Agenda

Thread concurrency and synchronization
- race conditions
- critical section

Tools for synchronization
- mutex
- barrier
- conditional variable

Deadlock

Concurrency examples: Producer/Consumer and Dining Philosophers

Thread Safety

Thread concurrency and synchronization

- Need to think about memory and scope
  - Share: global & heap space
  - Own: stack & copy of local variables and parameters (but via pointers could share)
- Need to think about which parts of code can be executed simultaneously by multiple threads
  - May need to coordinate their access to the things they share (e.g. global variables)
  - May only want 1 thread to execute some parts (e.g. printing out final result)

Exercise

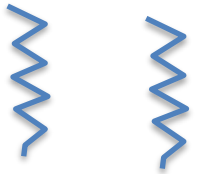
NOTE: Assume usr is the same for both threads

```
static int x = 0;

void* foo(void *usr) {
    int* p = (int*) usr;
    int y = *p;
    *p = *p + 1;
    x += y;
}
```

Q2

Tid i Tid j



Q1: own? y

shared? p/usr

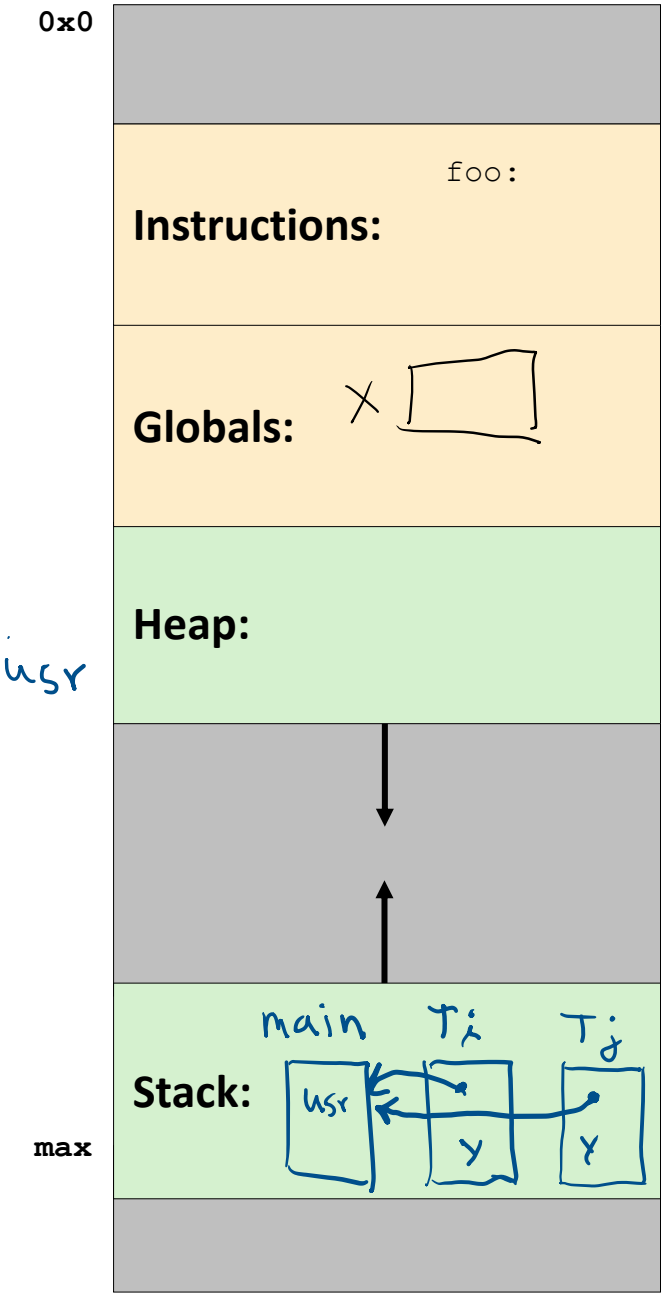
X

If threads i and j both execute function foo code:

Q1: which variables do they each get own copy of? which do they share?

Q2: which stmts can affect values seen by the other thread?

Shared Virtual Address Space:



Exercise: Draw a stack diagram

```
static int x = 0;

void* foo(void *usr) {
   int* p = (int*) usr;
   int y = *p;
   *p = *p + 1;
   x += y;
}

int main() {
 int pvalue = 35;
 pthread_t thread1, thread2;
 pthread_create(&thread1, NULL, foo, &pvalue);
 pthread_create(&thread2, NULL, foo, &pvalue);
 pthread_join(thread1, NULL);
 pthread_join(thread2, NULL);
 return 0;
}
```

Exercise: Draw a stack diagram (Possibility #1)

```
static int x = 0;

void* foo(void *usr) {
   int* p = (int*) usr;
   int y = *p;
   *p = *p + 1;
   x += y;
}
```

Exercise: Draw a stack diagram (Possibility #2)

```
static int x = 0;

void* foo(void *usr) {
   int* p = (int*) usr;
   int y = *p;
   *p = *p + 1;
   x += y;
}
```

Thread Synchronization

It is up to the Programmer to ensure that threads don’t interfere in undesired ways

OS provides synchronization primitives that threads can use to coordinate their execution: mutex, barrier

Synchronizing access to shared variables:

- block thread(s) to wait until it is safe for them to execute a section of code that manipulates shared state
- notify blocked thread(s) that it is safe to proceed

Thread synchronization

- A **race condition** occurs when a program's outcome differs based on CPU scheduling

- A **critical section** is a portion of code in which only one thread at a time can be executing

Tools for synchronizing threads:

- **mutex** (mutual exclusion): guard that ensures only one thread executes a section of code
- **barrier**: guard that waits for all threads before continuing
- **semaphore**: maintains a count that is associated with a resource. Users decrement semaphore to "check out" resource and increment it when finished
- **condition variable**: a shared variable for coordinating the actions between threads

