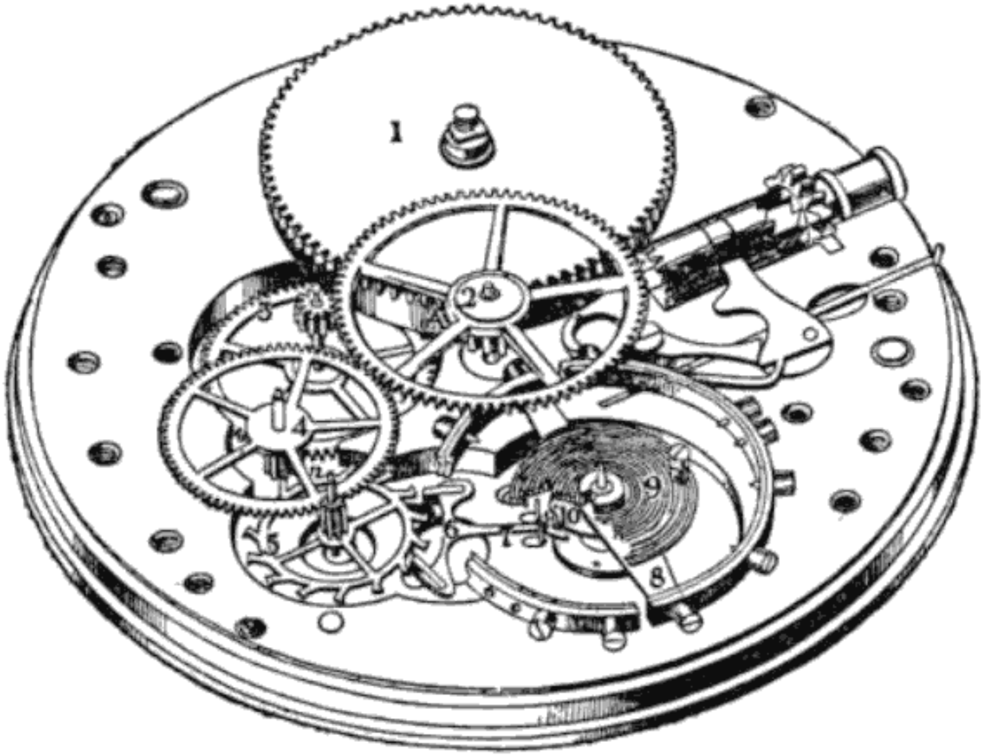
Using Semaphores



CS 241

March 12, 2014

University of Illinois

Slides adapted in part from material accompanying Bryant
"Computer Systems: A Programmer's Perspective", 2/E

Announcements

Midterm

- Grades by Friday
- No discussion of solutions yet
  - We will discuss them next week

Brighten lecturing now

- Office hours: Mondays right after lecture

Today

- Using semaphores: the producer-consumer problem
- Using semaphores: the readers-writers problem

Using Semaphores

Review: Semaphores

Problem: coordinating simultaneous access to shared data

```
int cnt = 0;          <- Shared data

void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++)
        cnt++;        <- Critical section
}                        (just one line in this simple example)
```

Solution: mutually exclusive access to critical region

- Only one thread/process accesses shared data at a time

Semaphores for mutual exclusion

Basic idea

- Associate a unique semaphore *mutex*, initially 1, with each shared variable (or related set of shared variables)
- Surround corresponding critical sections with *wait(mutex)* and *post(mutex)* operations.

Terminology

- **Binary semaphore**: semaphore whose value is always 0 or 1
- **Mutex:** binary semaphore used for mutual exclusion
  - *wait* operation: "locking" the mutex
  - *post* operation: "unlocking" or "releasing" the mutex
  - "Holding" a mutex: locked and not yet unlocked
- **Counting semaphore**: used to count a set of available resources

Before: Basic use of semaphores

```
void * worker( void *ptr )
{
    int i;
    for (i = 0; i < ITERATIONS_PER_THREAD; i++) {
        sem_wait(&cnt_mutex);
        cnt++;
        sem_post(&cnt_mutex);
    }
}
```

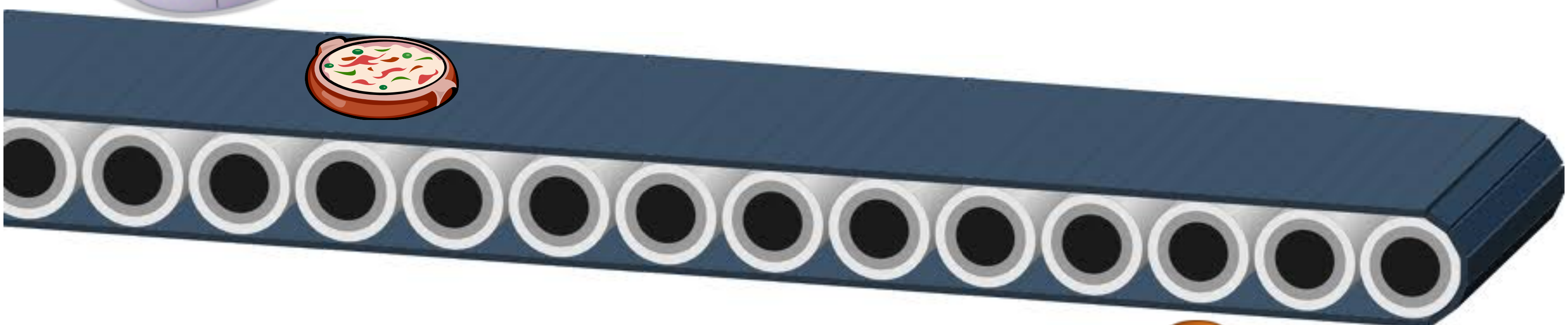
Today: Advanced use of semaphores

[Monty Python's Flying Circus]

