Condition Variables Revisited

Condition Variable

- Without condition variables,
  - Threads continually poll to check if the condition is met
  - Busy waiting!
- With condition variables
  - Same goal without polling

Inside a condition variable

```
struct pthread_cond {
    int waiting;
    handle_t semaphore;
};
```

Number of threads waiting on the condition variable

A semaphore for synchronization

Inside a condition variable

Have lock

`pthread_mutex_lock` is always called before **`pthread_cond_wait`** to acquire lock

```
int pthread_cond_wait(pthread_cond_t *cond, pthread_mutex_
    *mutex) {
    atomic_increment(&cond->waiting);
    pthread_mutex_unlock(mutex);
    if (wait(cond->semaphore, INFINITE) < 0)
        return errno;
    atomic_decrement(&cond->waiting);
    pthread_mutex_lock(mutex);
    return 0;
}
```

Have lock

Thread always has lock when returning from **`pthread_cond_wait`**

```
int pthread_cond_signal(pthread_cond_t
    *cond) {
    if (cond->waiting)
        semrel(cond->semaphore, 1);
    return 0;
}
```

More Complex Example

- Master thread
  - Spawns a number of concurrent slaves
  - Waits until all of the slaves have finished to exit
  - Tracks current number of slaves executing
- A mutex is associated with count and a condition variable with the mutex

Example

```
#include <stdio.h>
#include <pthread.h>

#define NO_OF_PROCS  4

typedef struct _SharedType {
  int count;                     /* number of active slaves */
  pthread_mutex_t lock;          /* mutex for count */
  pthread_cond_t done;           /* sig. by finished slave */
} SharedType, *SharedType_ptr;

SharedType_ptr shared_data;
```

Example: Main

```
main(int argc, char **argv) {
  int res;
  /* allocate shared data */
  if ((sh_data = (SharedType *)
    malloc(sizeof(SharedType))) ==
    NULL) {
      exit(1);
  }
  sh_data->count = 0;

  /* allocate mutex */
  if ((res =
    pthread_mutex_init(&sh_data-
    >lock, NULL)) != 0) {
     exit(1);
  }
```

```
/* allocate condition var */
  if ((res =
    pthread_cond_init(&sh_data-
    >done, NULL)) != 0) {
     exit(1);
  }

  /* generate number of slaves
    to create */
  srandom(0);
  /* create up to 15 slaves */
  master((int) random()%16);
}
```

Example: Main

```
main(int argc, char **argv) {
  int res;
  /* allocate shared data */
  if ((sh_data = (SharedType *)
    malloc(sizeof(SharedType))) ==
    NULL) {
      exit(1);
  }
  sh_data->count = 0;
```

```
pthread_mutex_t data_mutex =
PTHREAD_MUTEX_INITIALIZER;
```

```
pthread_cont_t data_cond =
PTHREAD_COND_INITIALIZER;
```

```
  /* generate number of slaves
    to create */
  srandom(0);
  /* create up to 15 slaves */
  master((int) random()%16);
}
```

Example: Master

```
master(int nslaves) {
  int i;
  pthread_t id;
  for (i = 1; i <= nslaves; i +=
    1) {
    pthread_mutex_lock(&sh_data-
    >lock);
    /* start slave and detach */
    shared_data->count += 1;
    pthread_create(&id, NULL,
       (void* (*)(void *))slave,
       (void *)sh_data);
    pthread_mutex_unlock(&sh_data-
    >lock);
  }
  pthread_mutex_lock(&sh_data-
    >lock);

  while (sh_data->count != 0)
    pthread_cond_wait(&sh_data-
    >done, &sh_data->lock);

  pthread_mutex_unlock(&sh_data-
    >lock);

  printf("All %d slaves have
    finished.\n", nslaves);
  pthread_exit(0);
}
```

Example: Slave

```
void slave(void *shared) {
  int i, n;
  sh_data = shared;
  printf("Slave.\n", n);
  n = random() % 1000;

  for (i = 0; i < n; i+= 1)
    Sleep(10);

  /* mutex for shared data */
  pthread_mutex_lock(&sh_data->lock);

  /* dec number of slaves */
  sh_data->count -= 1;

  /* done running */
  printf("Slave finished %d cycles.\n", n);

  /* signal that you are done working */
  pthread_cond_signal(&sh_data->done);

  /* release mutex for shared data */
  pthread_mutex_unlock(&sh_data->lock);
}
```

Semaphores vs. CVs

Semaphore

- Integer value (>=0)
- Wait does not always block
- Signal either releases thread or inc's counter
- If signal releases thread, both threads continue afterwards

Condition Variables

- No integer value
- Wait always blocks
- Signal either releases thread or is lost
- If signal releases thread, only one of them continue