Race Condition Example

```
main() {
  int i;
  for (i = 0; i < 100; i++) {
    pthread_create(&tid, NULL, thread_main, &i);
  }
```

```
void *thread_main(void *arg) {
  int i = *((int *)arg);
  printf("%d: i=%d\n", pthread_self(), i);
  ...
```

Race Condition: outcome depends on scheduling order of concurrent threads on CPUs

If no race:

- each thread would ALWAYS get a unique value of i
- set of printed values would be 0 through 99 for every run
  (not necessarily printed in order, but each printed exactly once by a unique thread)

Race condition example

hello I'm thread 61 with pthread_id 140566268266240
hello I'm thread 62 with pthread_id 140566259873536
hello I'm thread 29 with pthread_id 140566545225472
hello I'm thread 64 with pthread_id 140566243088128
hello I'm thread 67 with pthread_id 140566217910016
hello I'm thread 29 with pthread_id 140566536832768
hello I'm thread 30 with pthread_id 140566587188992
hello I'm thread 30 with pthread_id 140566578796288
hello I'm thread 63 with pthread_id 140566251480832

A Race Condition

In mult-threaded process, race conditions occur when multiple threads' access to shared state is interleaved and (could) affect program results/output/behavior

(ex) Sum of values from 1 to 100 is 5050

if one run of threaded Sum computes 5050, other 5040

An **atomic** action is a task that cannot be interrupted (no risk of a race condition)

(ex) single read or write of up to some (small) HW defined size

`int x = 6;` // `x` gets all bits of `6` or none but not partial

```
movl $6, -8(%ebp)
```

Atomic instructions (all or nothing?)

- Single Instruction either executed or not
  - OS can context switch *at any time (at any clock cycle)*
  - OS restarts thread at interrupted instruction(s)
    - All instructions in the pipeline that did not complete their STORE phase (F,D,E,S) are restarted

- But actions of a single instruction may not be atomic

```
addl $20, (%eax)  # not atomic:  a Read-Modify-Write op.
```

- Atomic action: single read (load) or write (store) of up to some max size (typically 4 or 8 bytes)

```
movl $20, (%eax)  # atomic:  all or none of 20 is written
```

pthread Synchronization

Mutex: mutually exclusive access

```
pthread_mutex_t mutex;
pthread_mutex_init(&mutex, NULL);

pthread_mutex_lock(&mutex);
pthread_mutex_unlock(&mutex);
pthread_mutex_destroy(&mutex);
```

Condition variable

```
pthread_condition_t shared;
pthread_condition_init(&shared, NULL);

pthread_condition_signal(&shared);
pthread_condition_wait(&shared);
pthread_condition_destroy(& shared);
```

Barrier : block until all threads have called wait
"wait until we all get to this point"

```
pthread_barrier_t mybarrier;
pthread_barrier_init(&mybarrier,NULL,numtids);

pthread_barrier_wait(&mybarrier);
pthread_barrier_destroy(&mybarrier);
```

Demo: Updating a counter

```
static unsigned long long count = 0;  // global variable

int main(int argc, char *argv) {
   pthread_t *tids;
   int ntids, i, *tid_args;

   ntids = atoi(argv[1]);
   tids = (pthread_t *)malloc(sizeof(pthread_t)*ntids);
   tid_args = (int *)malloc(sizeof(int)*ntids);

   for (i=0; i < ntids; i++) {
      tid_args[i] = i;
      pthread_create(&tids[i], 0, thread_hello, &tid_args[i]);
   }
   for (i=0; i < ntids; i++) {
       pthread_join(tids[i], 0);
   }
   …
}
```

```
thread_hello:    // each spawned thread's "main" function
tid_args[i]:     // each spawned thread's logical tid
tids[i]:         // each spawned thread's pthread tid
```

Demo: Updating a counter (thread main function)

```
static unsigned long long count =0;  // global variable

void *thread_count(void *arg) {


  int myid, i;
  myid = *((int *)arg);


  printf("hello I'm thread %d with pthread_id %lu\n",
      myid, pthread_self());

  for(i = 0; i < 100000; i++) {

    count += 1;
  }

  printf("goodbye I'm thread %d\n",myid);
  return (void *)0;  // recast 0 to return type (void *)
}
```

thread get own copy of local vars and params on its stack

all threads can access global variable (shared access)

Some runs with 4 threads:

result with 4 threads should be `400000`

```
hello I'm thread 0 with pthread_id 140449083262720
hello I'm thread 1 with pthread_id 140449074870016
goodbye I'm thread 0
goodbye I'm thread 1
hello I'm thread 2 with pthread_id 140448987346688
hello I'm thread 3 with pthread_id 140449066477312
goodbye I'm thread 3
goodbye I'm thread 2
count = 263742
count time is 0.010365
```

Critical Section

Let's put `count++` in a critical section:

```
pthread_mutex_t mutex;

pthread_mutex_lock(&mutex);
count++;
pthread_mutex_unlock(&mutex);
```

Visualizing our counter program: flow diagram

Visualizing our counter program: timeline

Aside: thread performance with mutex

Threads incur overhead

more threads not necessarily faster!

mutex is expensive

“embarrassingly parallel”: algorithms in which the same work is done for lots of data

Compare the performance

```c
void *thread_count(void* args) {
  int myid, i;
  myid = *((int*) args);
  printf("hello I'm thread %d (%lu)\n",
      myid, pthread_self());

  for(i = 0; i < 100000; i++) {
    pthread_mutex_lock(&mutex);
    count += 1;
    pthread_mutex_unlock(&mutex);
  }

  printf("goodbye I'm thread %d\n",myid);
  return (void *)0;
}
```

```c
void *thread_count(void* args) {
  int myid, i;
  myid = *((int*) args);
  printf("hello I'm thread %d (%lu)\n",
      myid, pthread_self());

  int total = 0;
  for(i = 0; i < 100000; i++) {
    total += 1;
  }

  pthread_mutex_lock(&mutex);
  count += total;
  pthread_mutex_unlock(&mutex);

  printf("goodbye I'm thread %d\n",myid);
  return (void *)0;
}
```

Exercise: mutex

Sketch a program where two threads count the number of letters in tolstoy.txt:

letter count = 2513005

What data needs to be shared?