Using semaphores:
The Producer-Consumer Problem

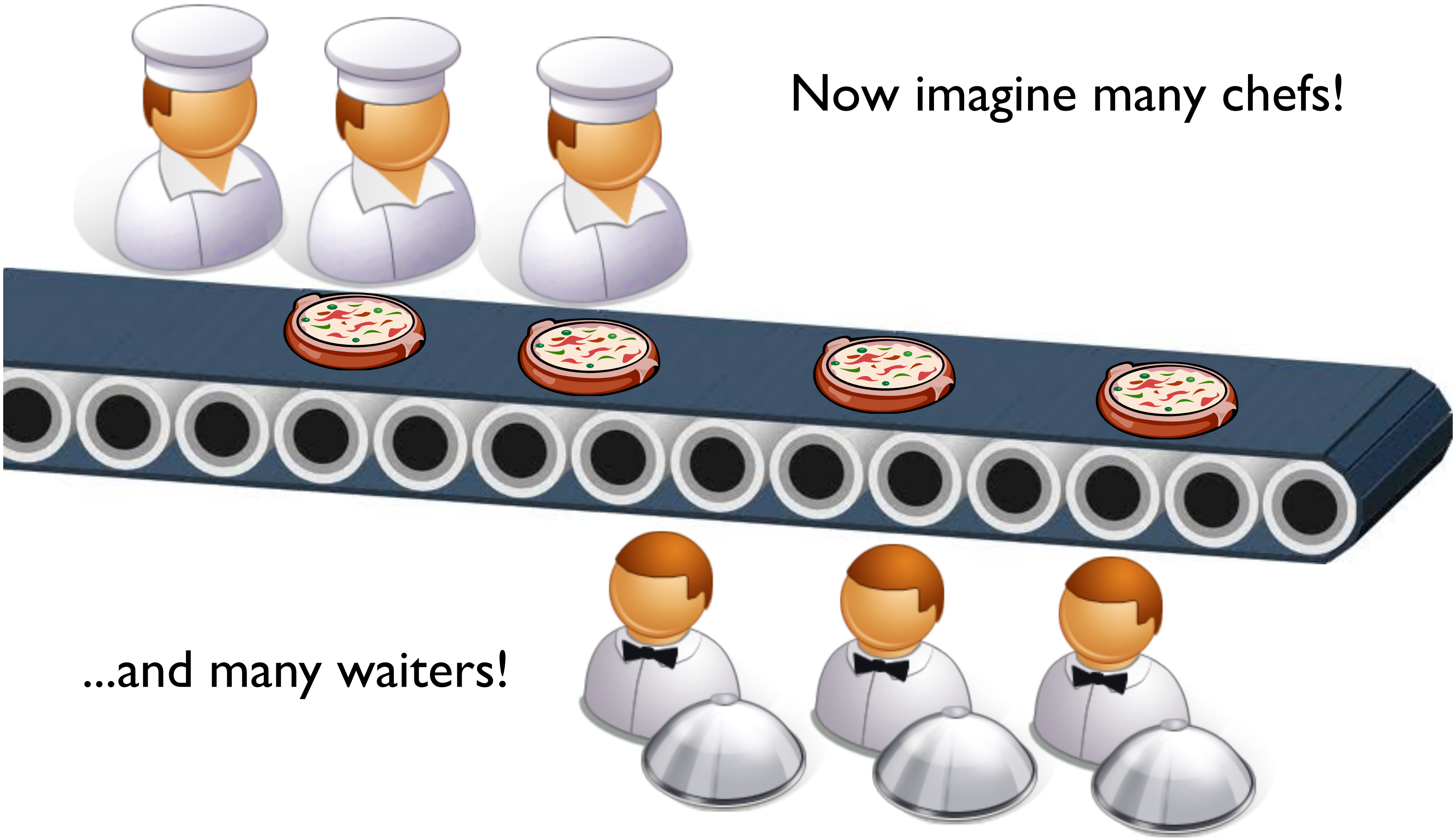
Producer-consumer problem

Chefs cook items and put them on a conveyer belt



Waiters pick items off the belt

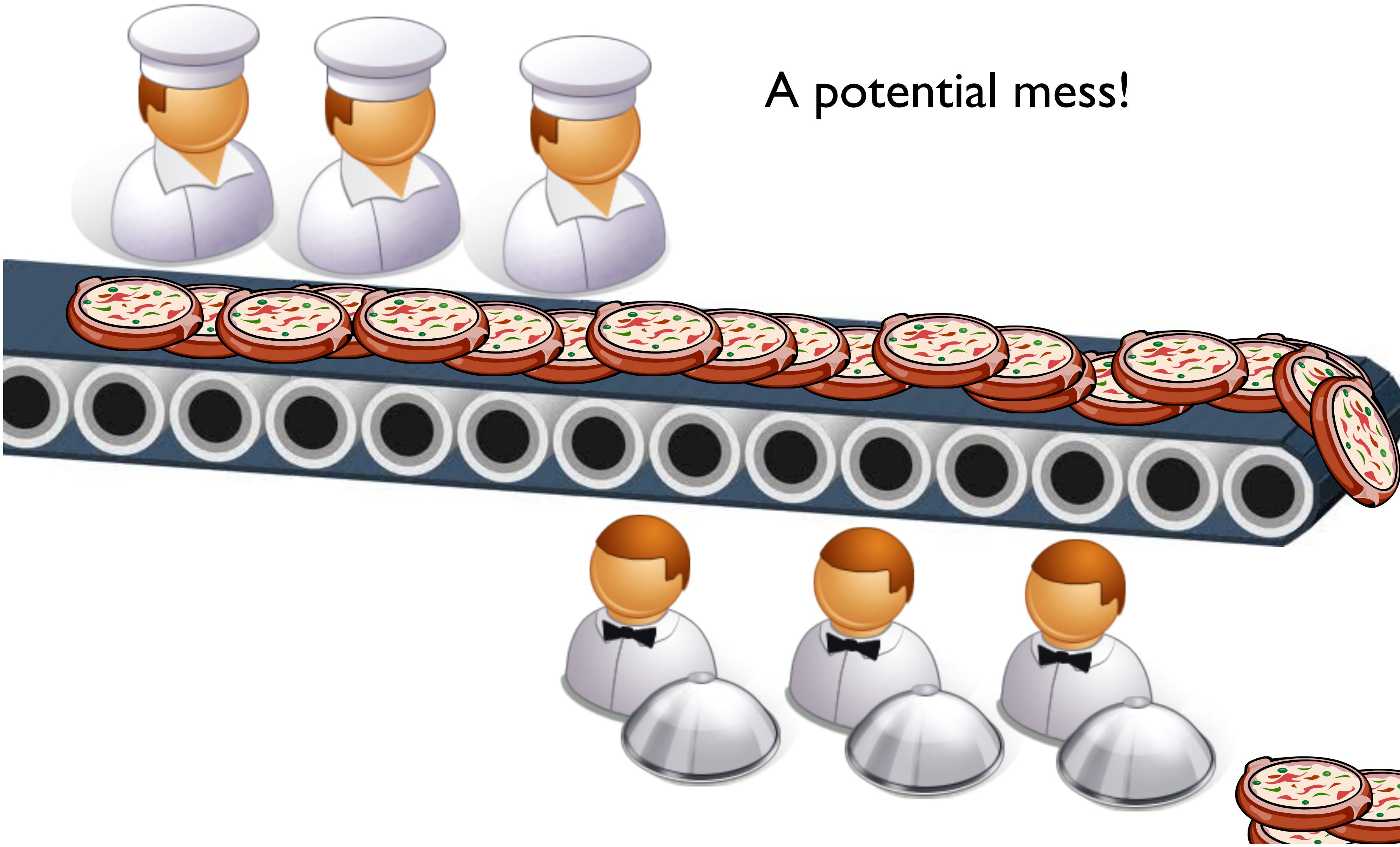
Producer-consumer problem



Now imagine many chefs!

...and many waiters!

Producer-consumer problem



A potential mess!

Producer-consumer problem

