Thread Synchronization

11/17/16

Threading: core ideas

- Threads allow more efficient use of resources.
  - Multiple cores
  - Down time while waiting for I/O
- Threads are better than processes for parallelism.
  - Cheaper to create and context switch
  - Easier to share information
- Threading makes programming harder.
  - Need to think about how to split a problem up
  - Need to think about how threads interact

Create and Join

- Each process starts with a single thread.
- Any thread can spawn new threads with `create`.
  - Starts a new call stack for the thread.
  - `create` specifies what function the thread starts with.
    - Processes always start with `main`.
    - Different threads can start with different functions.
  - Returns the ID of the new thread.

- `join` causes one thread to block until another thread completes.
  - `join` must specify the ID of the thread to wait for.
  - `join` gives access to the thread function's return value.

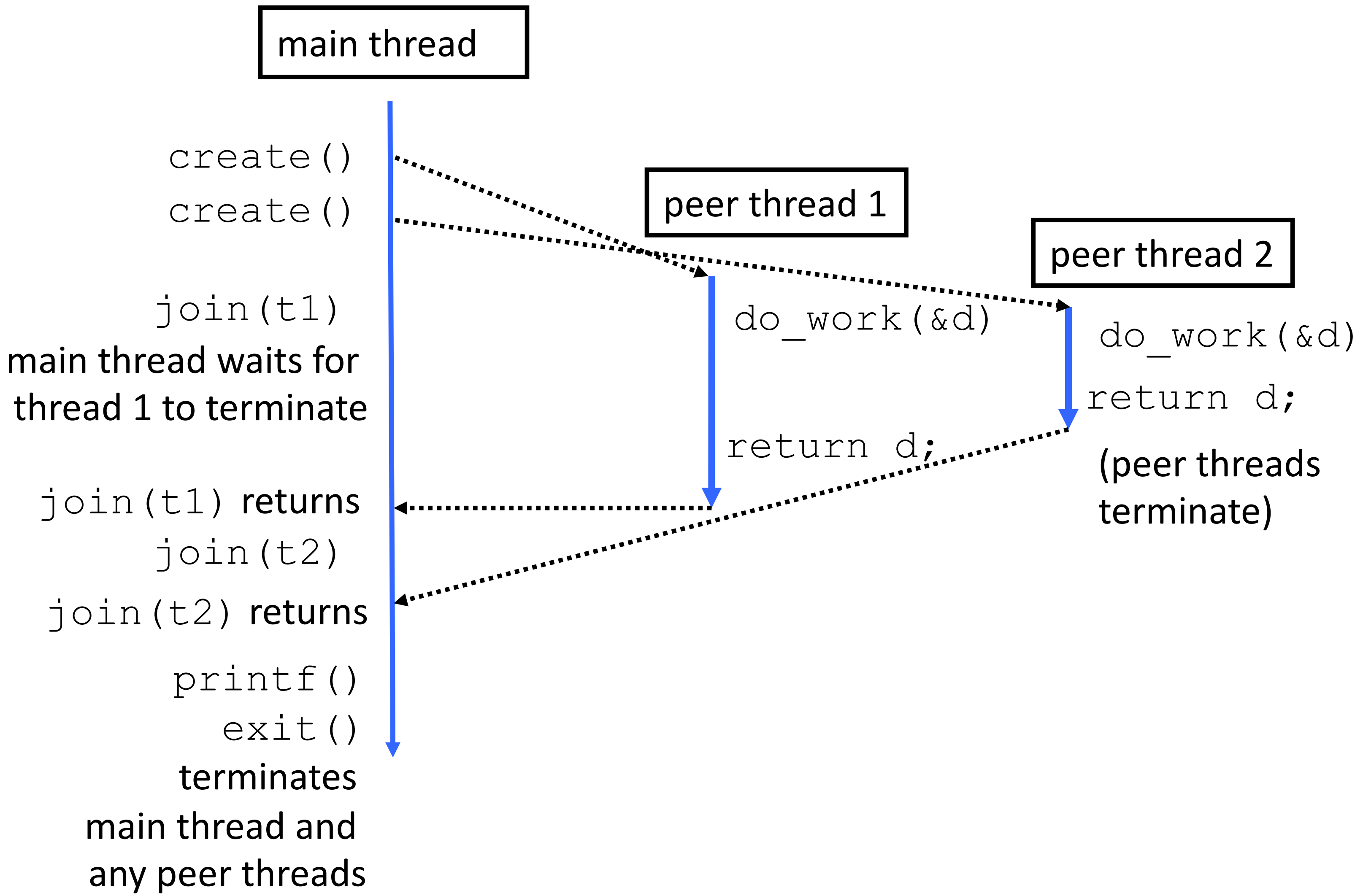
Create and Join example

IMPORTANT: this is not correct C code. We will talk about the pthreads library next week.

```
main(){
   double x = 1, y = -1;
   tid t1, t2;
   double res;
   t1 = create(worker, x);
   t2 = create(worker, y);
   res = join(t1);
   res += join(t2);
   printf("%d\n",res);
}
```

```
worker(double d){
   do_work(&d);
   return d;
}
```

Create and Join illustrated



Thread Ordering

(Why threads require care. Reasoning about this is hard.)

