# CS 31: Intro to Systems
# Misc. Threading

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# Agenda

- Classic thread patterns

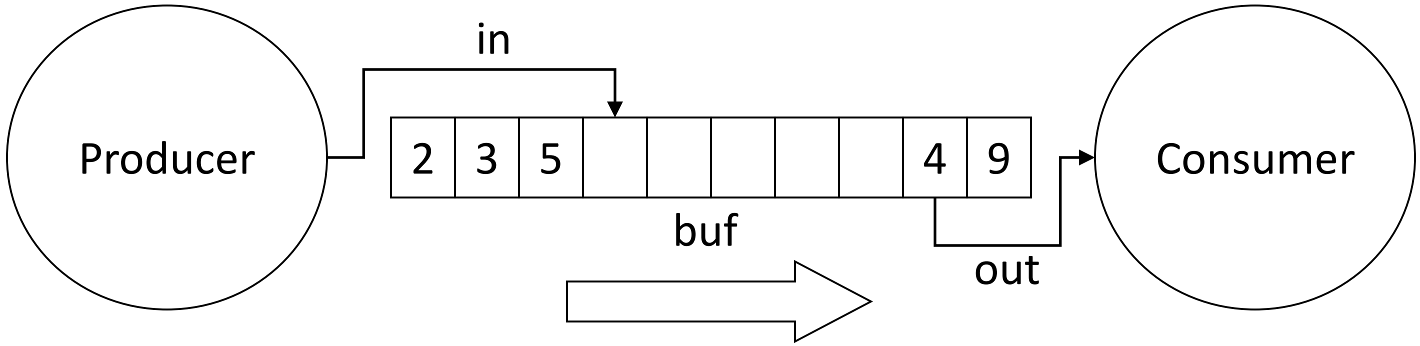
- Pthreads primitives and examples of other forms of synchronization:
  - Condition variables
  - Barriers
  - RW locks
  - Message passing

- Message passing: alternative to shared memory

# Common Thread Patterns

- Producer / Consumer (a.k.a. Bounded buffer)
- Thread pool (a.k.a. work queue)
- Thread per client connection

# The Producer/Consumer Problem




- Producer produces data, places it in shared buffer
- Consumer consumes data, removes from buffer
- Cooperation: Producer feeds Consumer
  - How does data get from Producer to Consumer?
  - How does Consumer wait for Producer?

# Producer/Consumer: Shared Memory

```
shared int buf[N], in = 0, out = 0;
```

**Producer**

```
while (TRUE) {
    buf[in] = Produce ();
    in = (in + 1)%N;
}
```

**Consumer**

```
while (TRUE) {
    Consume (buf[out]);
    out = (out + 1)%N;
}
```

- Data transferred in shared memory buffer.

# Producer/Consumer: Shared Memory

```
shared int buf[N], in = 0, out = 0;
```

**Producer**

```
while (TRUE) {
    buf[in] = Produce ();
    in = (in + 1)%N;
}
```

**Consumer**

```
while (TRUE) {
    Consume (buf[out]);
    out = (out + 1)%N;
}
```

- Data transferred in shared memory buffer.

- Is there a problem with this code?
  - A. Yes, this is broken.
  - B. No, this ought to be fine.

# This producer/consumer scenario requires synchronization to…

```
shared int buf[N], in = 0, out = 0;
```

**Producer**

```
while (TRUE) {
    buf[in] = Produce ();
    in = (in + 1)%N;
}
```

**Consumer**

```
while (TRUE) {
    Consume (buf[out]);
    out = (out + 1)%N;
}
```

A. Avoid deadlock

B. Avoid double writes or empty consumes of buf[] slots

C. Protect a critical section with mutual exclusion

D. Copy data from producer to consumer

# Adding Semaphores

```
shared int buf[N], in = 0, out = 0;
shared sem filledslots = 0, emptyslots = N;
```

**Producer**

```
while (TRUE) {
    wait (X);
    buf[in] = Produce ();
    in = (in + 1)%N;
    signal (Y);
}
```

**Consumer**

```
while (TRUE) {
    wait (Z);
    Consume (buf[out]);
    out = (out + 1)%N;
    signal (W);
}
```

- Recall semaphores:
  - wait(): decrement sem and block if sem value < 0
  - signal(): increment sem and unblock a waiting process (if any)