Chef (Producer)

Waiter (Consumer)

inserts items

removes items

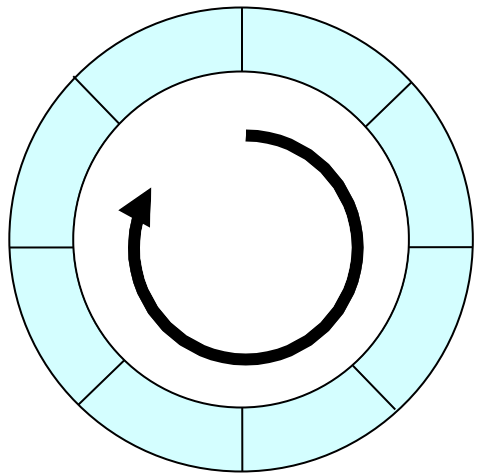
Shared resource:
bounded buffer

Efficient implementation:
circular fixed-size buffer

Shared buffer

Chef (Producer)

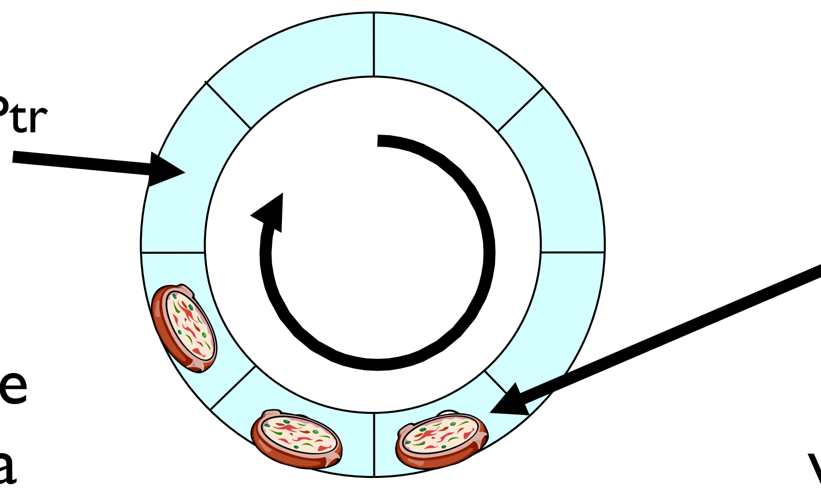
Waiter (Consumer)



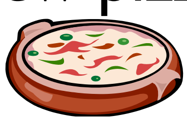
Shared buffer

Chef (Producer)

Waiter (Consumer)