- As a programmer you have *no idea* when threads will run. The OS schedules them, and the schedule will vary across runs.
- It might decide to context switch from one thread to another *at any time*.
- Your code must be prepared for this!
  - Ask yourself: “Would something bad happen if we context switched here?”

Example: The Credit/Debit Problem

- Say you have $1000 in your bank account
  - You deposit $100
  - You also withdraw $100

- How much should be in your account?

- What if your deposit and withdrawal occur at the same time, at different ATMs?

Credit/Debit Problem: Race Condition

Thread T_0

```
Credit (int a) {
  int b;

  b = ReadBalance ();
  b = b + a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Thread T_1

```
Debit (int a) {
  int b;

  b = ReadBalance ();
  b = b - a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Credit/Debit Problem: Race Condition

Say T_0 runs first
Read $1000 into b

Thread T_0

```
Credit (int a) {
  int b;

  b = ReadBalance ();
  b = b + a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Thread T_1

```
Debit (int a) {
  int b;

  b = ReadBalance ();
  b = b - a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Credit/Debit Problem: Race Condition

Say T_0 runs first
Read \$1000 into b
Switch to T_1
Read \$1000 into b Debit by \$100 Write \$900

Thread T_0

```
Credit (int a) {
  int b;

  b = ReadBalance ();
  b = b + a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Thread T_1

```
Debit (int a) {
  int b;

  b = ReadBalance ();
  b = b - a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Credit/Debit Problem: Race Condition

<u>Race Condition</u>: outcome depends on scheduling order of concurrent threads.

Say T_0 runs first
Read \$1000 into b
Switch to T_1
Read \$1000 into b Debit by \$100 Write \$900

Thread T_0

```
Credit (int a) {
  int b;

  b = ReadBalance ();
  b = b + a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Thread T_1

```
Debit (int a) {
  int b;

  b = ReadBalance ();
  b = b - a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Switch back to T_0
Read \$1000 into b Credit \$100 Write \$1100

Bank gave you \$100!

What went wrong?

“Critical Section”

Thread T_0

```
Credit (int a) {
  int b;

  b = ReadBalance ();
  b = b + a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Badness if context switch here!

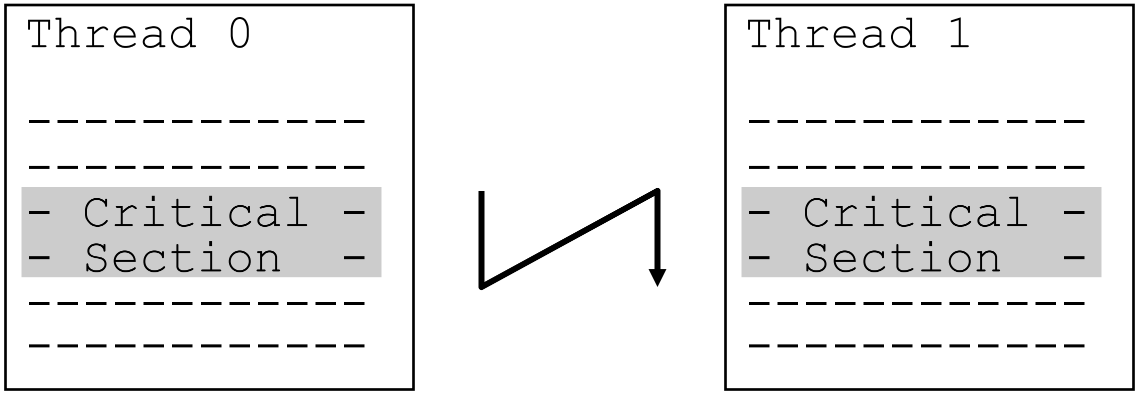
Thread T_1

```
Debit (int a) {
  int b;

  b = ReadBalance ();
  b = b - a;
  WriteBalance (b);