Classical Synchronization Problems

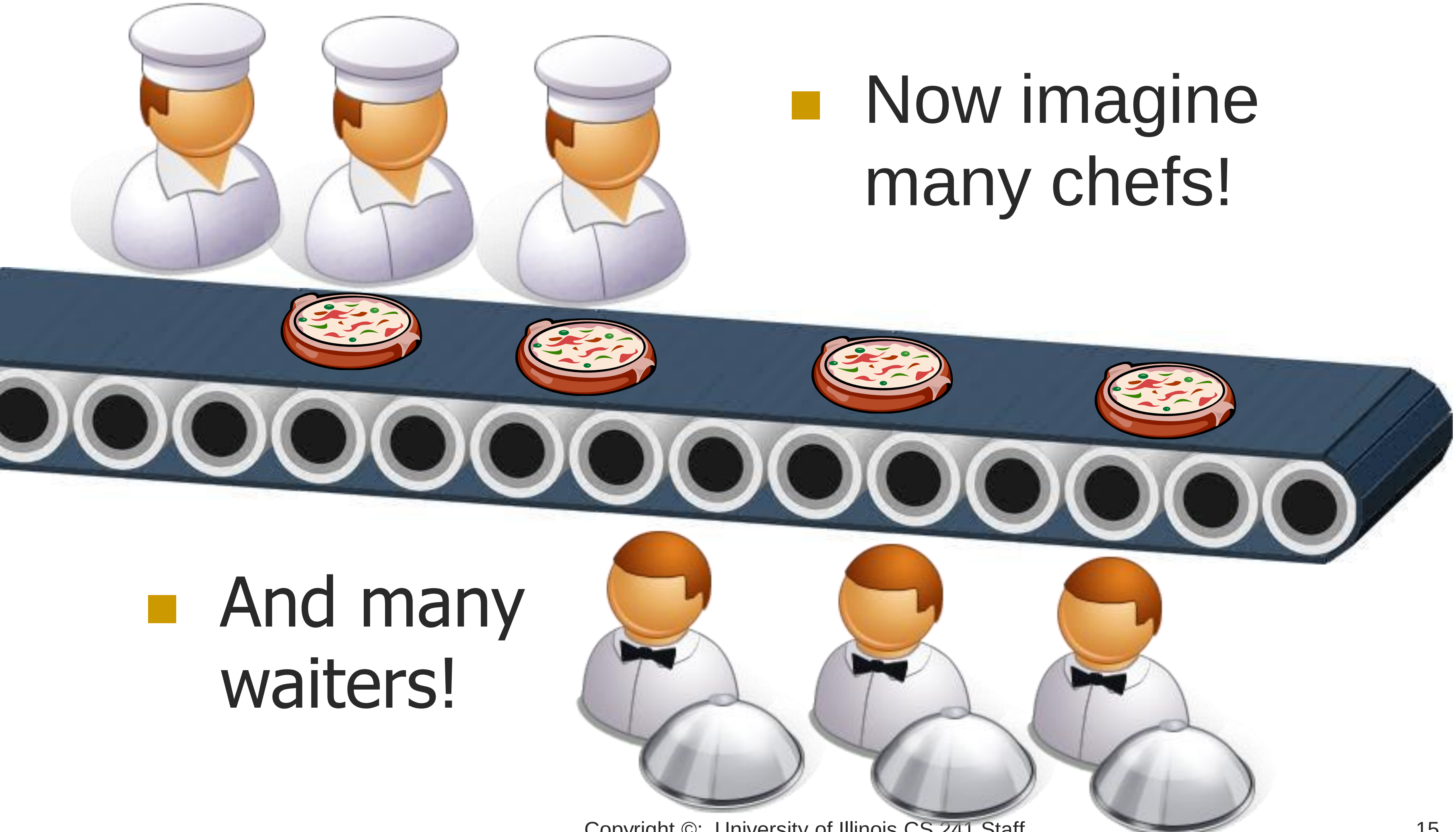
This lecture

- Goals
  - Introduce classical synchronization problems
- Topics
  - Producer-Consumer Problem
  - Reader-Writer Problem
  - Dining Philosophers Problem
  - Sleeping Barber’s Problem

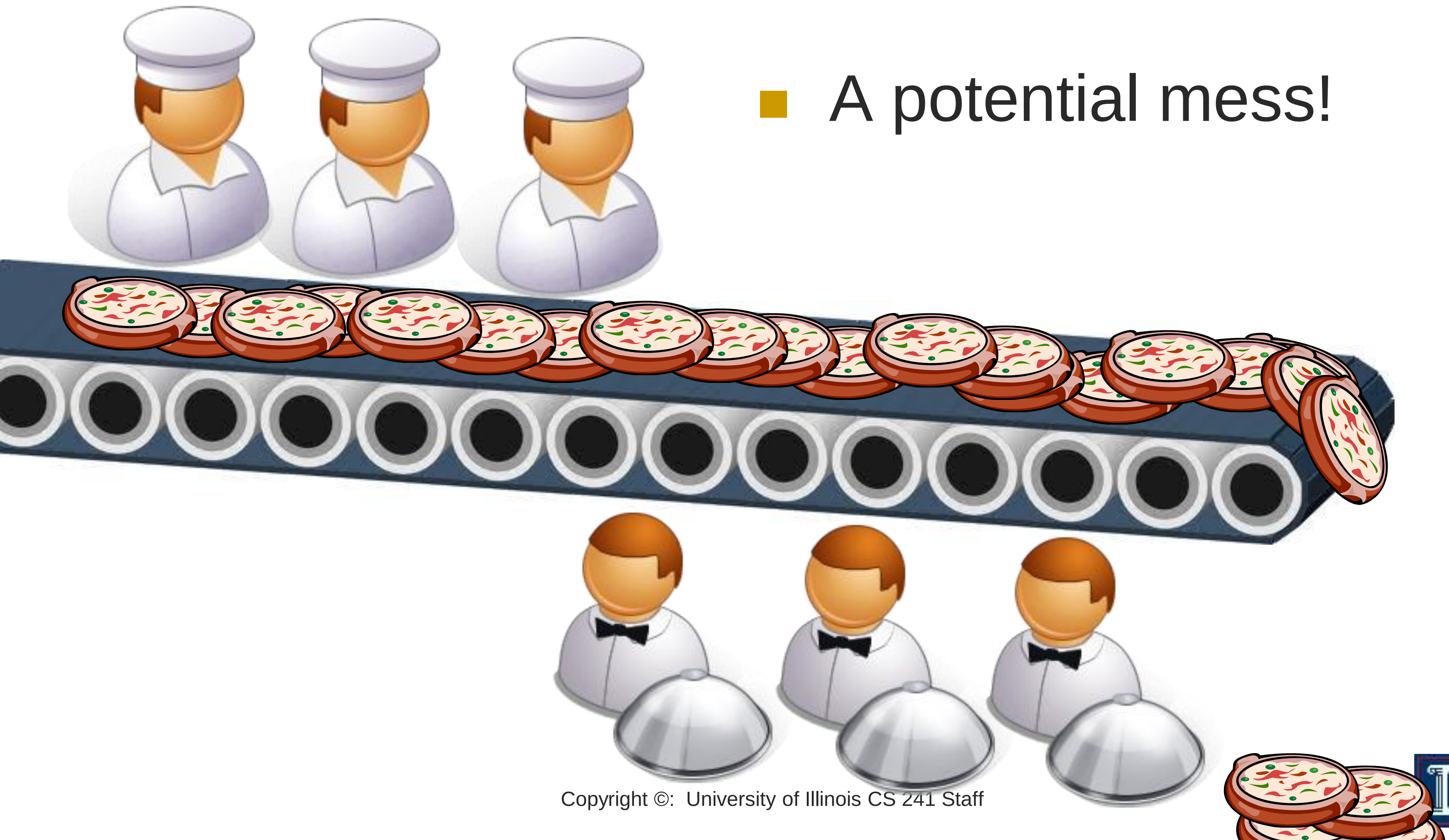
- Chefs cook items and put them on a conveyer belt

- Waiters pick items off the belt

- Now imagine many chefs!



- And many waiters!



- A potential mess!

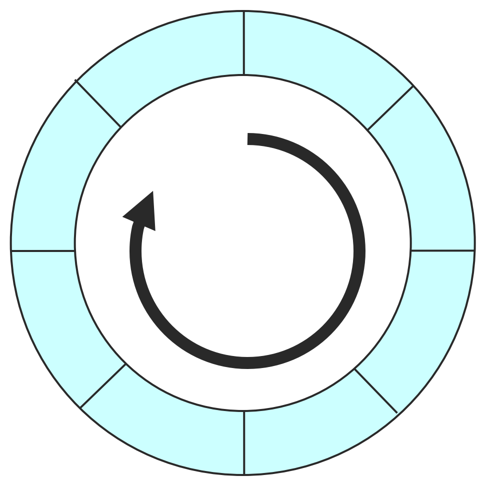
Producer-Consumer Problem

Chef = Producer
Waiter = Consumer

- Producers insert items
- Consumers remove items
- Shared resource: bounded buffer
  - Efficient implementation: circular buffer with an insert and a removal pointer