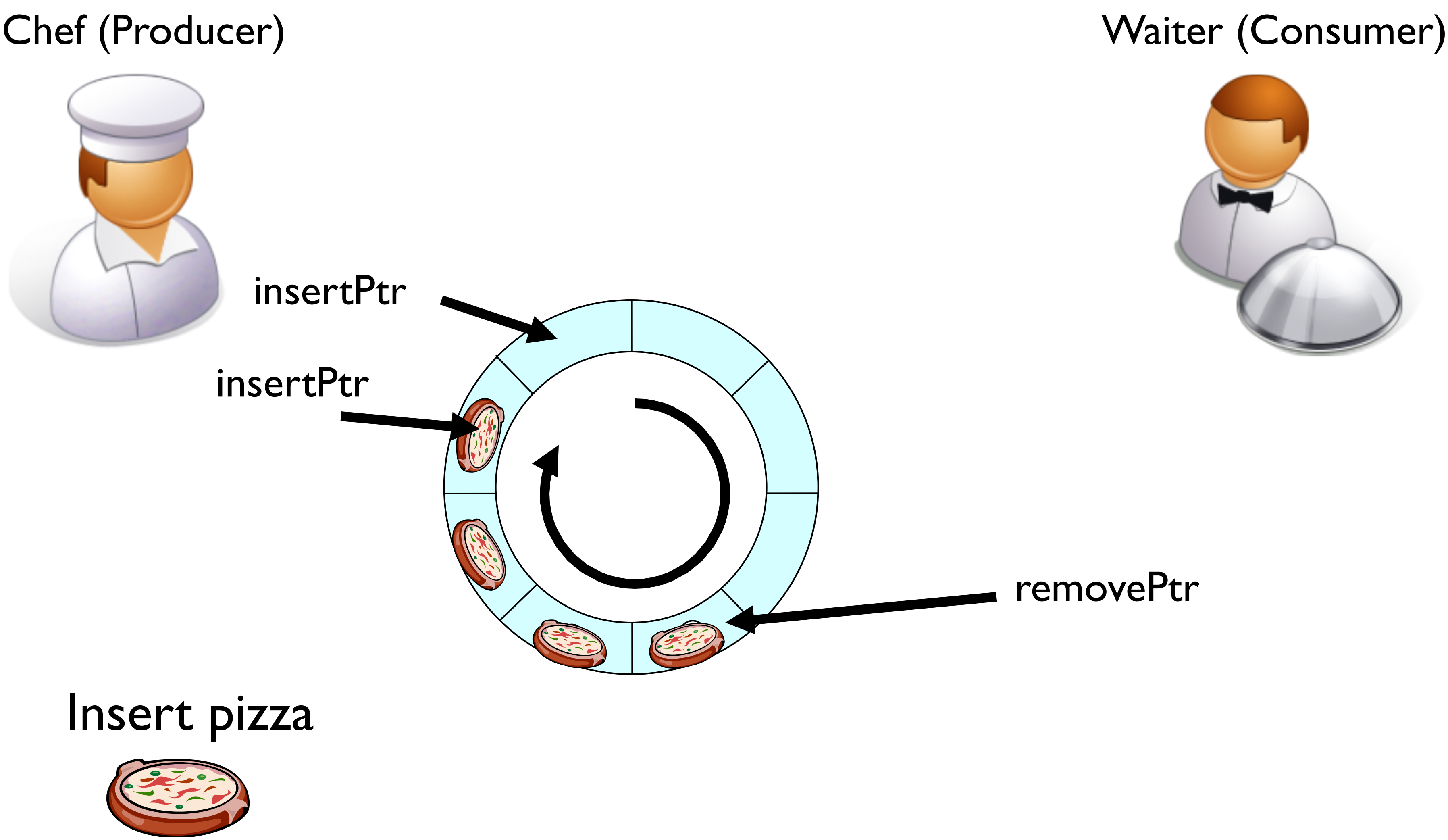


What does the chef do with a new pizza?



Where does the waiter take a pizza from?

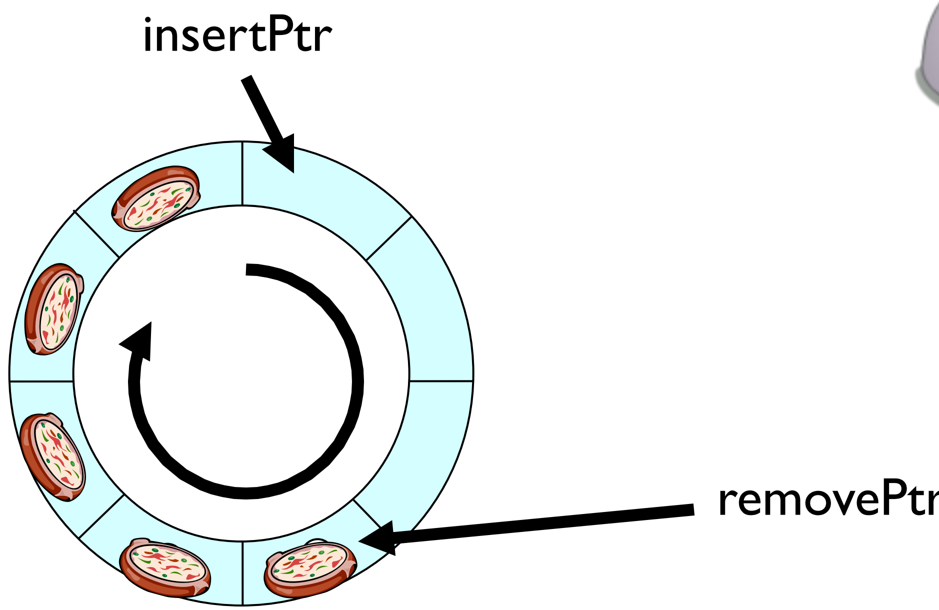
Shared buffer



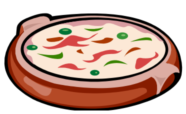
Shared buffer

Chef (Producer)