# Suppose we now have two semaphores to protect our array. Where do we use them?

```
shared int buf[N], in = 0, out = 0;
shared sem filledslots = 0, emptyslots = N;
```

**Producer**

```
while (TRUE) {
    wait (X);
    buf[in] = Produce ();
    in = (in + 1)%N;
    signal (Y);
}
```

**Consumer**

```
while (TRUE) {
    wait (Z);
    Consume (buf[out]);
    out = (out + 1)%N;
    signal (W);
}
```

| Answer choice | X | Y | Z | W |
|---|---|---|---|---|
| A. | emptyslots | emptyslots | filledslots | filledslots |
| B. | emptyslots | filledslots | filledslots | emptyslots |
| C. | filledslots | emptyslots | emptyslots | filledslots |

# Add Semaphores for Synchronization

```
shared int buf[N], in = 0, out = 0;
shared sem filledslots = 0, emptyslots = N;
```

**Producer**

```
while (TRUE) {
    wait (emptyslots);
    buf[in] = Produce ();
    in = (in + 1)%N;
    signal (filledslots);
}
```

**Consumer**

```
while (TRUE) {
    wait (filledslots);
    Consume (buf[out]);
    out = (out + 1)%N;
    signal (emptyslots);
}
```

- Buffer empty, Consumer waits
- Buffer full, Producer waits
- Don’t confuse synchronization with mutual exclusion

# Synchronization: More than Mutexes

- “I want to block a thread until something specific happens.”
  - Condition variable: wait for a condition to be true

# Condition Variables

- In the pthreads library:
  - pthread_cond_init: Initialize CV
  - pthread_cond_wait: Wait on CV
  - pthread_cond_signal: Wakeup one waiter
  - pthread_cond_broadcast: Wakeup all waiters

- Condition variable is associated with a mutex:
  1. Lock mutex, realize conditions aren’t ready yet
  2. Temporarily give up mutex until CV signaled
  3. Reacquire mutex and wake up when ready

# Condition Variable Pattern

```
while (TRUE) {
    //independent code

    lock(m);
    while (conditions bad)
       wait(cond, m);

    //proceed knowing that conditions are now good

    signal (other_cond);  // Let other thread know
    unlock(m);
}
```

# Condition Variable Example

```
shared int buf[N], in = 0, out = 0;
shared int count = 0;  // # of items in buffer
shared mutex m;
shared cond notempty, notfull;
```

**Producer**

```
while (TRUE) {
   item = Produce();

   lock(m);
   while (count == N)
      wait(m, notfull);

   buf[in] = item;
   in = (in + 1)%N;
   count += 1;

   signal (notempty);
   unlock(m);
}
```

**Consumer**

```
while (TRUE) {
   lock(m);
   while (count == 0)
      wait(m, notempty);

   item = buf[out];
   out = (out + 1)%N;
   count -= 1;

   signal (notfull);
   unlock(m);

   Consume(item);
}
```

# Synchronization: More than Mutexes

- “I want to block a thread until something specific happens.”
  - Condition variable: wait for a condition to be true
- “I want all my threads to sync up at the same point.”
  - Barrier: wait for everyone to catch up.

# Barriers

- Used to coordinate threads, but also other forms of concurrent execution.