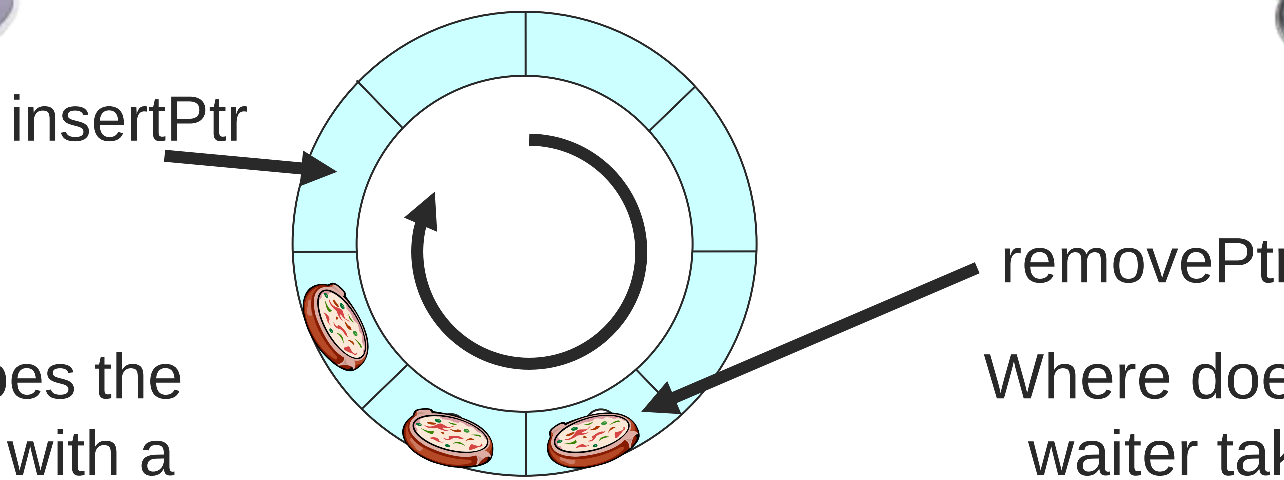
Producer-Consumer

Chef = Producer
Waiter = Consumer

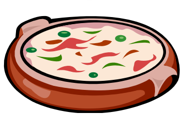


Producer-Consumer

Chef = Producer
Waiter = Consumer



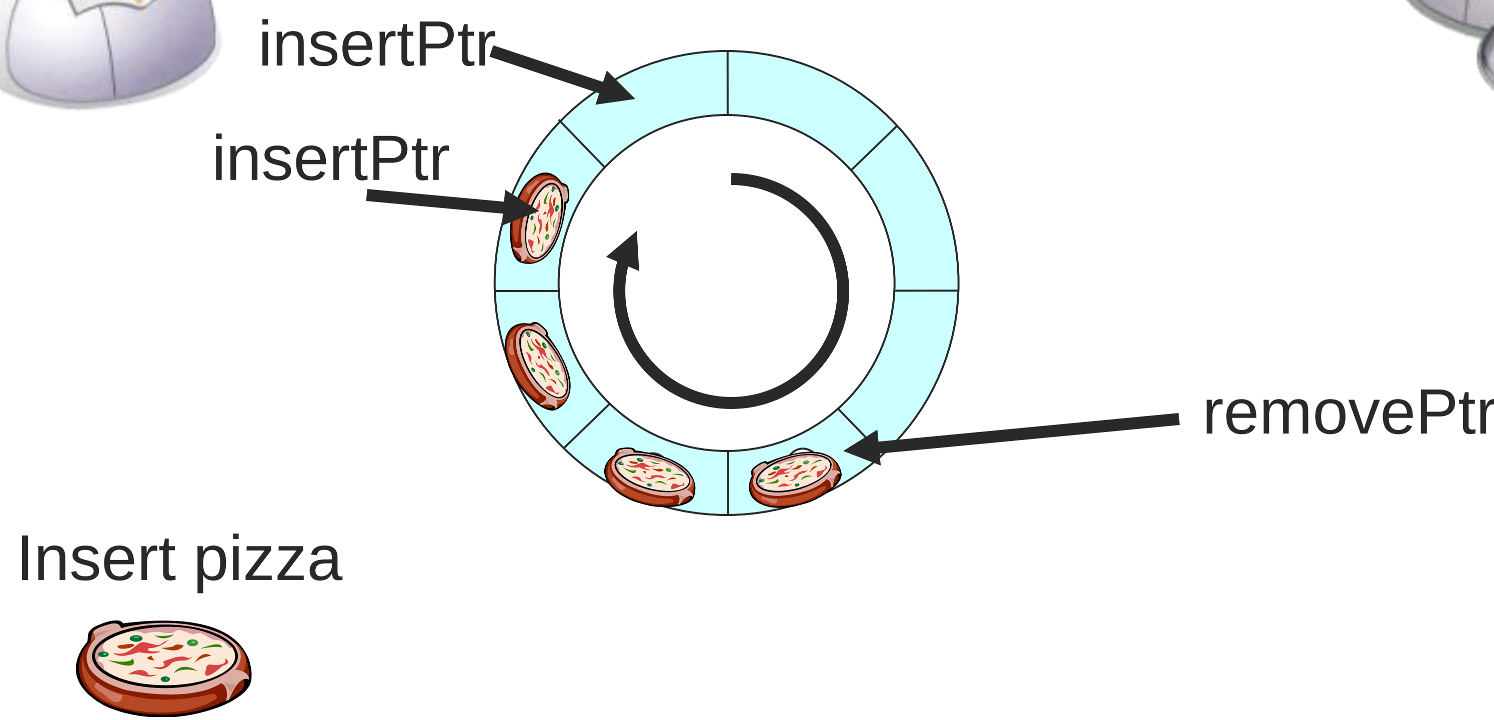
What does the chef do with a new pizza?



Where does the waiter take a pizza from?