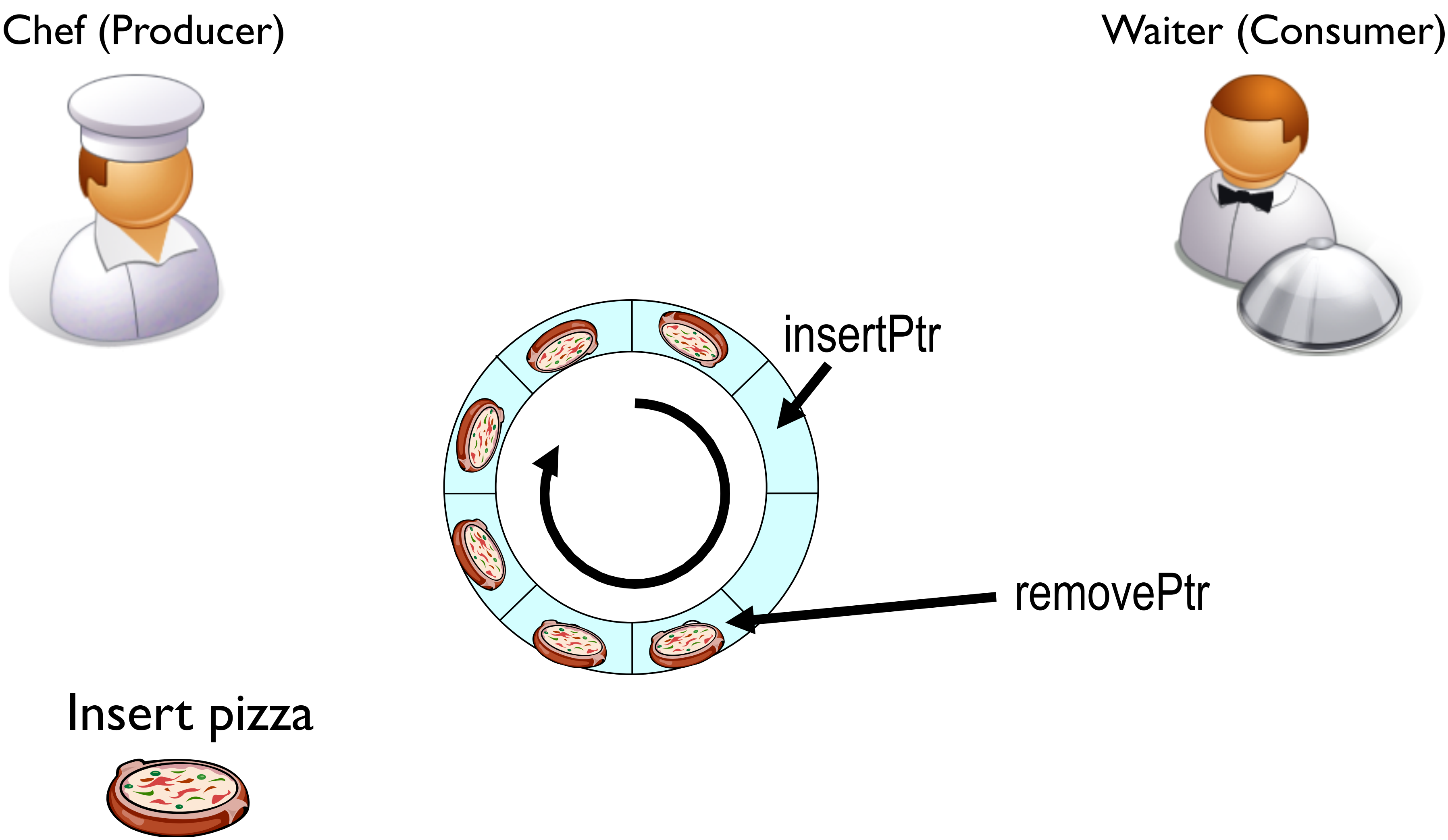
Waiter (Consumer)



Insert pizza



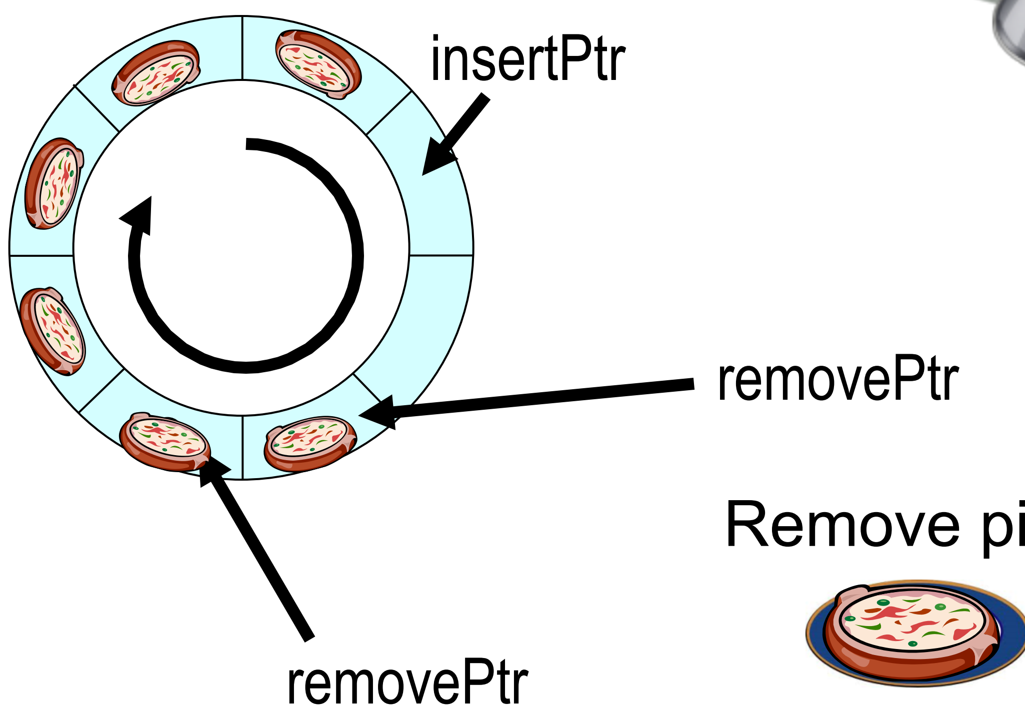
Shared buffer



Shared buffer

Chef (Producer)

Waiter (Consumer)

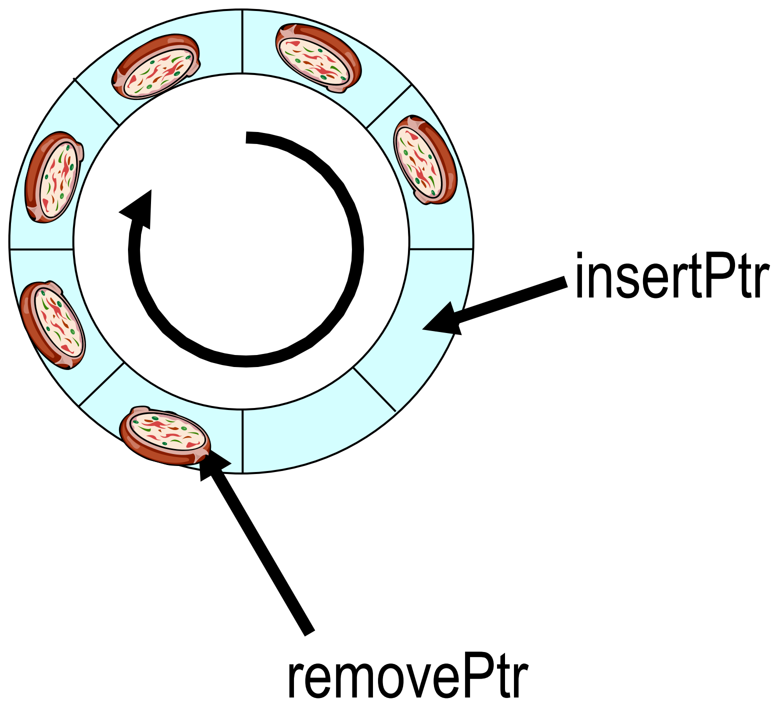


Remove pizza

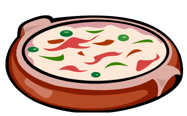
Shared buffer

Chef (Producer)