  PrintReceipt (b);
}
```

Bank gave you $100!

What went wrong?

To Avoid Race Conditions



1. Identify critical sections

2. Use synchronization to enforce mutual exclusion
   - Only one thread active in a critical section

What Are Critical Sections?

- Sections of code executed by multiple threads
  - Access shared variables, often making local copy
  - Places where order of execution or thread interleaving will affect the outcome

- Must run atomically with respect to each other
  - Atomicity: runs as an entire unit or not at all. Cannot be divided into smaller parts.

Which code region is a critical section?

Thread A

```
thread_main ()
{ int a,b;

  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);

  a += 1

  return a;
}
```

A B C D E

shared memory

```
s = 40;
```

Thread B

```
thread_main()
{ int a,b;

  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);

  a += 1

  return a;
}
```

Which values might the shared `s` variable hold after both threads finish?

Thread A

```
thread_main ()
{ int a,b;

  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);

  return a;
}
```

Thread B

```
thread_main ()
{ int a,b;

  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);

  return a;
}
```

shared memory

```
s = 40;
```

A. 30
B. 20 or 30
C. 20, 30, or 50
D. Another set of values

If A runs first

Thread A

```
main ()
{ int a,b;

  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);

  return a;
}
```

shared memory

```
s = 50;
```

Thread B

```
main ()
{ int a,b;

  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);

  return a;
}
```

B runs after A Completes

Thread A

```
main ()
{ int a,b;

  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);

  return a;
}
```

Thread B

```
main ()
{ int a,b;

  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);

  return a;
}
```

shared memory

```
s = 30;
```

What about interleaving?

Thread A

```
main ()
{  int a,b;

   a = getShared();
   b = 10;
   a = a + b;
   saveShared(a);

   return a;
}
```

Thread B

```
main ()
{  int a,b;

   a = getShared();
   b = 20;
   a = a - b;
   saveShared(a);

   return a;
}
```

shared memory

```
s = 40;
```

Is there a race condition?

Suppose `count` is a global variable, multiple threads increment it:

```
count++;
```

A. Yes, there's a race condition (`count++` is a critical section).

B. No, there's no race condition (`count++` is not a critical section).

C. Cannot be determined.

How about if compiler implements it as:

```
movl (%edx), %eax    // read count value
addl $1, %eax        // modify value
movl %eax, (%edx)    // write count
```

How about if compiler implements it as:

```
incl (%edx)                    //
increment value
```

Mutex Locks

The OS provides the following atomic operations:

- Acquire/lock a mutex.
  - If no other thread has locked the mutex, claim it.
  - If another thread holds the mutex, block.
  - Threads unblocked in FIFO order.
- Release/unlock a mutex.

To enforce a critical section:

- Before the critical section, lock the mutex.
- After the critical section unlock the mutex.

Using Locks

Thread A

```
main ()
{ int a,b;



  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);



  return a;
}
```

shared memory

```
s = 40;
```

Thread B

```
main ()
{ int a,b;



  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);



  return a;
}
```

Using Locks

Thread A

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);
  release(l);

  return a;
}
```

Thread B

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);
  release(l);

  return a;
}
```

shared memory

```
s = 40;
Lock l;
```

Held by: Nobody

Using Locks

Thread A

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);
  release(l);

  return a;
}
```

Thread B

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);
  release(l);

  return a;
}
```

shared memory

```
s = 40;
Lock l;
```

Held by: Thread A

Using Locks

Thread A

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);
  release(l);

  return a;
}
```

Thread B

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);
  release(l);

  return a;
}
```

shared memory

```
s = 40;
Lock l;
```

Held by: Thread A

Using Locks

Lock already owned.

Must Wait!

Thread A

```
main ()
{  int a,b;

   acquire(l);
   a = getShared();
   b = 10;
   a = a + b;
   saveShared(a);
   release(l);

   return a;
}
```

Thread B

```
main ()
{  int a,b;

   acquire(l);
   a = getShared();
   b = 20;
   a = a - b;
   saveShared(a);
   release(l);

   return a;
}
```

shared memory

```
s = 40;
Lock l;
```

Held by: Thread A

Using Locks

Thread A

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);
  release(l);

  return a;
}
```

Thread B

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);
  release(l);

  return a;
}
```

shared memory

```
s = 50;
Lock l;
```

Held by: Nobody

Using Locks

Thread A

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);
  release(l);

  return a;
}
```

shared memory

```
s = 30;
Lock l;
```

Held by: Thread B

Thread B

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);
  release(l);

  return a;
}
```

Using Locks

Thread A

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 10;
  a = a + b;
  saveShared(a);
  release(l);

  return a;
}
```

Thread B

```
main ()
{ int a,b;

  acquire(l);
  a = getShared();
  b = 20;
  a = a - b;
  saveShared(a);
  release(l);

  return a;
}
```

shared memory

```
s = 30;
Lock l;
```

Held by: Nobody

- No matter how we order threads or when we context switch, result will always be 30, like we expected (and probably wanted).