Deadlock

Idea: All threads are simultaneously blocked, waiting for other threads!

- synchronization problem!

Potential problem with all distributed systems, not just threads

Deadlock: Example

Idea: Transferring money from A to B and from B to A simultaneously

```
void *Transfer(void *args){
   //argument passing removed to increase readability
   //...
   pthread_mutex_lock(&fromAcct->lock);
   pthread_mutex_lock(&toAcct->lock);

   fromAcct->balance -= amt;
   toAcct->balance += amt;

   pthread_mutex_unlock(&fromAcct->lock);
   pthread_mutex_unlock(&toAcct->lock);
   return NULL;
}
```

Deadlock: example

Thread 0

```
Transfer(…) {
    //acctA is fromAcct
    //acctB is toAcct
    pthread_mutex_lock(&acctA->lock);
        Thread 0 gets here
    pthread_mutex_lock(&acctB->lock);
```

Thread 1

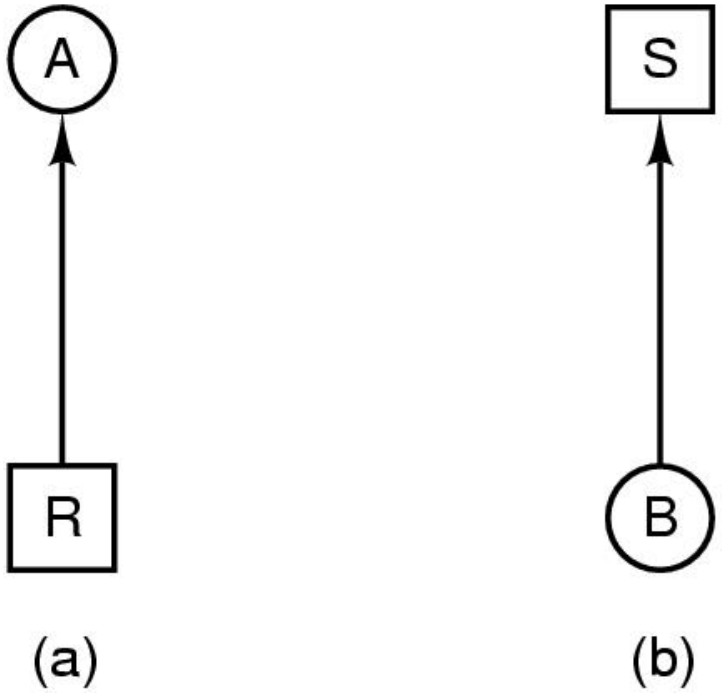
```
Transfer(…) {
    //acctB is fromAcct
    //acctA is toAcct
    pthread_mutex_lock(&acctB->lock);
        Thread 1 gets here
    pthread_mutex_lock(&acctA->lock);
```

Figure 1. An example of deadlock

Suppose that Threads 0 and 1 are executing concurrently and represent users A and B, respectively. Now consider the situation in which A and B want to transfer money to each other: A wants to transfer 20 dollars to B, while B wants to transfer 40 to A.

Deadlock: Visualization

Circles represent processes/threads
Squares represent resources



A **holds** resource R

B **requests** resource S

Resource Allocation Graph (RAG)

If our graph has a cycle, then we have deadlock

Deadlock: Visualization

Thread 0

```
Transfer(…) {
    //acctA is fromAcct
    //acctB is toAcct
    pthread_mutex_lock(&acctA->lock);
```

Thread 0 gets here

```
    pthread_mutex_lock(&acctB->lock);
```

Thread 1

```
Transfer(…) {
    //acctB is fromAcct
    //acctA is toAcct
    pthread_mutex_lock(&acctB->lock);
```

Thread 1 gets here

```
    pthread_mutex_lock(&acctA->lock);
```

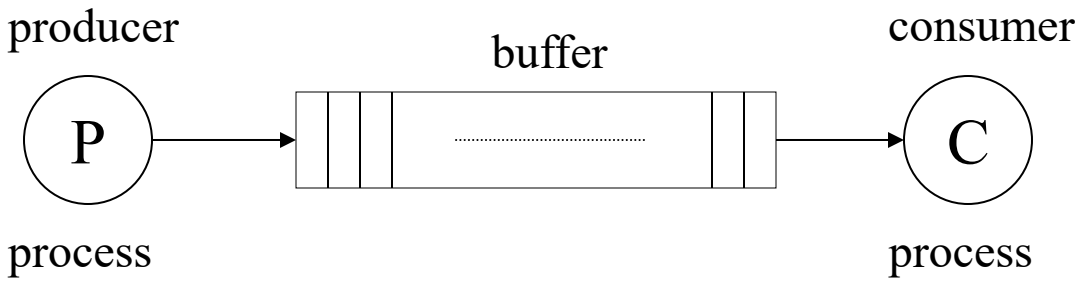
Deadlock: Fixed

```
void *Transfer(void *args){
   //argument passing removed to increase readability
   //...

   pthread_mutex_lock(&fromAcct->lock);
   fromAcct->balance -= amt;
   pthread_mutex_unlock(&fromAcct->lock);

   pthread_mutex_lock(&toAcct->lock);
   toAcct->balance += amt;
   pthread_mutex_unlock(&toAcct->lock);
   return NULL;
}
```

The Producer/Consumer Problem



A shared fixed-size buffer

Two types of threads

1. Producer: creates items and adds them to the buffer. Must wait if the buffer is full
2. Consumer: removes items. Must wait if the buffer is empty.