Waiter (Consumer)



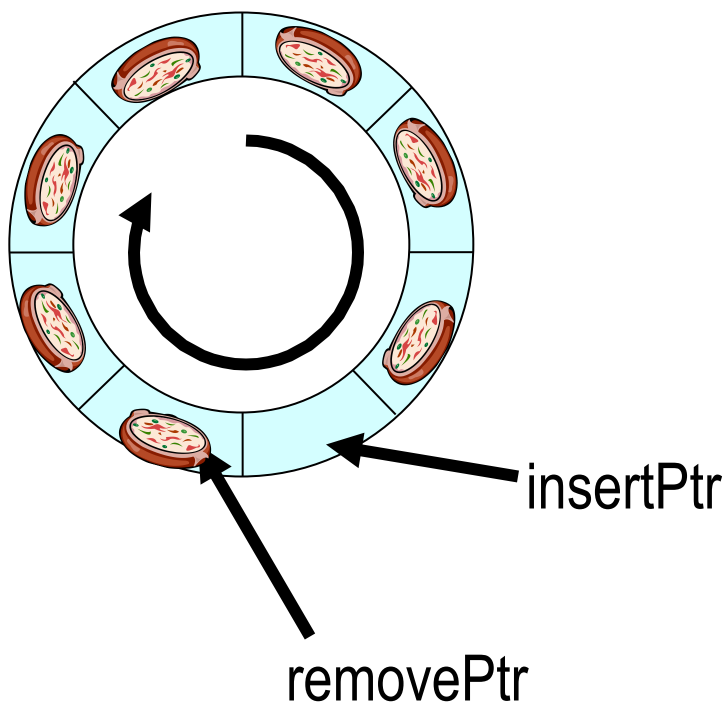
Insert pizza



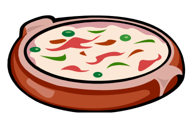
Shared buffer

Chef (Producer)

Waiter (Consumer)



Insert pizza

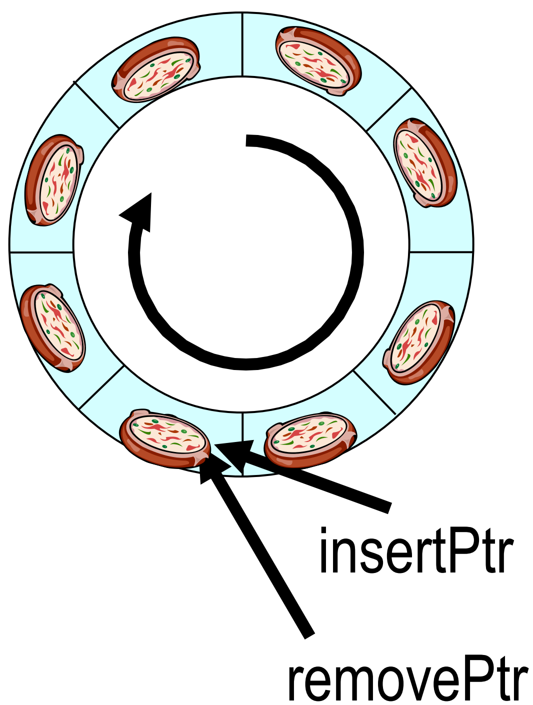


Shared buffer

Chef (Producer)

Waiter (Consumer)

BUFFER FULL:
Producer must wait!

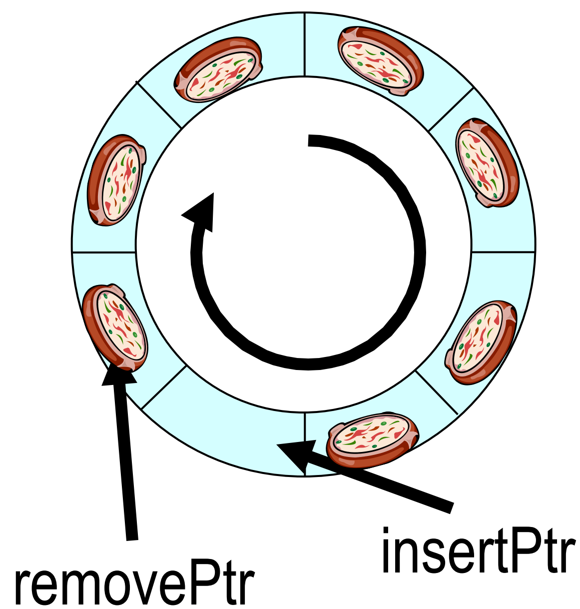


Insert pizza

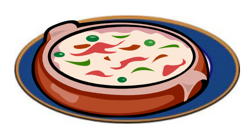
Shared buffer

Chef (Producer)

Waiter (Consumer)