Producer-Consumer

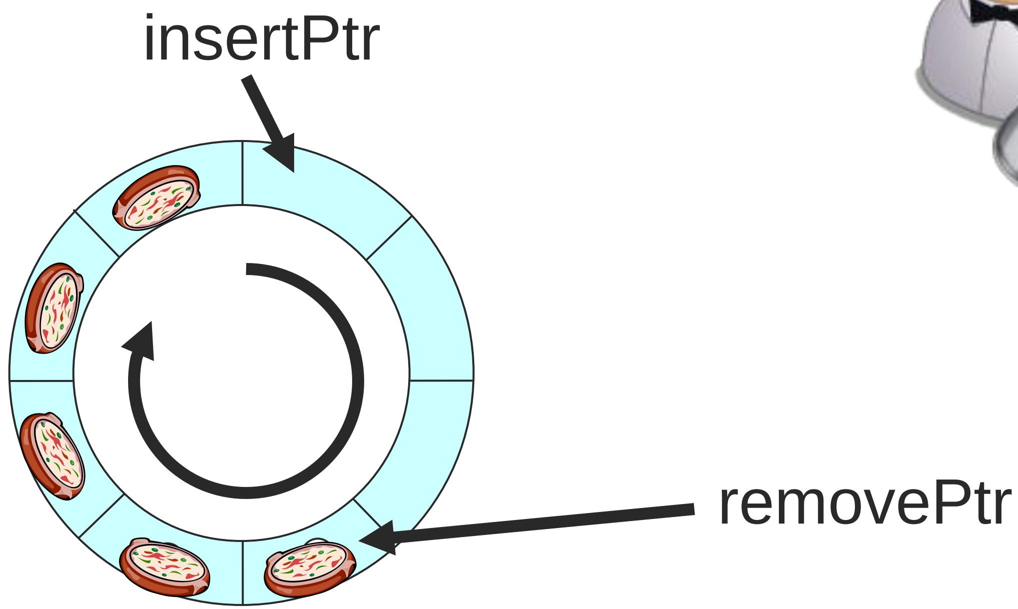
Chef = Producer
Waiter = Consumer



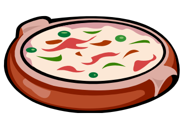
Producer-Consumer

Chef = Producer

Waiter = Consumer

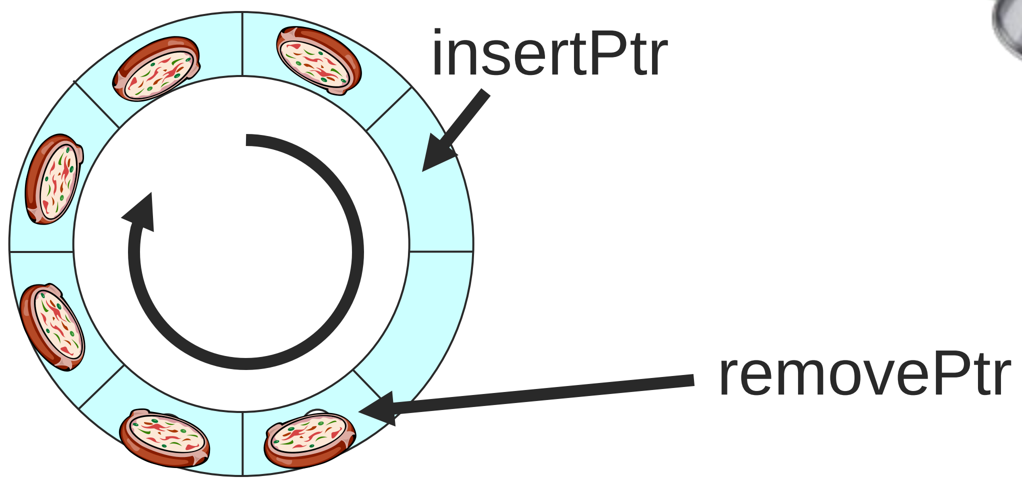


Insert pizza

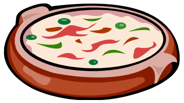


Producer-Consumer

Chef = Producer
Waiter = Consumer

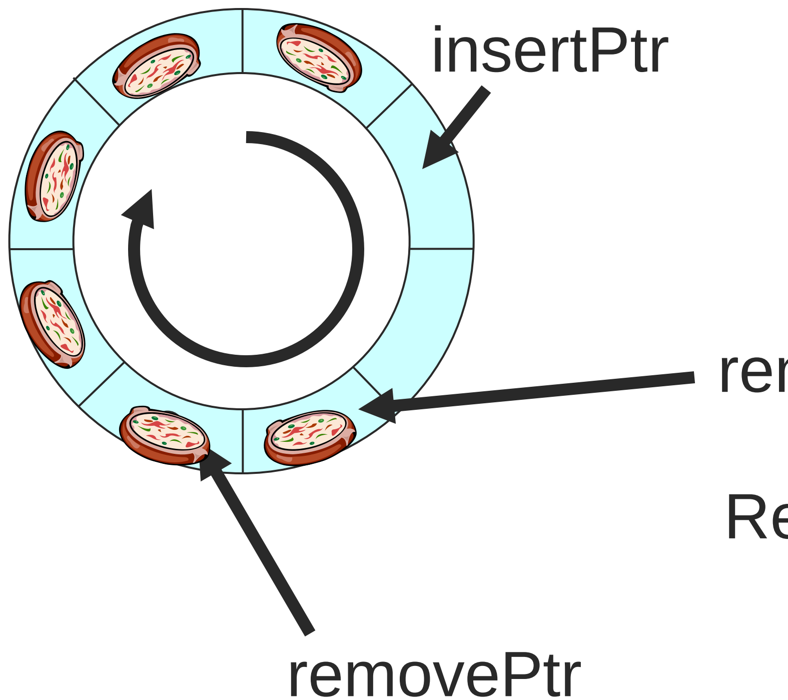


Insert pizza

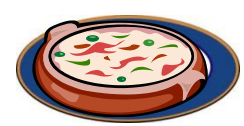


Producer-Consumer

Chef = Producer
Waiter = Consumer