- Often found in simulations that have discrete rounds.  (e.g., game of life)

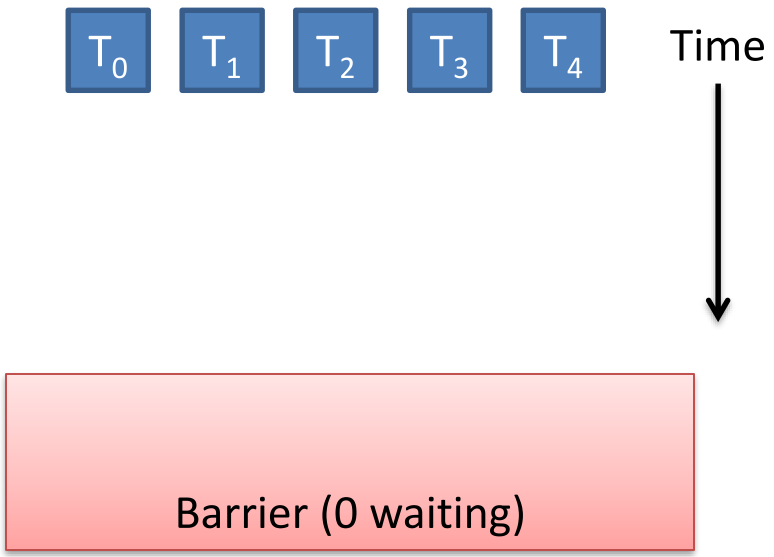
# Barrier Example, N Threads

```
shared barrier b;

init_barrier(&b, N);

create_threads(N, func);

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



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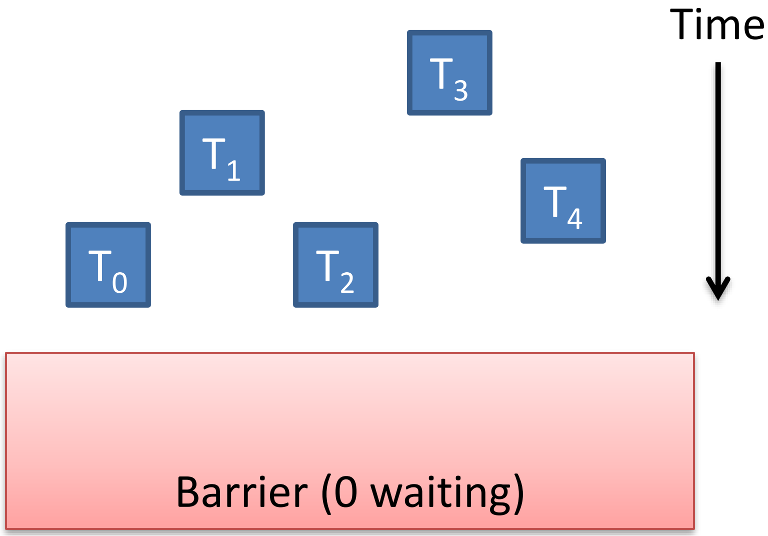
```

Threads make progress computing current round at different rates.



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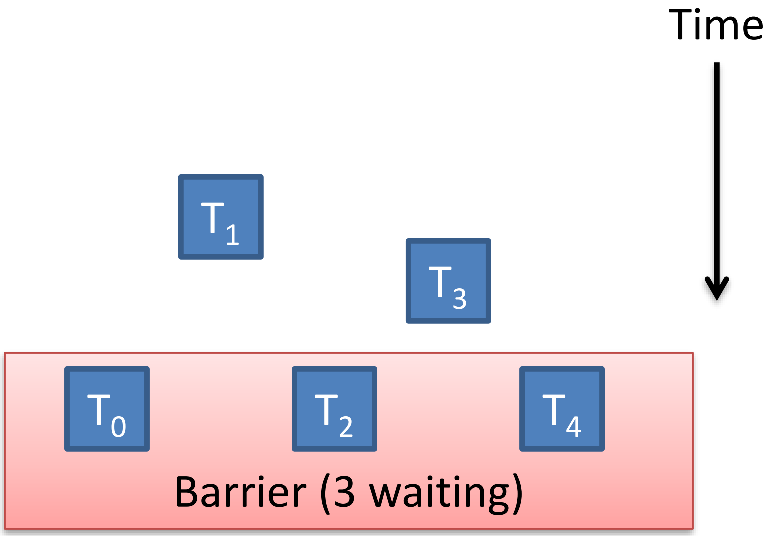
Threads that make it to barrier must wait for all others to get there.