Many real-world examples:

Printer queue

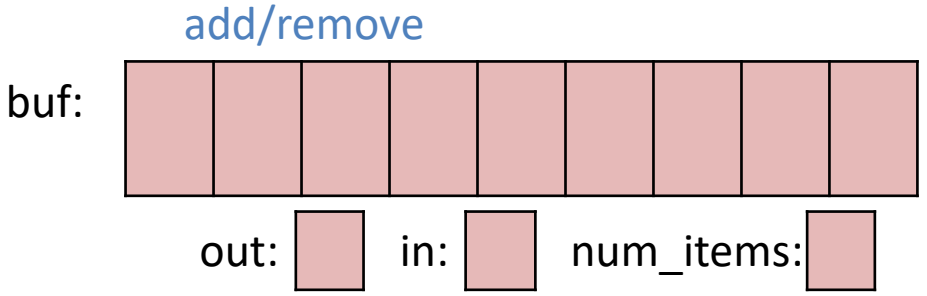
CPU queue of ready threads/processes

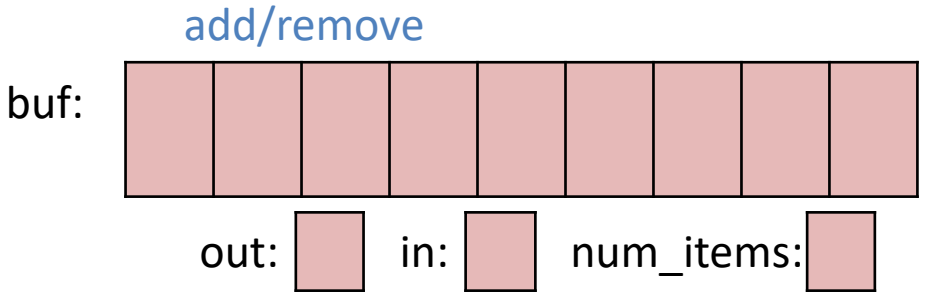
Network messaging

Example: Producer/Consumer

Producer: Add 2,4,6,8

Consumer: Read 2 elements

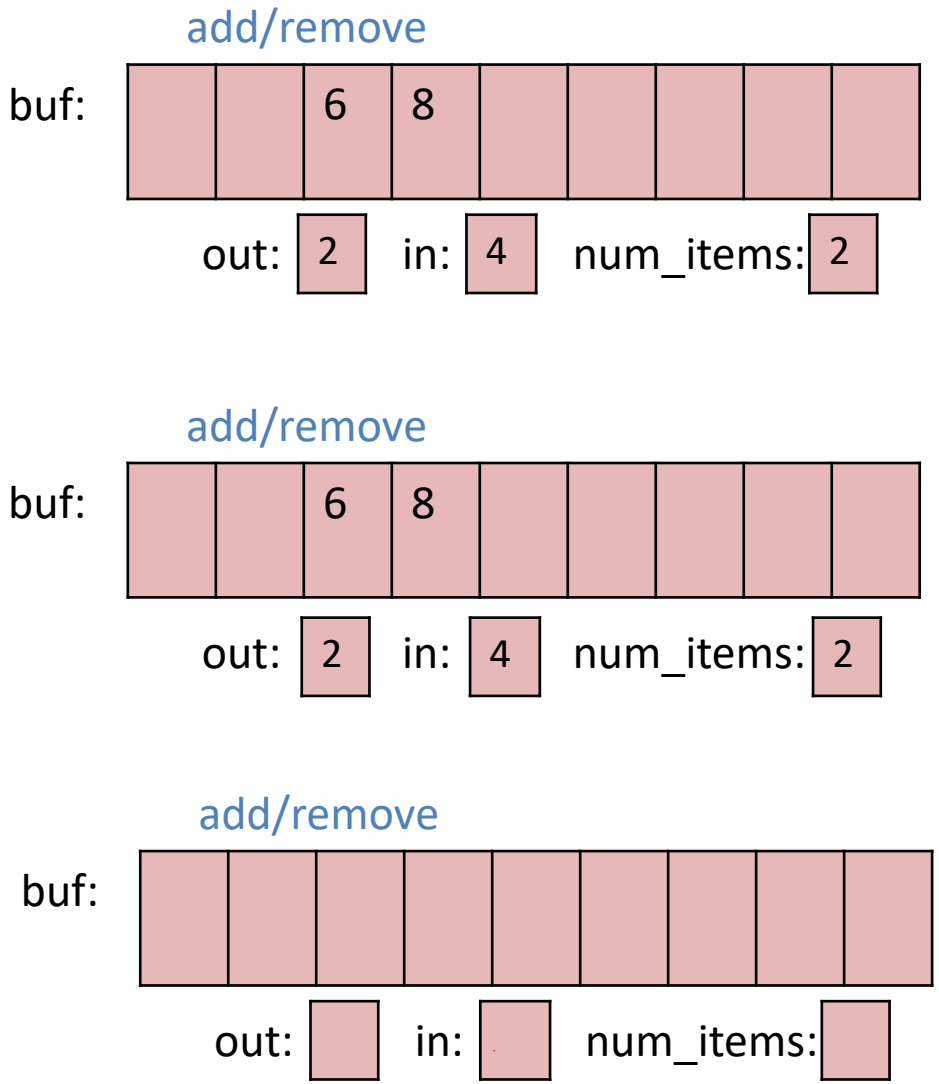




Example: Producer/Consumer

Producer: Add 10,12,14,16,18

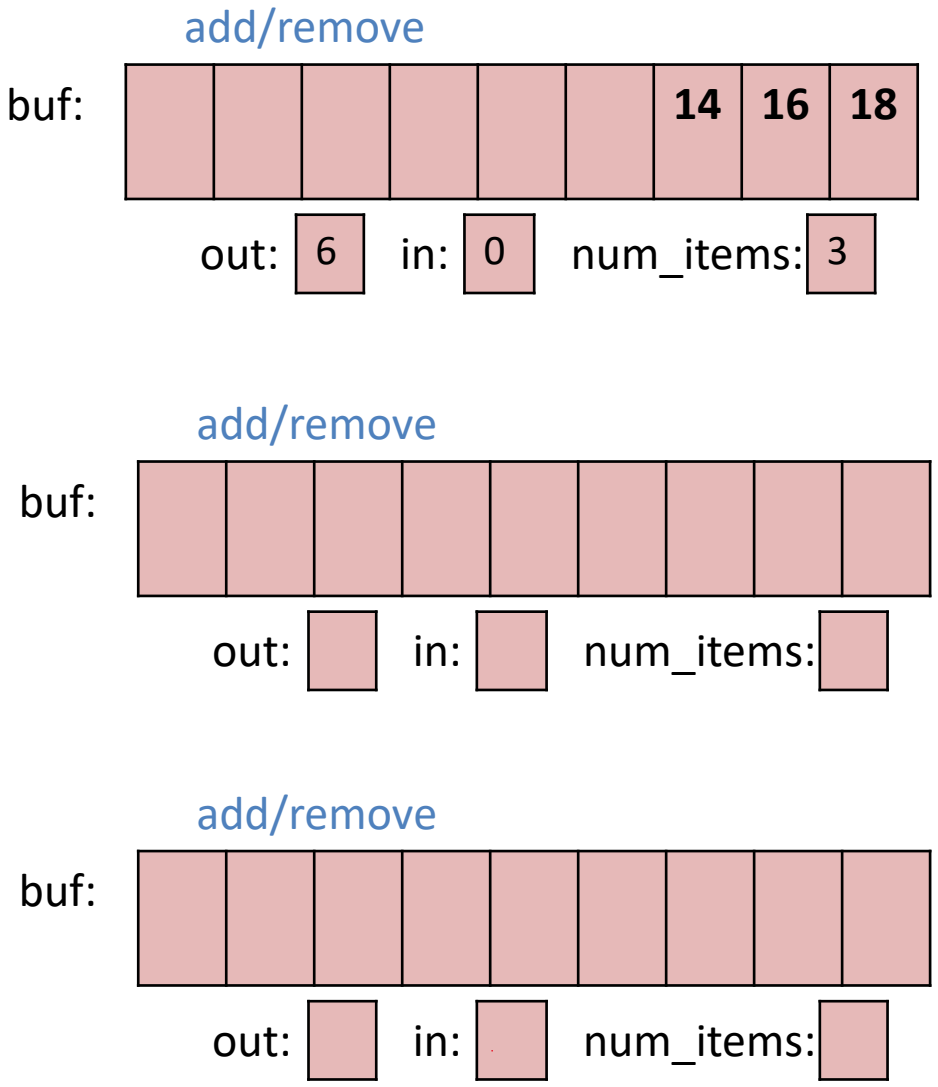
Consumer: Read 4 elements



Example: Producer/Consumer

Producer: 20,22,24,26

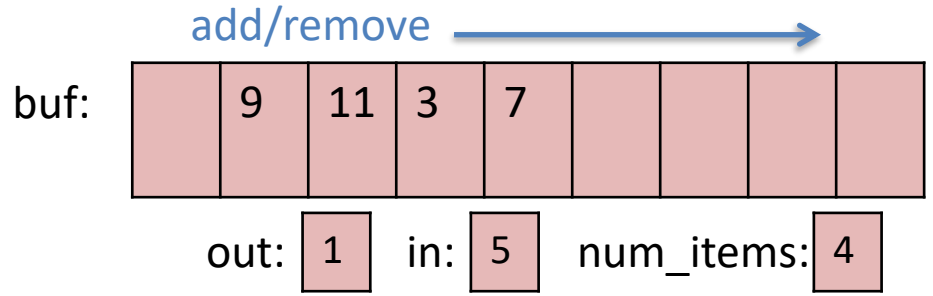
Consumer: Read 4



Producer/Consumer Synchronization?

Circular Queue Buffer: add to one end (in), remove from other (out)

```
int buf[N];
int in, out;
int num_items;
```



Assume Producers & Consumers forever produce & consume

Q: Where is Synchronization Needed in Producer & Consumer?

Producer: Consumer:

Producer/Consumer Synchronization?

Producer:

- Needs to wait if there is no space to put a new item in the buffer (Scheduling)
- Needs to wait to have mutually exclusive access to shared state associated with the buffer (Atomic):
  - Size of the buffer (num_items)
  - Next spot to insert into (in)

Consumer:

- Needs to wait if there is nothing in the buffer to consume (Scheduling)
- Needs to wait to have mutually exclusive access to shared state associated with the buffer (Atomic):
  - Size of the buffer (num_items)
  - Next spot to remove from (out)