Synchronizing Threads

Sometimes we want all threads to catch up to a specific point before we continue.

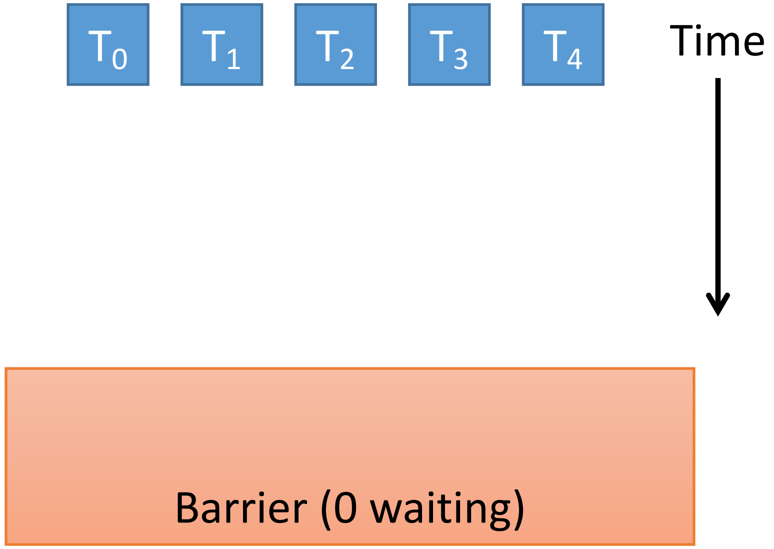
- Think about parallelizing the polygons simulator.
  - We could split up regions of the world across threads.
  - We don’t want one thread to start round 2 before another has finished round 1.

Solution: barriers

- A thread that calls barrier_wait will block until all other threads have also called barrier_wait.

Barrier Example, N Threads

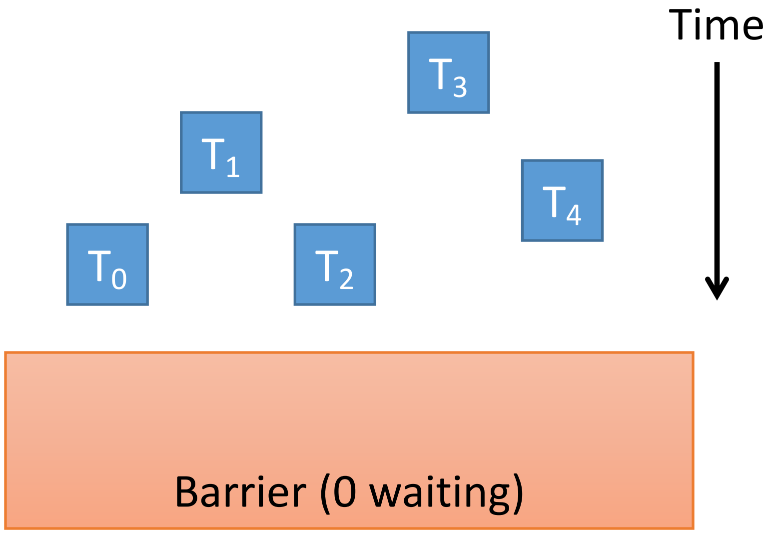
```
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
  while (…) {
    compute_sim_round()
    barrier_wait(&b)
  }
}
```



Barrier Example, N Threads

```
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
  while (…) {
    compute_sim_round()
    barrier_wait(&b)
  }
}
```

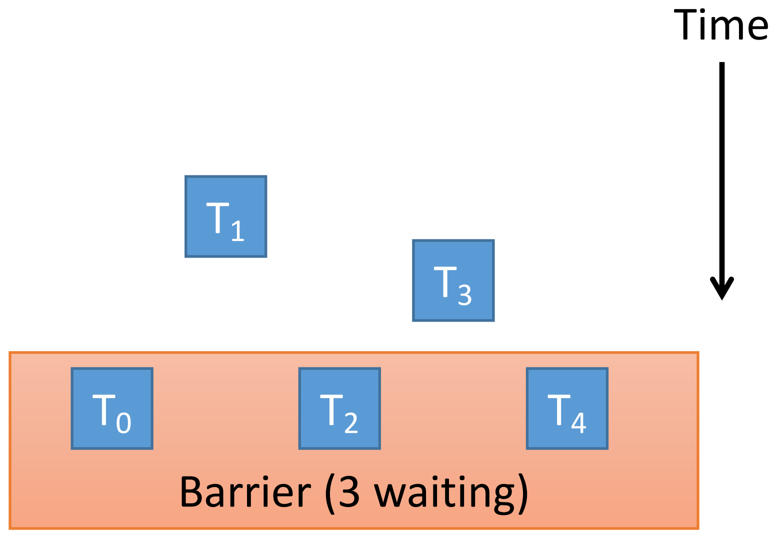
Threads make progress computing current round at different rates.