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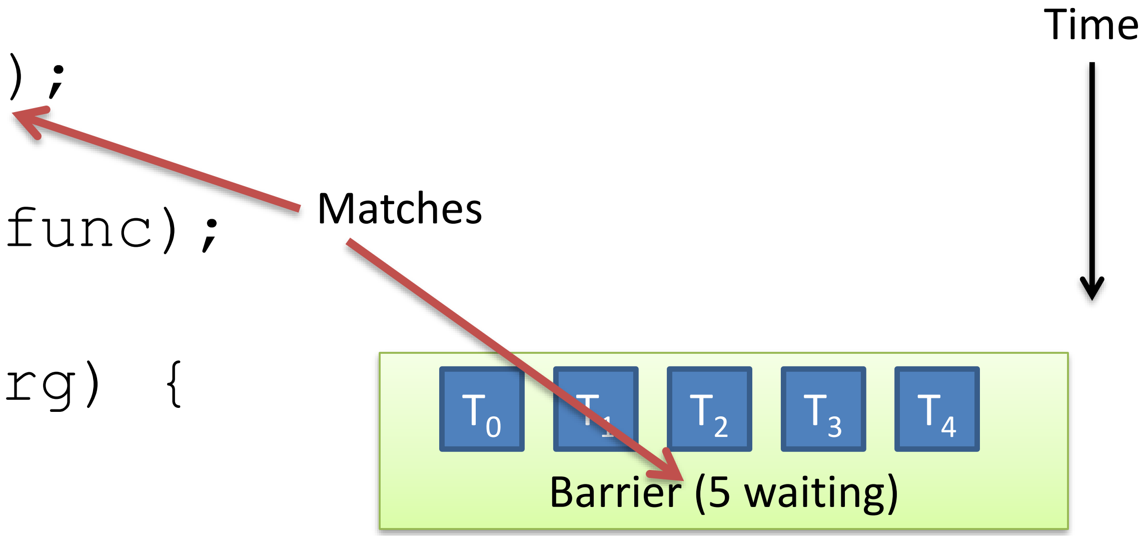
Barrier allows threads to pass when N threads reach it.



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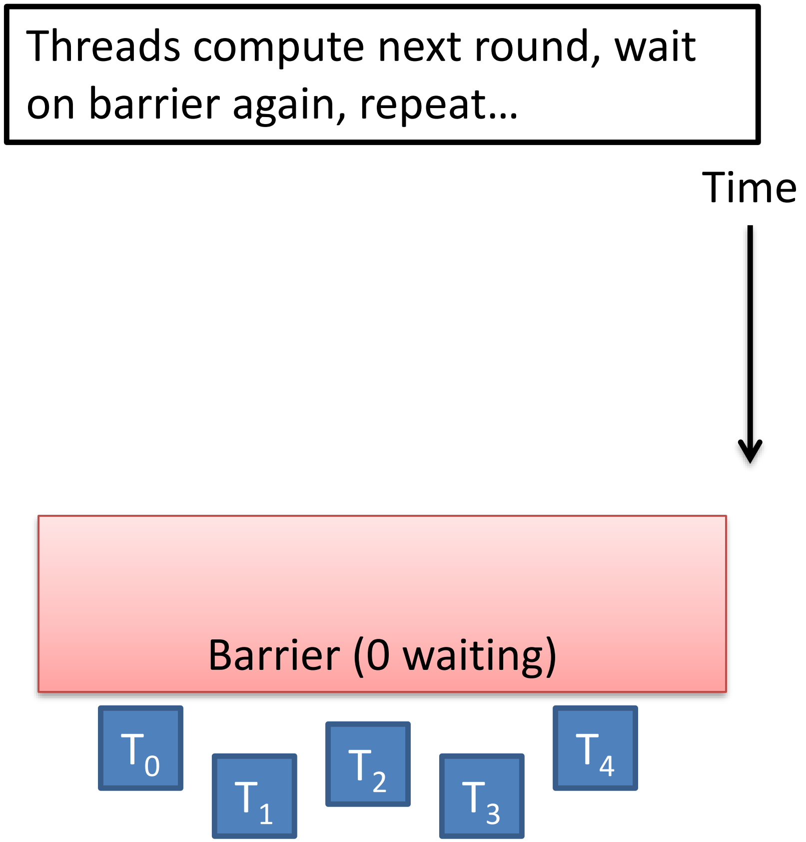