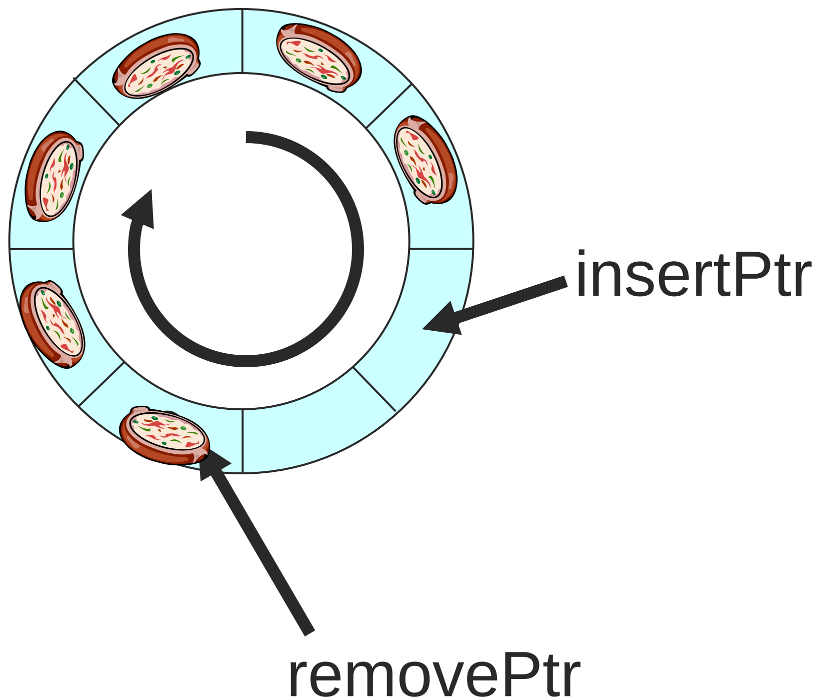


Remove pizza

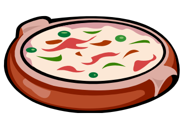


Producer-Consumer

Chef = Producer
Waiter = Consumer

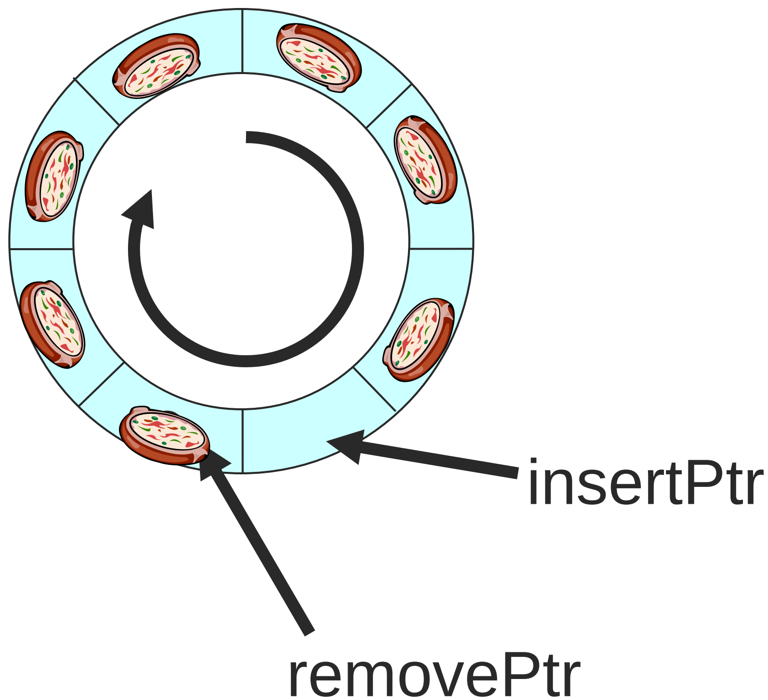


Insert pizza

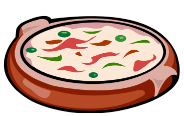


Producer-Consumer

Chef	= Producer
Waiter	= Consumer



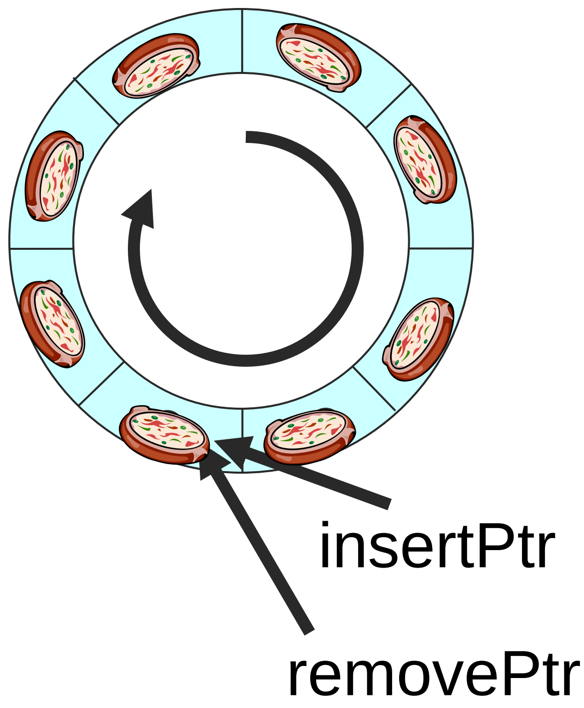
Insert pizza



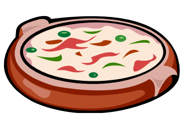
Producer-Consumer

Chef	= Producer
Waiter	= Consumer

BUFFER FULL:
Producer must be blocked!