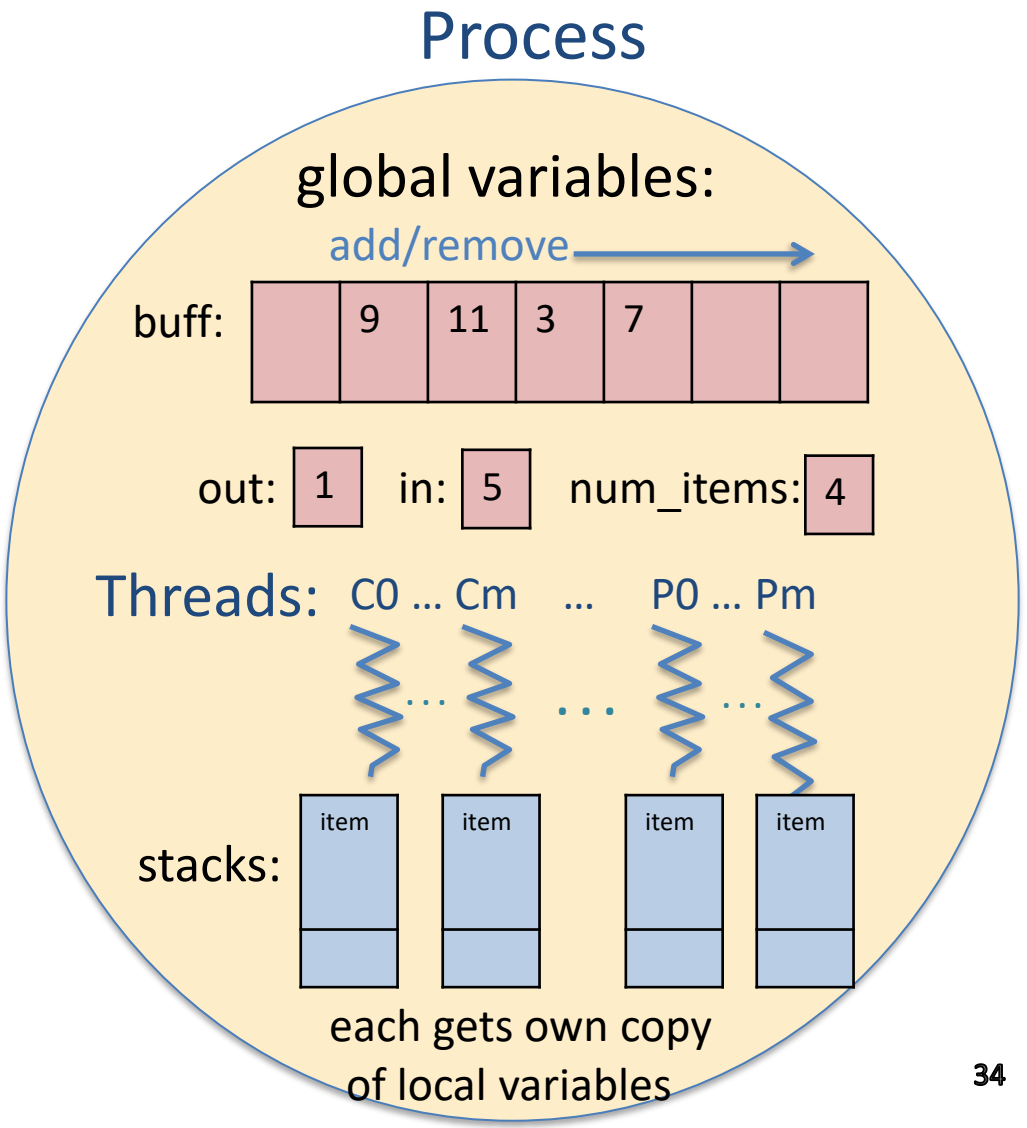
Assume: Producer & Consumer thread execute forever

Circular Queue Buffer: add to one end, remove from another

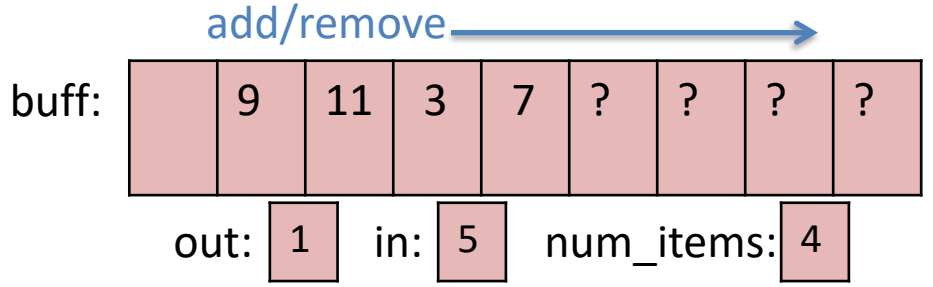
Producer/Consumer

```
int  num_items=0, in=0, out=0, buff[N];

void producer_threads(){
  int item;
  while(1) {
    item = produce_item();
    //add to queue
    buff[in] = item;
    in = (in+1)%N;
    num_items++;
  }
}
void consumer_threads(){
  int item;
  while(1) {
    //remove from queue
    item = buff[out];
    out = (out+1)%N;
    num_items--;
    consume_item(item);
  }
}
```



Producer/Consumer Solution




```
// Global Variables:
pthread_mutex_t mux  = PTHREAD_MUTEX_INITIALIZER;
int  num_items=0, in=0, out=0, buff[N];
```

Producer Threads:

```
int item;
while(1) {
  item = produce_item();
  pthread_mutex_lock(&mux);
  buff[in] = item;
  in = (in+1)%N;
  num_items++;
  pthread_mutex_unlock(&mux);
}
```

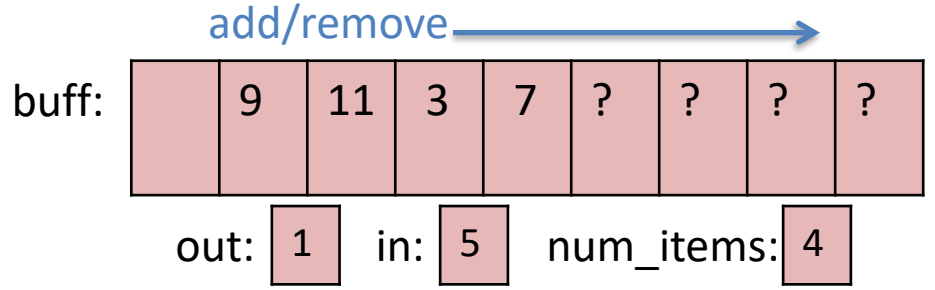
Consumer Threads:

```
int item;
while(1) {
  pthread_mutex_lock(&mux);
  item = buff[out];
  out = (out+1)%N;
  num_items--;
  pthread_mutex_unlock(&mux);
  consume_item(item);
}
```