# Synchronization: More than Mutexes

- "I want to block a thread until something specific happens."
  - Condition variable: wait for a condition to be true
- "I want all my threads to sync up at the same point."
  - Barrier: wait for everyone to catch up.
- "I want my threads to share a critical section when they're reading, but still safely write."
  - Readers/writers lock: distinguish how lock is used

# Readers/Writers

- Readers/Writers Problem:
  - An object is shared among several threads
  - Some threads only read the object, others only write it
  - We can safely allow multiple readers
  - But only one writer
- pthread_rwlock_t:
  - pthread_rwlock_init: initialize rwlock
  - pthread_rwlock_rdlock: lock for reading
  - pthread_rwlock_wrlock: lock for writing

# Common Thread Patterns

- Producer / Consumer (a.k.a. Bounded buffer)
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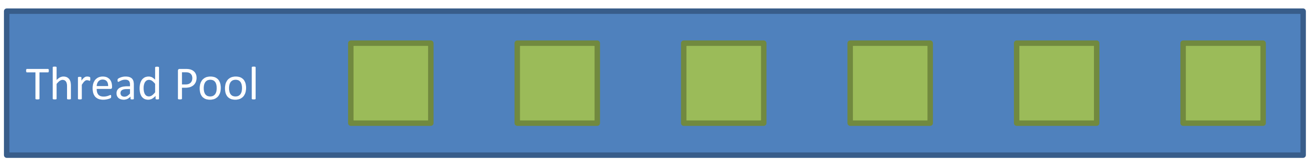
# Thread Pool / Work Queue

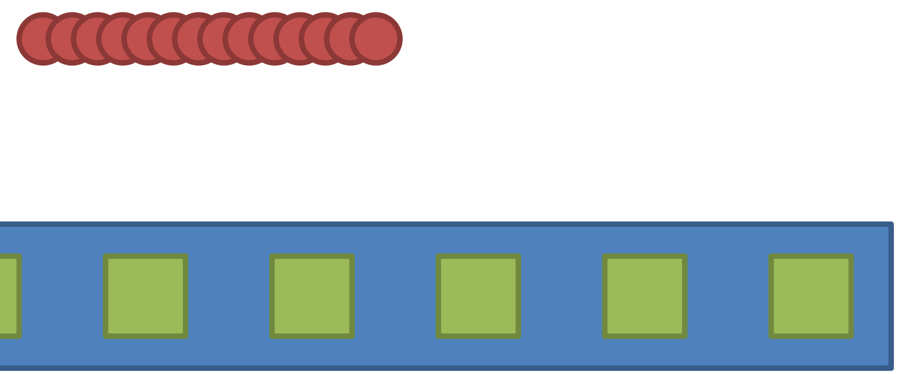
- Common way of structuring threaded apps:



# Thread Pool / Work Queue

- Common way of structuring threaded apps:

Queue of work to be done:



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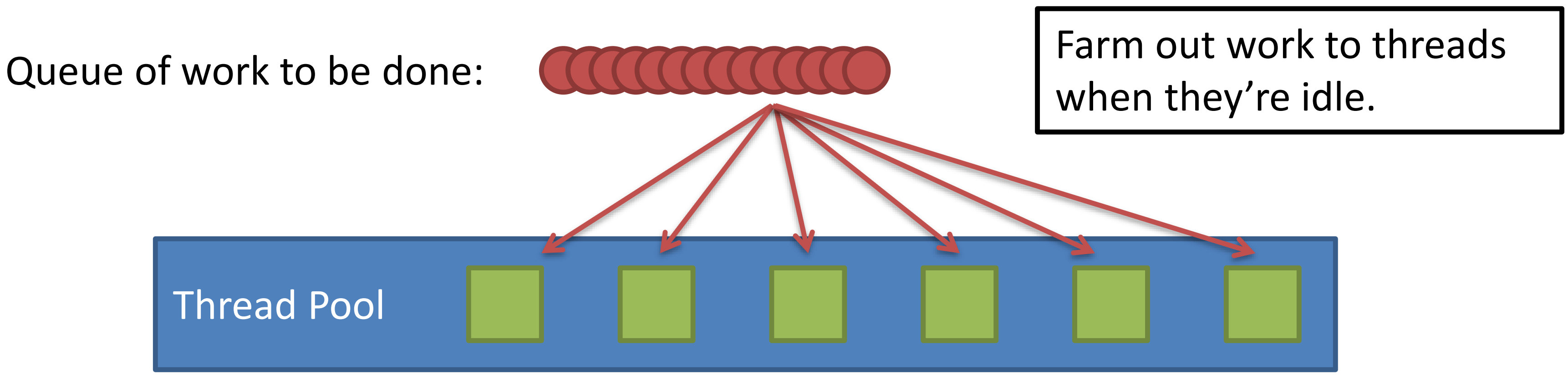

# Thread Pool / Work Queue

- Common way of structuring threaded apps:

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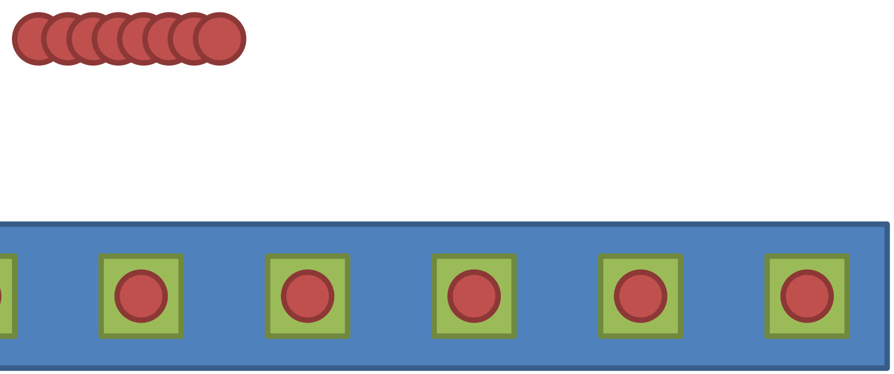



As threads finish work at their own rate, they grab the next item in queue.

Common for "embarrassingly parallel" algorithms.

Works across the network too!

# Thread Per Client

- Consider Web server:
  - Client connects
  - Client asks for a page:
    - http://web.cs.swarthmore.edu/~kwebb/cs31
    - “Give me /~kwebb/cs31”
  - Server looks through file system to find path (I/O)
  - Server sends back html for client browser (I/O)