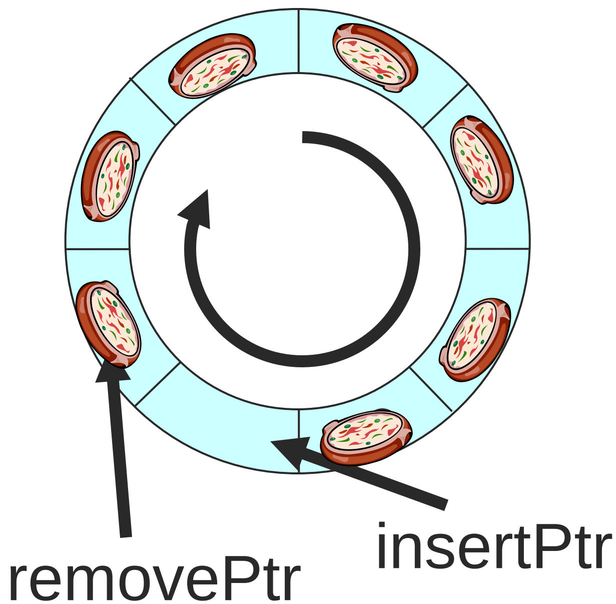
Insert pizza



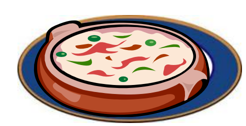
Producer-Consumer

Chef = Producer

Waiter = Consumer

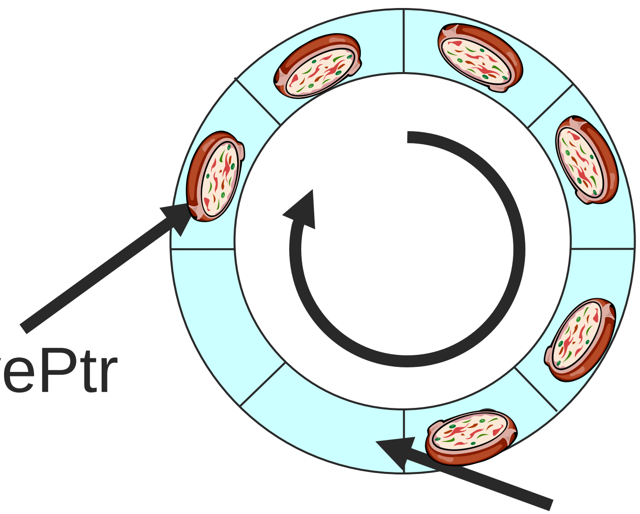


Remove pizza



Producer-Consumer

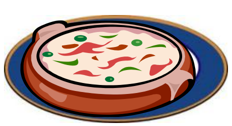
Chef = Producer
Waiter = Consumer



removePtr

insertPtr

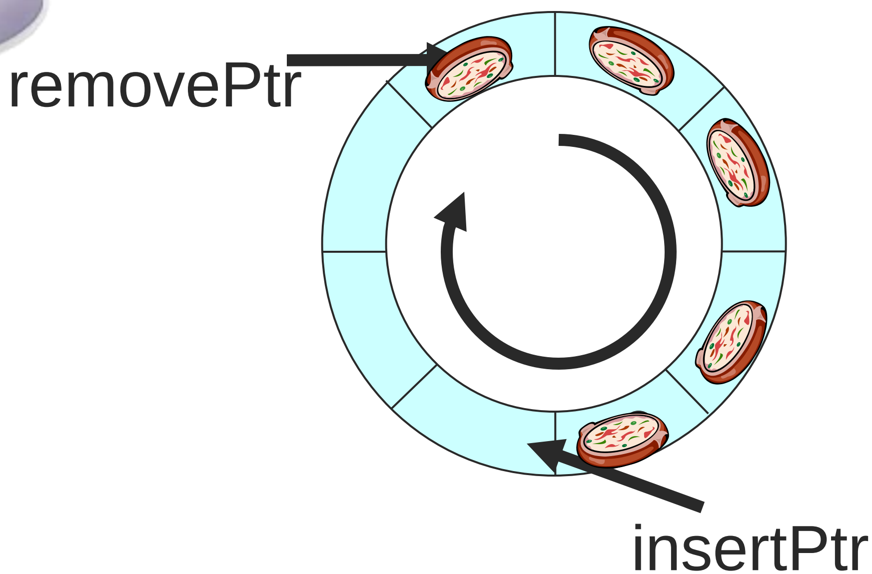
Remove pizza



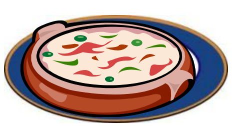
Producer-Consumer

Chef = Producer

Waiter = Consumer

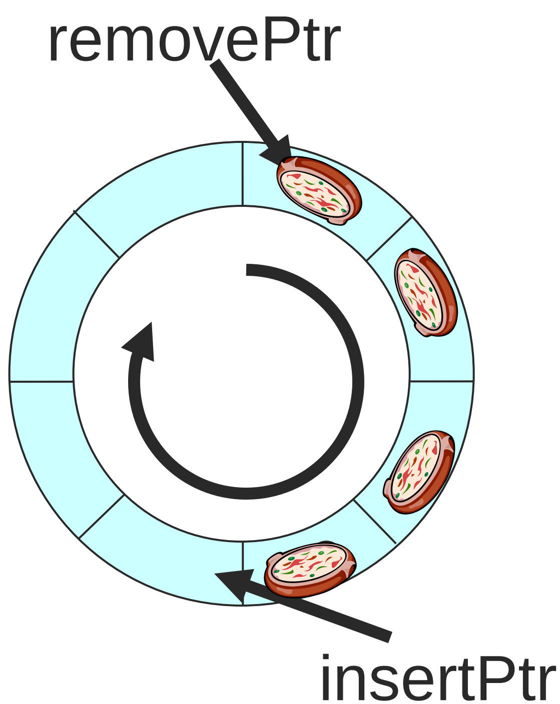


Remove pizza

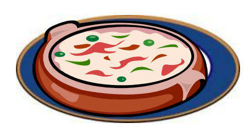


Producer-Consumer

Chef = Producer
Waiter = Consumer



Remove pizza



Producer-Consumer

Chef = Producer
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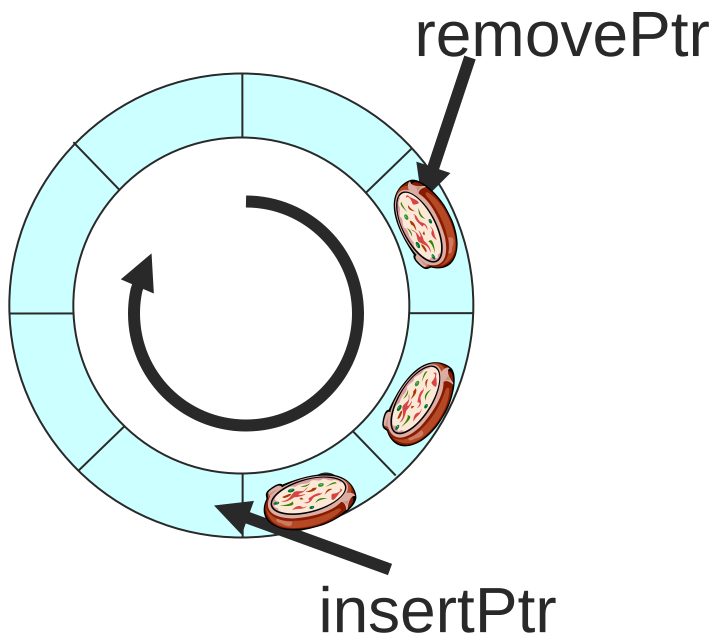
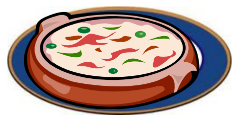