Need Atomic Access to buff state: `num_items,buff,in,out`

- Want `num_items++` and `num_items--` to be atomic
- Don't want multiple consumer threads simultaneously using or updating `out`
- Don't want multiple producer threads simultaneously using or updating `in`

Producer/Consumer Solution



// Global Variables:

```
pthread_mutex_t mux  = PTHREAD_MUTEX_INITIALIZER;
int  num_items=0, in=0, out=0, buff[N];
```

Producer Threads:

```
int item;
while(1) {
  item = produce_item();
  pthread_mutex_lock(&mux);
  buff[in] = item;
  in = (in+1)%N;
  num_items++;
  pthread_mutex_unlock(&mux);
}
```

Consumer Threads:

```
int item;
while(1) {
  pthread_mutex_lock(&mux);
  item = buff[out];
  out = (out+1)%N;
  num_items--;
  pthread_mutex_unlock(&mux);
  consume_item(item);
}
```

Still need some Scheduling Type of Synchronization:

- Consumer threads must wait when there are no items in buff to consume
- Producer threads must wait when there there is no space in buff to put item

Producer/Consumer Solution

```
// Global Variables:
pthread_cond_t full  = PTHREAD_COND_INITIALIZER;
pthread_cond_t empty = PTHREAD_COND_INITIALIZER;
pthread_mutex_t mux  = PTHREAD_MUTEX_INITIALIZER;
int  num_items=0, in=0, out=0, buff[N];
```

Producer Threads:

```
int item;
while(1) {
  item = produce_item();
  pthread_mutex_lock(&mux);
  while(num_items >= N) {
    pthread_cond_wait(&full,
                      &mux);
  }
  buff[in] = item;
  in = (in+1)%N;
  num_items++;
  pthread_cond_signal(&empty);
  pthread_mutex_unlock(&mux);
}
```

Consumer Threads:

```
int item;
while(1) {
  pthread_mutex_lock(&mux);
  while(num_items == 0) {
    pthread_cond_wait(&empty,
                      &mux);
  }
  item = buff[out];
  out = (out+1)%N;
  num_items--;
  pthread_cond_signal(&full);
  pthread_mutex_unlock(&mux);
  consume_item(item);
}
```

Synchronization Can be Tricky

- Race Condition: missing synchronization

```
if(num_items > 0) {
  pthread_mutex_lock(&mutex);
  item = buff[out];
  out = (out+1)%N;
  num_items--;
  pthread_mutex_unlock(&mutex);
}
…
if(num_items > 0) {
  pthread_mutex_lock(&mutex);
  item = buff[out];
  out = (out+1)%N;
  num_items--;
  pthread_mutex_unlock(&mutex);
}
```

Q: Where is the Race Condition?

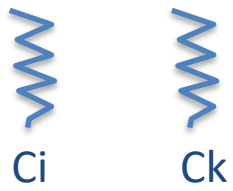
Race Condition:

Reading value of `num_items` is NOT Atomic

```
if(num_items > 0) {
  pthread_mutex_lock(&mutex);
  item = buff[out];
  out = (out+1)%N;
  num_items--;
  pthread_mutex_unlock(&mutex);
}
…
if(num_items > 0) {
  pthread_mutex_lock(&mutex);
  item = buff[out];
  out = (out+1)%N;
  num_items--;
  pthread_mutex_unlock(&mutex);
}
```

item = buff[0]
out = 1
0
item = buff[1] //garbage
out = 2
-1

num_items: 1



(1) threads both read 1 simultaneously, and evaluate (1 > 0) is TRUE
(2) One gets mutex first, gets valid item from buff
(3) Other gets mutex second, gets garbage item from buff

Synchronization Can be Tricky

- Deadlock: tid(s) blocked waiting forever
  - bad ordering of concurrent synch calls:

Tid 1:	Tid 2:
`pthread_mutex_lock(&mux1);`	`pthread_mutex_lock(&mux2);`
`pthread_mutex_lock(&mux2);`	`Pthread_mutex_lock(&mux1);`

  - Forgetting to unlock (must be on every path):

```
pthread_mutex_lock(&mux1);
if(some bool expr) {
  // do some atomic stuff
  pthread_mutex_unlock(&mux1);
}
```

If cond isn't true, then no call to unlock mutex -> next call to lock will block forever