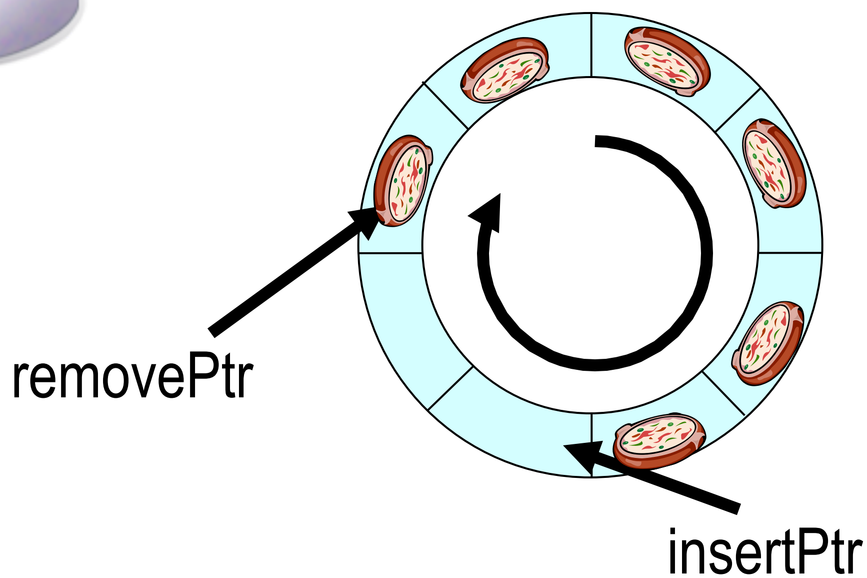
Remove pizza



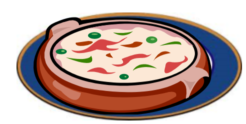
Shared buffer

Chef (Producer)

Waiter (Consumer)



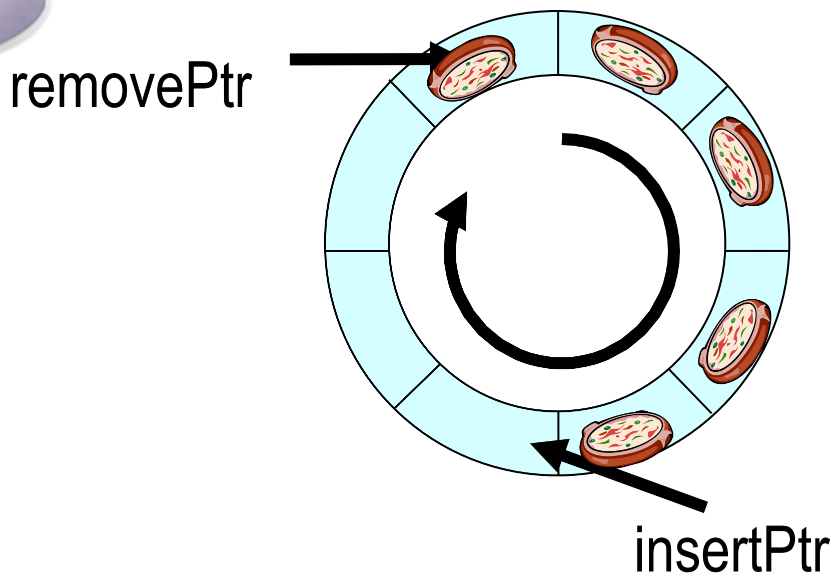
Remove pizza



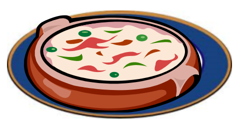
Shared buffer

Chef (Producer)

Waiter (Consumer)



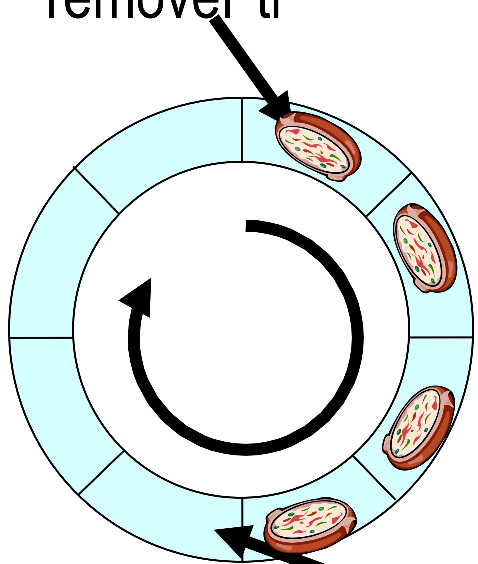
Remove pizza



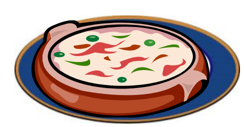
Shared buffer

Chef (Producer)

Waiter (Consumer)



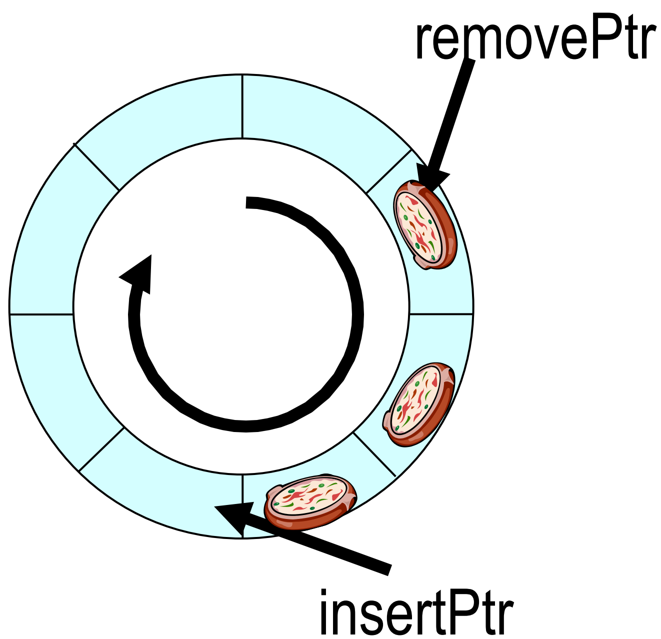
Remove pizza



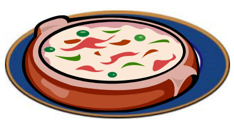
Shared buffer

Chef (Producer)

Waiter (Consumer)