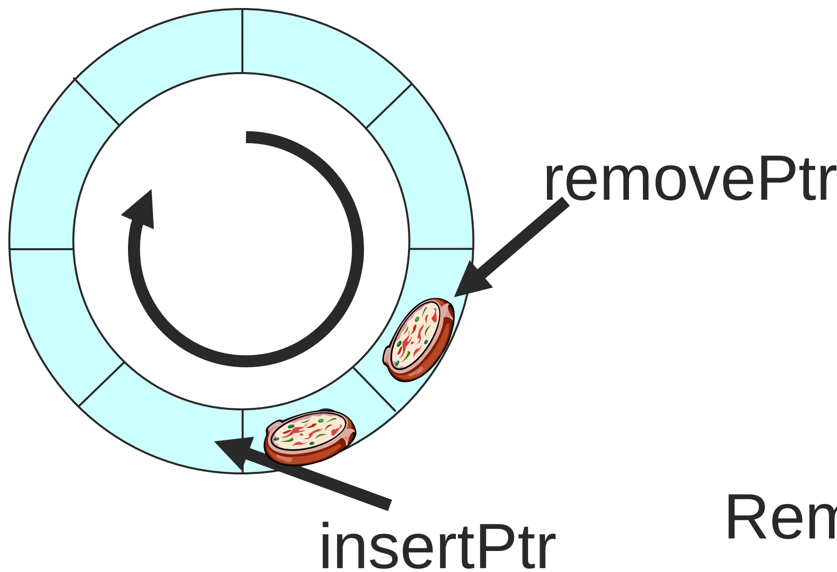
Remove pizza



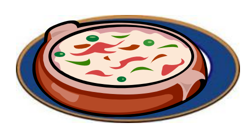
Producer-Consumer

Chef = Producer

Waiter = Consumer

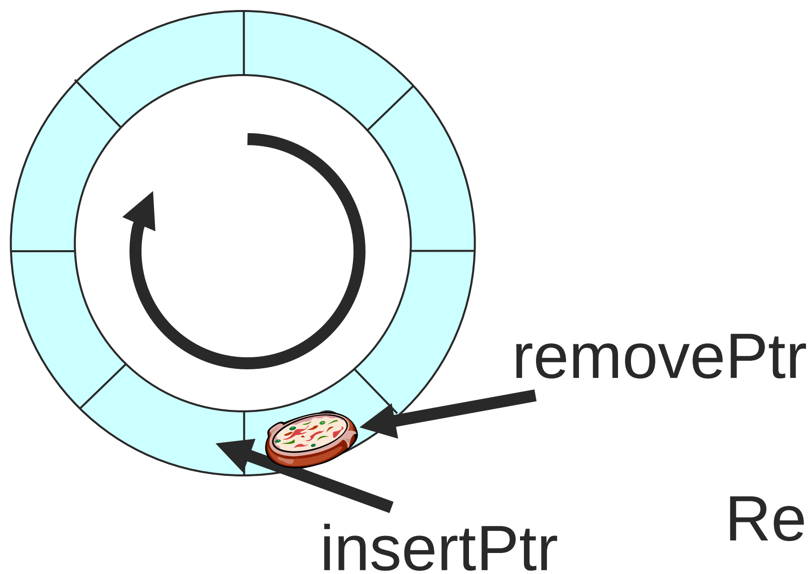


Remove pizza

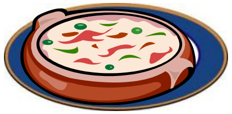


Producer-Consumer

Chef = Producer
Waiter = Consumer



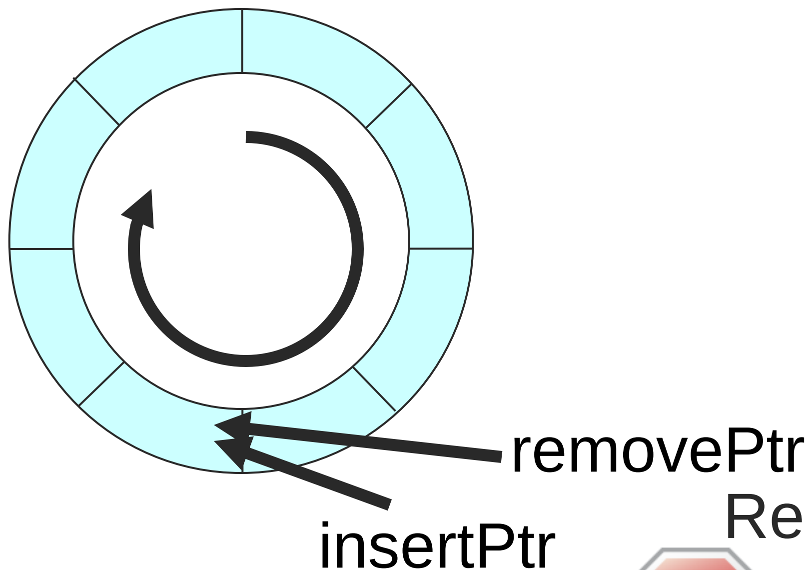
Remove pizza



Producer-Consumer

Chef = Producer
Waiter = Consumer

BUFFER EMPTY:
Consumer must be blocked!



Remove pizza

Producer-Consumer Summary

- Producer
  - Insert items
  - Update insertion pointer

- Consumer
  - Execute destructive read on the buffer
  - Update removal pointer

- Both
  - Update information about how full/empty the buffer is
- Solution
  - Must allow multiple producers and consumers

Challenges

- Prevent buffer <u>over</u>flow
- Prevent buffer <u>under</u>flow
- Mutual exclusion when modifying the buffer data structure

Solutions

- Prevent buffer overflow
  - Block producer when full
  - Counting semaphore to count #free slots
  - 0 → block producer
- Prevent buffer underflow
- Mutual exclusion when modifying the buffer data structure

Solutions

- Prevent buffer overflow
  - Block producer when full
  - Counting semaphore to count #free slots
  - 0 ➔ block producer
- Prevent buffer underflow
  - Block consumer when empty
  - Counting semaphore to count #items in buffer
  - 0 ➔ block consumer
- Mutual exclusion when modifying the buffer data structure

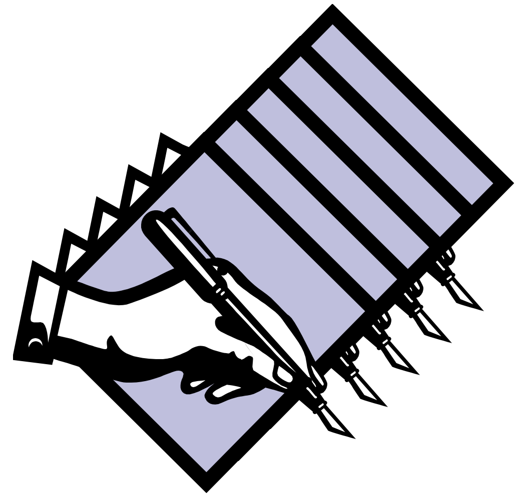
Solutions

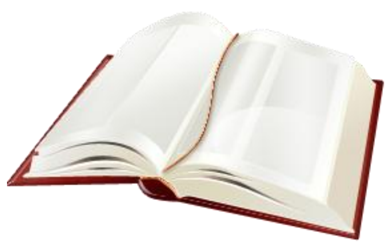
- Prevent buffer overflow
  - Block producer when full
  - Counting semaphore to count #free slots
  - 0 ➔ block producer
- Prevent buffer underflow
  - Block consumer when empty
  - Counting semaphore to count #items in buffer
  - 0 ➔ block consumer
- Mutual exclusion when modifying the buffer data structure
  - Mutex protects shared buffer & pointers

Assembling the solution

- Producer
  - `sem_wait(slots)`, `sem_signal(slots)`
  - Initialize `slots` to `N`
- Consumer
  - `sem_wait(items)`, `sem_signal(items)`
  - Initialize semaphore `items` to `0`
- Synchronization
  - `mutex_lock(m)`, `mutex_unlock(m)`
- Buffer management
  - `insertptr = (insertptr+1) % N`
  - `removalptr = (removalptr+1) % N`