Dining Philosophers

5 Philosophers

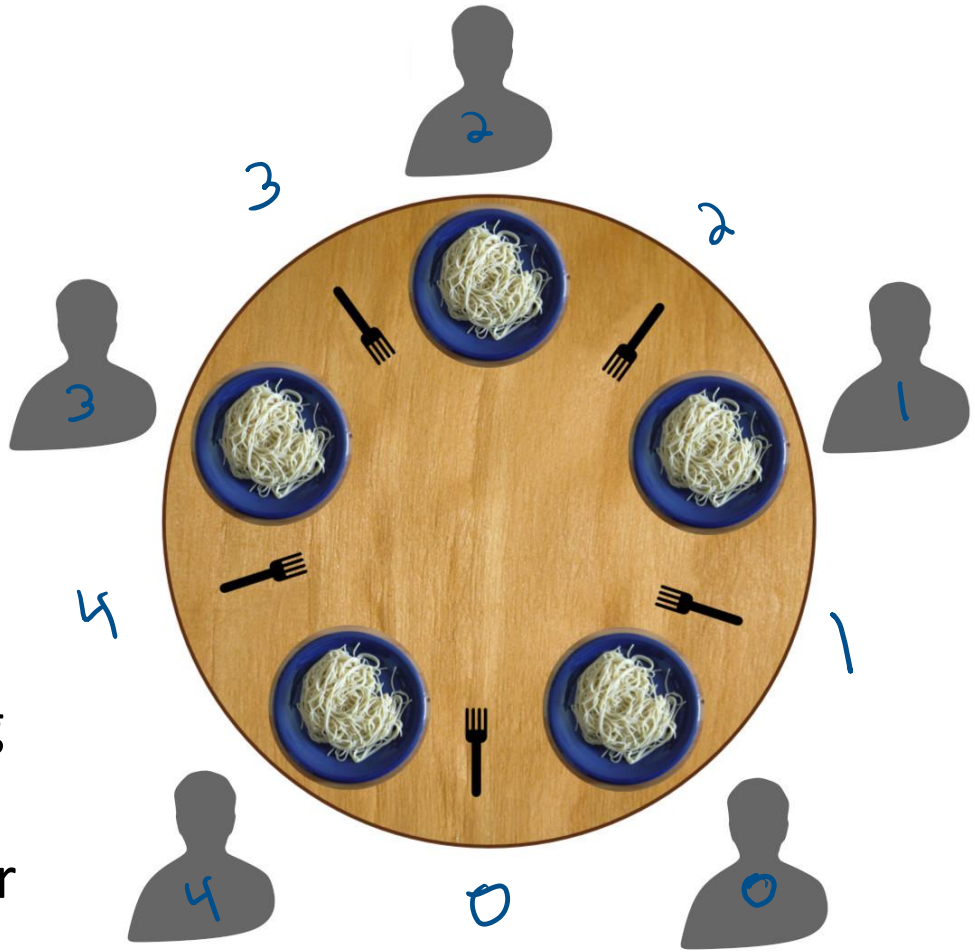
5 plates of spaghetti

5 forks

Philosophers alternate between eating and thinking

A philosopher can only eat if they can use both their left and right forks

Simulate the philosophers using a thread for each philosopher, such that no philosopher starves!



Dining Philosophers: Can this deadlock?

```
printf("%d is hungry\n", data->id);

int leftFork = data->id;
int rightFork = (data->id + 1) % N;

pthread_mutex_lock(&mutex[rightFork]);
pthread_mutex_lock(&mutex[leftFork]);
printf("%d is eating\n", data->id);
sleep(duration);
pthread_mutex_unlock(&mutex[rightFork]);
pthread_mutex_unlock(&mutex[leftFork]);
```

```
pthread_mutex_t mutex[N]
struct thread_data {
  int id;
};
```

Dining Philosophers: Can this deadlock?

```
printf("%d is hungry\n", data->id);

int leftFork = data->id;
int rightFork = (data->id + 1) % N;

pthread_mutex_lock(&mutex[leftFork]);
pthread_mutex_lock(&mutex[rightFork]);
printf("%d is eating\n", data->id);
sleep(duration);
pthread_mutex_unlock(&mutex[rightFork]);
pthread_mutex_unlock(&mutex[leftFork]);
```

```
pthread_mutex_t mutex[N]
struct thread_data {
  int id;
};
```

Dining Philosophers: Can this deadlock?

```
printf("%d is hungry\n", data->id);

int fork1 = (data->id); // left
int fork2 = (data->id + 1) % N; // right

if (fork1 > fork2) {
  int tmp = fork2;
  fork2 = fork1;
  fork1 = tmp;
}

pthread_mutex_lock(&mutex[fork1]);
pthread_mutex_lock(&mutex[fork2]);
printf("%d is eating\n", data->id);
sleep(duration);
pthread_mutex_unlock(&mutex[fork2]);
pthread_mutex_unlock(&mutex[fork1]);
```

Thread safety

A function is **thread safe** if it can be used by multiple threads with reliable behavior

Example: Most C library function **are not** thread safe, such as strtok

Example: When we do not properly protect critical sections of code, our thread routines are not thread safe either!

Review: strtok

```
int main() {
  char input_str[64];
  strcpy(input_str, “cat bear turtle”);

  char *token = strtok(input_str, " ");
  while (token != NULL) {
      token = strtok(NULL, " ");
  }
  return 0;
}
```

Show that strtok is not threadsafe

Can show how using strtok could lead to a race condition? e.g. different program behaviors?

Thread safety: Demo

```
void countElemsStr(int *counts, char *input_str) {
  int val, i;
  char *token;
  token = strtok(input_str, " ");
  while (token != NULL) {
    val = atoi(token);
    counts[val] = counts[val] + 1;
    token = strtok(NULL, " ");
  }
}
int main( int argc, char **argv ) {
  //lines omitted for brevity, but gets user defined length of string

  char *inputString = calloc(length * 2, sizeof(char));
  fillString(inputString, length * 2);
  countElemsStr(counts, inputString);

  return 0;
}
```

Review: strtok_r

```
int main() {
  char input_str[64];
  strcpy(input_str, “cat bear turtle”);

   char* saveptr;
   char* token = strtok_r(input_str, " “, &saveptr);
   while (token != NULL) {
     token = strtok_r(NULL, " “, &saveptr);
   }
  return 0;
}
```

Thread safety: Demo

```
void *countElemsStr(void *args) {
   struct t_arg *myargs = (struct t_arg *)args;
   // get thread parameters from myargs (omitted for brevity)

   //tokenize values
   char* saveptr;
   token = strtok_r(input_str, " “, &saveptr);
   while (token != NULL) {
      val = atoi(token); //convert to an int
      local_counts[val] = local_counts[val] + 1; //update associated counts
      token = strtok_r(NULL, " “, &saveptr);
   }

   pthread_mutex_lock(&mutex);
   for (i =0; i < MAX; i++) {
      counts[i] += local_counts[i];
   }
   pthread_mutex_unlock(&mutex);
   return NULL;
}
```