Barrier Example, N Threads

```
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
  while (…) {
    compute_sim_round()
    barrier_wait(&b)
  }
}
```

Threads that make it to barrier must wait for all others to get there.



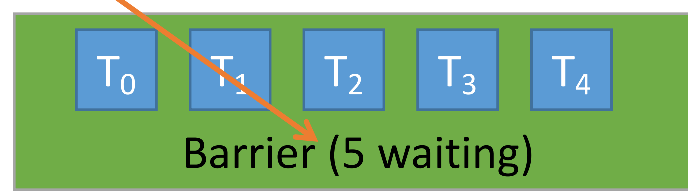
Barrier Example, N Threads

Barrier allows threads to pass when N threads reach it.

```
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
  while (…) {
    compute_sim_round()
    barrier_wait(&b)
  }
}
```

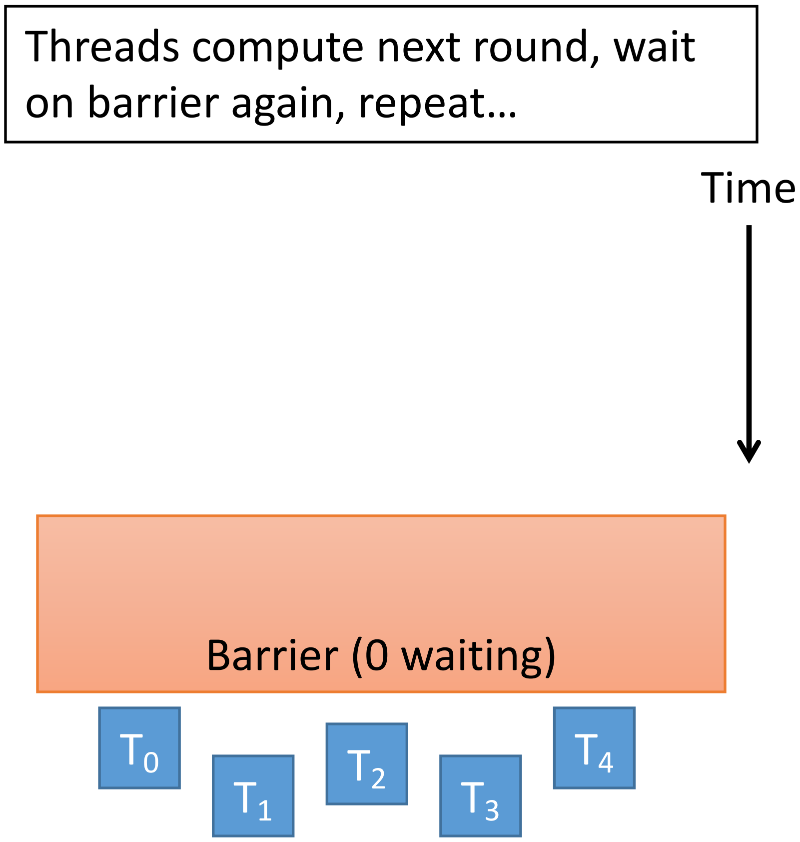
Matches

Time



Barrier Example, N Threads

```
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

void *func(void *arg) {
  while (…) {
    compute_sim_round()
    barrier_wait(&b)
  }
}
```



Thread operations

- create
  - Starts a new thread, calling a specified function.
  - Returns the thread’s ID.
- join
  - Block until a specified thread terminates.
  - Gives access to the thread function’s return value.
- mutex_lock
  - Block until the mutex is available, then claim it.
- mutex_unlock
  - Release a mutex.
- barrier_wait
  - Block until a specified number of threads reach the barrier.

Devise a parallel algorithm for max

Write pseudocode for main and a thread function that uses (some of) create, join, mutex_lock, mutex_unlock, and barrier_wait.

- Array size M
- N threads

- Version 1: each thread returns its local max
- Version 2: each thread updates a global max
- Version 3: the thread that found the max prints