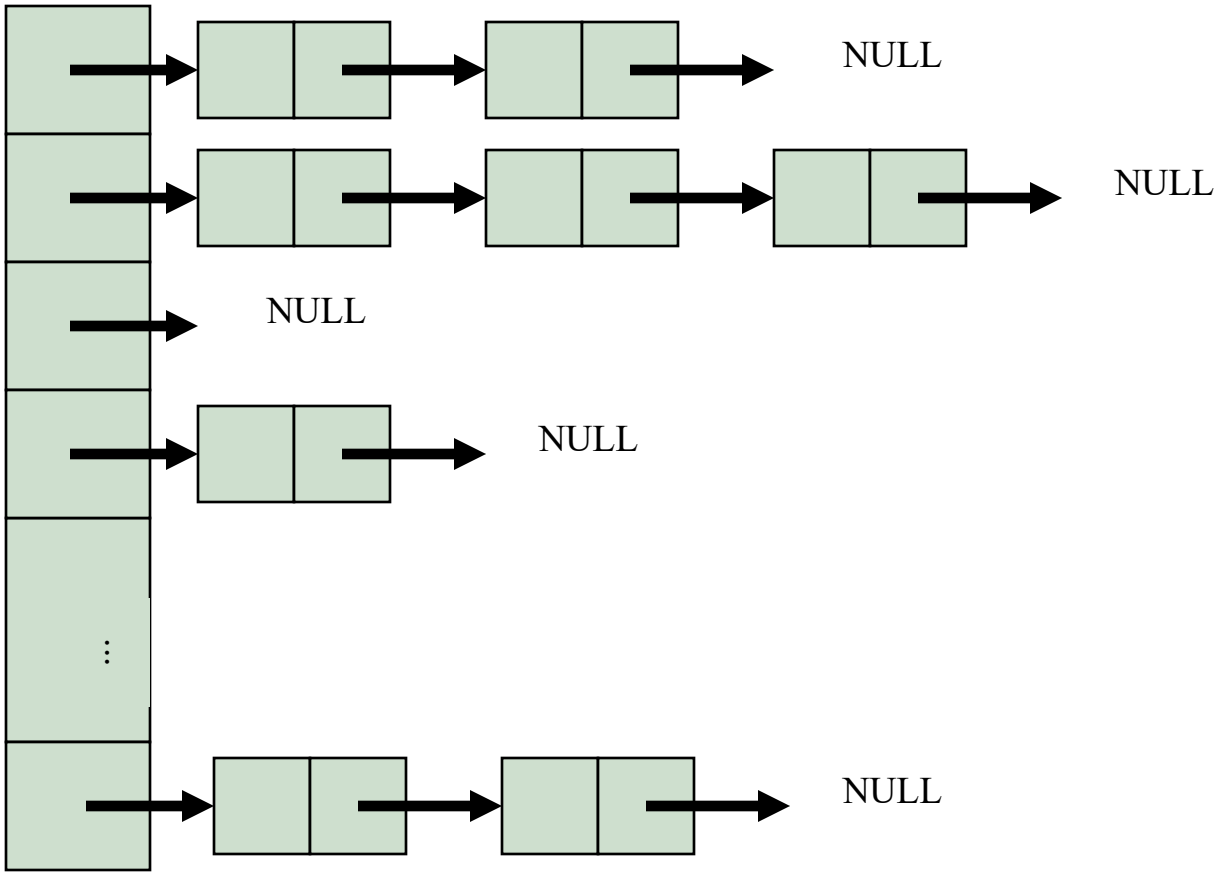
Critical Section for get_next_task

```
struct task_struct* get_next_task(struct task_struct** job_ptr) {
    struct task_struct* answer;
#pragma omp critical
    {
        if (*job_ptr == NULL) answer = NULL;
        else {
            answer = (*job_ptr)->task;
            *job_ptr = (*job_ptr)->next;
        }
    }
    return answer;
}
```

Important: Lock Data, Not Code

- **Locks should be associated with data objects**
- **Different data objects should have different locks**

Example: Hash Table Creation



Locking Code: Inefficient

```
#pragma omp parallel for private (index)
for (i = 0; i < elements; i++) {
   index = hash(element[i]);
   #pragma omp critical
   insert_element (element[i], index);
}
```

Locking Data: Efficient

Declaration

```
/* Static variable */
omp_lock_t hash_lock[HASH_TABLE_SIZE];
```

Initialization

```
/* Inside function 'main' */
for (i = 0; i < HASH_TABLE_SIZE; i++)
   omp_init_lock(&hash_lock[i]);
```

Use

```
void insert_element (ELEMENT e, int i)
{
   omp_set_lock (&hash_lock[i]);
   /* Code to insert element e */
   omp_unset_lock (&hash_lock[i]);
}
```