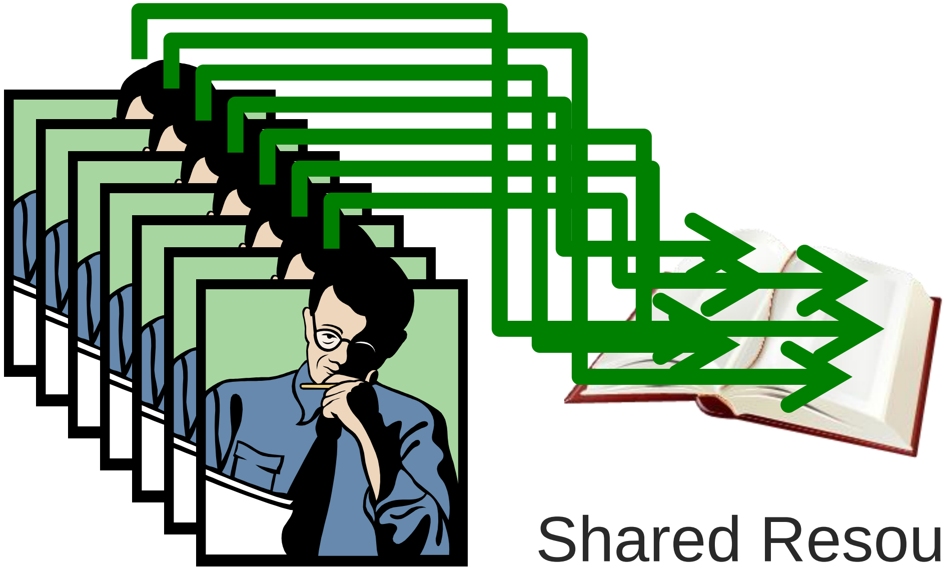
Readers-Writers Problem



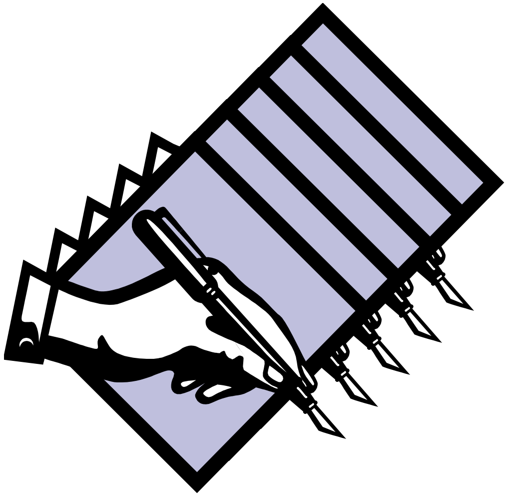


Shared Resource

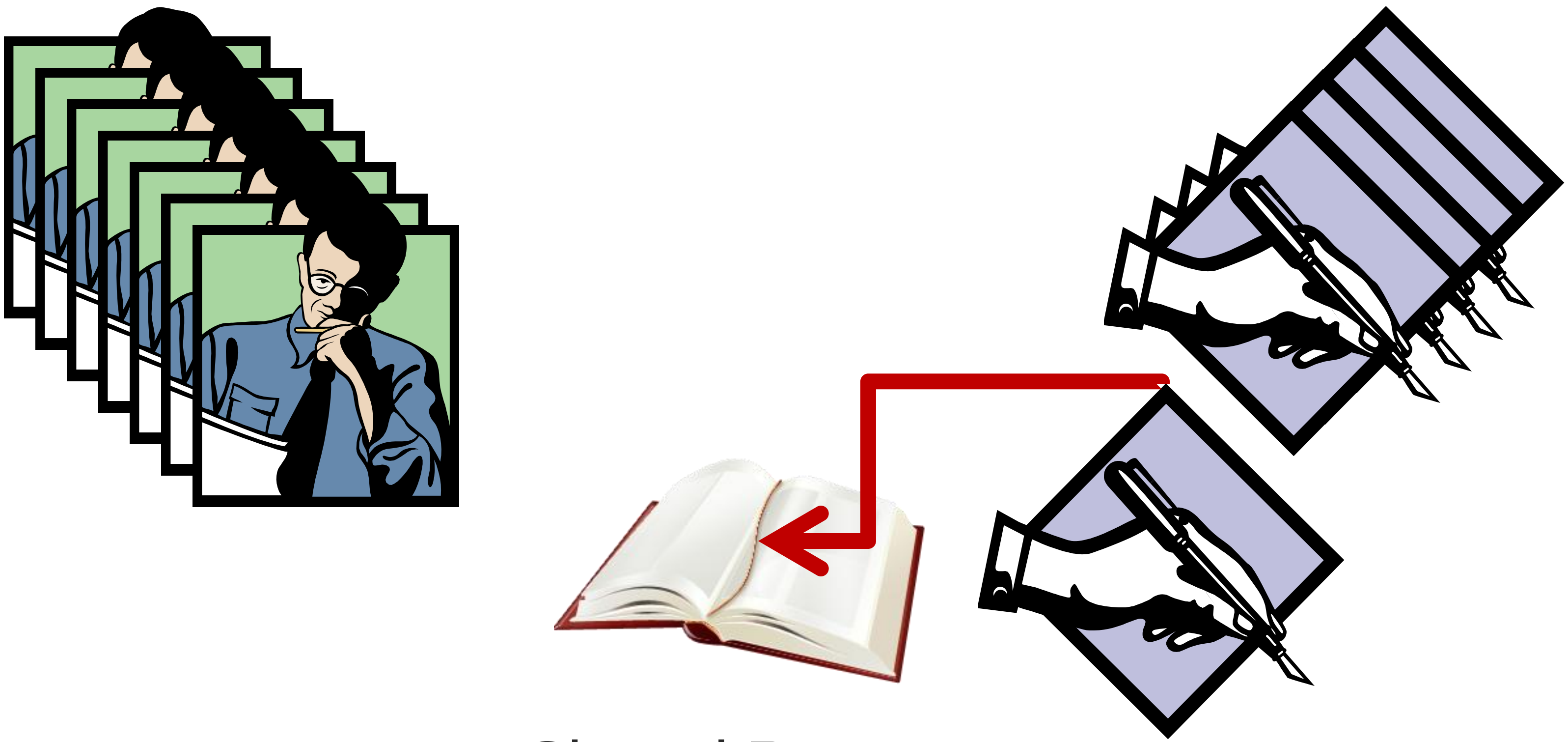
Readers-Writers Problem



Shared Resource



Readers-Writers Problem



Shared Resource

II. Reader-Writer Problem

- Readers read data
- Writers write data
- Rules
  - Multiple readers may read the data simultaneously
  - Only one writer can write the data at any time
  - A reader and a writer cannot access data simultaneously
- Locking table
  - Whether any two can be in the critical section simultaneously

	Reader	Writer
Reader	OK	No
Writer	No	No

Reader-Writer: First Solution

```
int readCount = 0;
semaphore mutex = 1;
semaphore writeBlock = 1;
```

```
reader() {
  while(TRUE) {
    <other stuff>;
    sem_wait(mutex);
    readCount++;

    if(readCount == 1)
      sem_wait(writeBlock);
    sem_signal(mutex);

    /* Critical section */
       access(resource);

    sem_wait(mutex);
    readCount--;
    if(readCount == 0)
      sem_signal(writeBlock);
    sem_post(mutex);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    sem_wait(writeBlock);
    /* Critical section */
    access(resource);
    sem_signal(writeBlock);
  }
}
```

Reader-Writer: Second Solution

```
int readCount=0, writeCount=0;
semaphore mutex1=1, mutex2=1;
Semaphore readBlock=1,writeBlock=1
```

```
reader() {
  while(TRUE) {
    <other computing>;
    sem_wait(readBlock);
    sem_wait(mutex1);
    readCount++;
    if(readCount == 1)
      sem_wait(writeBlock);
    sem_signal(mutex1);
    sem_signal(readBlock);

    access(resource);
    sem_wait(mutex1);
    readCount--;
    if(readCount == 0)
      sem_signal(writeBlock)
    sem_signal(mutex1);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    sem_wait(mutex2);
    writeCount++;
    if(writeCount == 1)
      sem_wait(readBlock);
    sem_signal(mutex2);
    sem_wait(writeBlock);
    access(resource);
    sem_signal(writeBlock);
    sem_wait(mutex2);
    writeCount--;
    if(writeCount == 0)
      sem_signal(readBlock);
    sem_signal(mutex2);
  }
}
```

Better R-W solution idea

- Idea: serve requests in order
  - Once a writer requests access, any entering readers have to block until the writer is done
- Advantage?
- Disadvantage?

Reader-Writer: Fairer Solution?

```
int readCount = 0, writeCount = 0;
semaphore mutex1 = 1, mutex2 = 1;
semaphore readBlock = 1, writeBlock = 1, writePending = 1;
```

```
reader() {
  while(TRUE) {
    <other computing>;
    sem_wait(writePending);
    sem_wait(readBlock);
    sem_wait(mutex1);
    readCount++;
    if(readCount == 1)
      sem_wait(writeBlock);
    sem_signal(mutex1);
    sem_signal(readBlock);
    sem_signal(writePending);
    access(resource);
    sem_wait(mutex1);
    readCount--;
    if(readCount == 0)
      sem_signal(writeBlock);
    sem_signal(mutex1);
  }
}
```

```
writer() {
  while(TRUE) {
    <other computing>;
    sem_wait(writePending);
    sem_wait(mutex2);
    writeCount++;
    if(writeCount == 1)
      sem_wait(readBlock);
    sem_signal(mutex2);
    sem_wait(writeBlock);
    access(resource);
    sem_signal(writeBlock);
    sem_signal(writePending);
    sem_wait(mutex2);
    writeCount--;
    if(writeCount == 0)
      sem_signal(readBlock);
    sem_signal(mutex2);
  }
}
```

Summary

- Classic synchronization problems
  - Producer-Consumer Problem
  - Reader-Writer Problem
- Saved for next time:
  - Sleeping Barber's Problem
  - Dining Philosophers Problem

Dining Philosophers

- N philosophers and N forks
  - Philosophers eat/think
  - Eating needs 2 forks
  - Pick one fork at a time