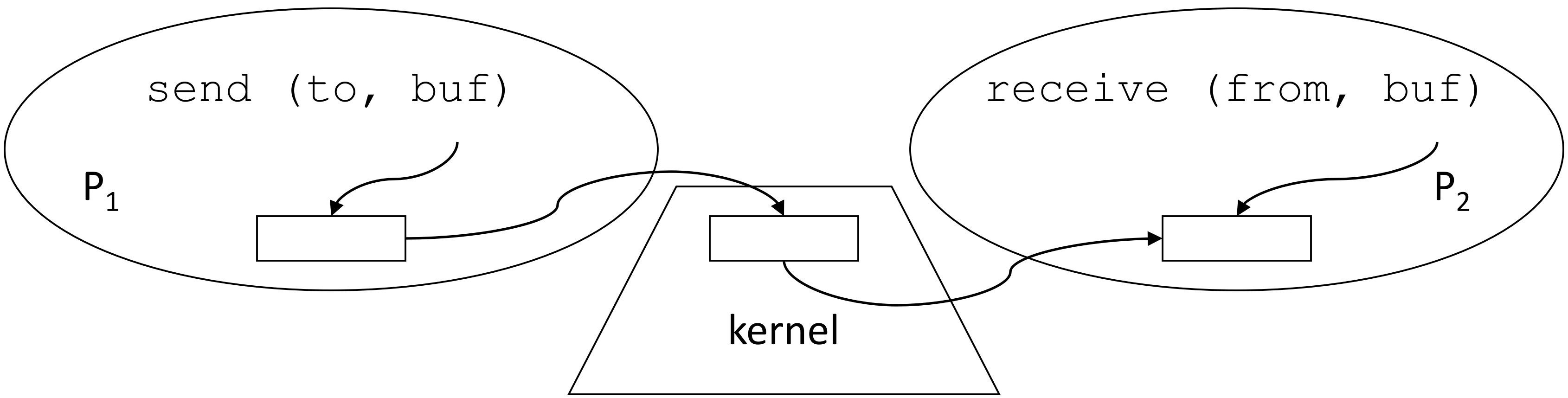
- Web server does this for MANY clients at once

# Thread Per Client

- Server "main" thread:
  - Wait for new connections
  - Upon receiving one, spawn new client thread
  - Continue waiting for new connections, repeat…

- Client threads:
  - Read client request, find files in file system
  - Send files back to client
  - <u>Nice property:</u> Each client is independent
  - <u>Nice property:</u> When a thread does I/O, it gets blocked for a while. OS can schedule another one.

# Message Passing




- Operating system mechanism for IPC
  - `send (destination, message_buffer)`
  - `receive (source, message_buffer)`
- Data transfer: in to and out of kernel message buffers
- Synchronization: can't receive until message is sent

# Suppose we're using message passing, will this code operate correctly?

```
/* NO SHARED MEMORY */
```

**Producer**

```
int item;

while (TRUE) {
    item = Produce ();
    send (Consumer, &item);
}
```

**Consumer**

```
int item;

while (TRUE) {
    receive (Producer, &item);
    Consume (item);
}
```

A. No, there is a race condition.

B. No, we need to protect *item*.

C. Yes, this code is correct.

# This code is correct and relatively simple. Why don't we always just use message passing (vs semaphores, etc.)?

```
/* NO SHARED MEMORY */

Producer                            Consumer
int item;                           int item;

while (TRUE) {                      while (TRUE) {
    item = Produce ();                  receive (Producer, &item);
    send (Consumer, &item);             Consume (item);
}                                   }
```

A. Message passing copies more data.
B. Message passing only works across a network.
C. Message passing is a security risk.
D. We usually do use message passing!

# Issues with Message Passing

- Who should messages be addressed to?
  - ports (mailboxes) rather than processes/threads
- What if it wants to receive from anyone?
  - `pid = receive (*, msg)`
- Synchronous (blocking) vs. asynchronous (non-blocking)
- Kernel buffering: how many sends w/o receives?
- Good paradigm for IPC over networks

# Summary

- Many ways to solve the same classic problems
  - Producer/Consumer: semaphores, CVs, messages
- There's more to synchronization than just mutual exclusion!
  - CVs, barriers, RWlocks, and others.
- Message passing doesn't require shared mem.
  - Useful for "threads" on different machines.