OpenMP atomic Construct

- **Special case of a critical section to ensure atomic update to memory location**
- **Applies only to simple operations:**
  - **Pre- or post-increment (++)**
  - **Pre- or post-decrement (--)**
  - **Assignment with binary operator (of scalar types)**
- **Works on a single statement**

```
#pragma omp atomic
counter += 5;
```

Critical vs. Atomic

```
#pragma omp parallel for
{
    for (i = 0; i < n; i++) {
#pragma omp critical
        x[index[i]] += WorkOne(i);
        y[i] += WorkTwo(i);
    }
}
```

- **Critical protect:**
  - **Call to WorkOne()**
  - **Finding value of index[i]**
  - **Addition of x[index[i]] and results of WorkOne()**
  - **Assignment to x array element**
- **Essentially, updates to elements in the x array are serialized**

```
#pragma omp parallel for
{
    for (i = 0; i < n; i++) {
#pragma omp atomic
        x[index[i]] += WorkOne(i);
        y[i] += WorkTwo(i);
    }
}
```

- **Atomic protects:**
  - **Addition and assignment to x array element**
- **Non-conflicting updates with be done in parallel**
- **Protection needed only if there are two threads where the index[i] values match**

Reminder: Motivating Example

```
double area, pi, x;
int i, n;
…
area = 0.0;
for (i = 0; i < n; i++) {
      x = (i + 0.5) / n;
      area += 4.0 / (1.0 + x*x);
}
pi = area / n;
```

- **Where is the critical section?**

Solution #1

```
double area, pi, tmp, x;
int i, n;
…
area = 0.0;
#pragma omp parallel for private(x)
for (i = 0; i < n; i++) {
      x = (i + 0.5) / n;
#pragma omp critical
      area += 4.0 / (1.0 + x*x);
}
pi = area / n;
```

- **This ensures area will end up with the correct value**
- **How can we do better?**

Solution #2

```
double area, pi, tmp, x;
int i, n;
…
area = 0.0;
#pragma omp parallel for private(x, tmp)
for (i = 0; i < n; i++) {
      x = (i + 0.5) / n;
      tmp = 4.0 / (1.0 + x*x);
#pragma omp critical
      area += tmp;
}
pi = area / n;
```

- **This reduces amount of time spent in critical section**
- **How can we do better?**

Solution #3

```
double area, pi, tmp, x;
int i, n;
…
area = 0.0;
#pragma omp parallel private(tmp)
{
    tmp = 0.0;
#pragma omp for private(x)
    for (i = 0; i < n; i++) {
        x = (i + 0.5) / n;
        tmp += 4.0 / (1.0 + x*x);
    }
#pragma omp critical
    area += tmp;
}
pi = area / n;
```

- **Why is this better?**
- **Can we still do better?**

Solution #4 Use Reduction

```
double area, pi, x;
int i, n;
...
area = 0.0;
#pragma omp parallel for private(x) \
                         reduction(+:area)
for (i = 0; i < n; i++) {
   x = (i + 0.5)/n;
   area += 4.0/(1.0 + x*x);
}
pi = area / n;
```

Memory Fences in OpenMP

- **Syntax**

  #pragma omp flush (<variable-list>)

  - **All the shared variables will be flushed without a list**
  - **Automatically inserted at most points where it is needed**
    - **at entry to and exit from** *parallel*
    - **at exit from** *for*
    - **at entry to and exit from** *parallel for*
    - *barrier*
    - **…**

- **identifies a point at which the compiler ensures that all threads in a parallel region have the same view of specified objects in memory**

Example: flush Pragma

```
int main() {
  int data;
  int flag = 0;
  #pragma omp parallel sections \
 num_threads(2)
  {
    #pragma omp section
    {
      printf_s("Thread %d: ",
omp_get_thread_num( ));
      read(&data);
      #pragma omp flush(data)
      flag = 1;
      #pragma omp flush(flag)
      // Do more work.
    }
```

```
    #pragma omp section
    {
      while (!flag) {
        #pragma omp flush(flag)
      }
      #pragma omp flush(data)

      printf_s("Thread %d: ",
omp_get_thread_num( ));
      process(&data);
      printf_s("data = %d\n", data);
    }
  }
}
```

Implicit flush at …

- barrier
- parallel - upon entry and exit
- critical - upon entry and exit
- ordered - upon entry and exit
- for - upon exit
- sections - upon exit
- single - upon exit

Summary

- **Synchronization (in OpenMP)**
  - **Barrier**
    - Statement ordering among different threads
    - Any statement after the barrier will be executed after the statements before the barrier in every thread
  - **Mutual Exclusion**
    - Access ordering of shared resources
    - A mechanism to avoid race conditions
  - **Memory fence**
    - Data-related statement ordering in the same threads
    - Any data-related statement before the memory fence will be executed before the statements after the memory fence

Further Readings

- **Real-world example**
  - Pandemic modeling using OpenMP
  - http://selkie.macalester.edu/csinparallel/modules/PandemicWithoutMPI/build/html/