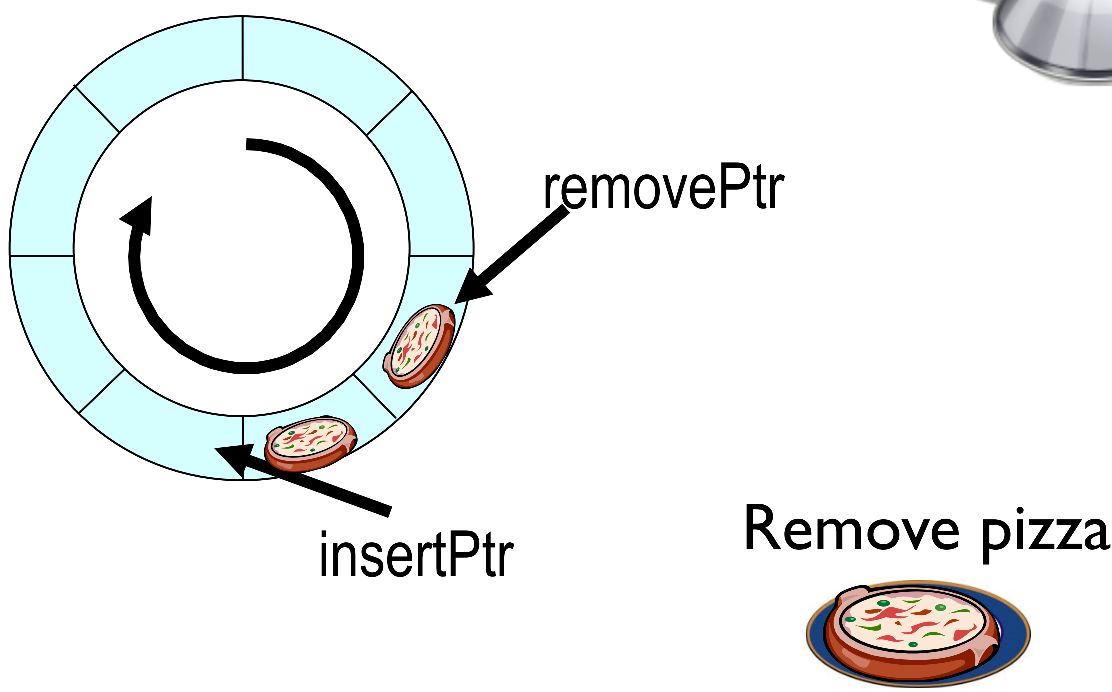
Remove pizza



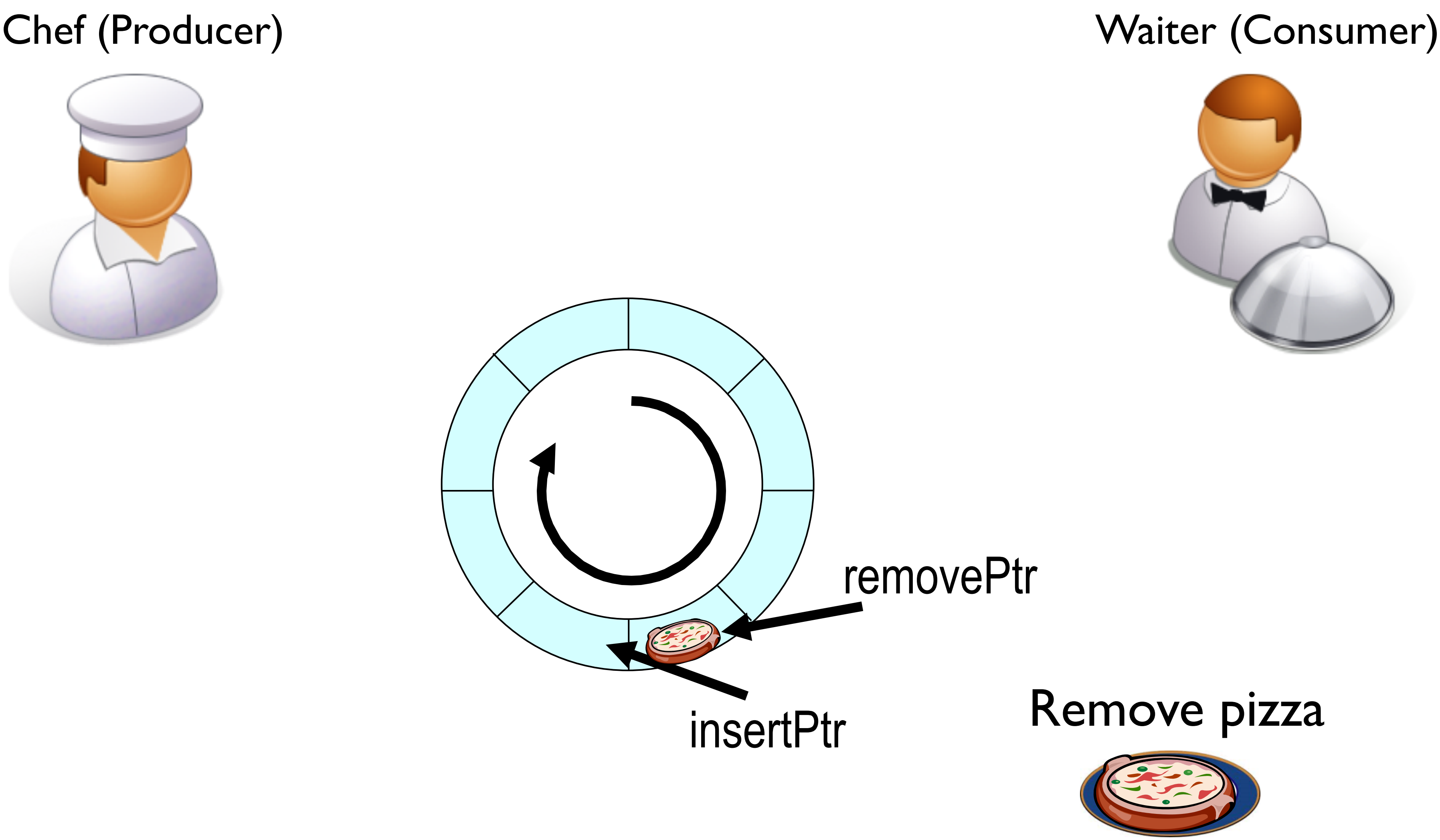
Shared buffer

Chef (Producer)

Waiter (Consumer)



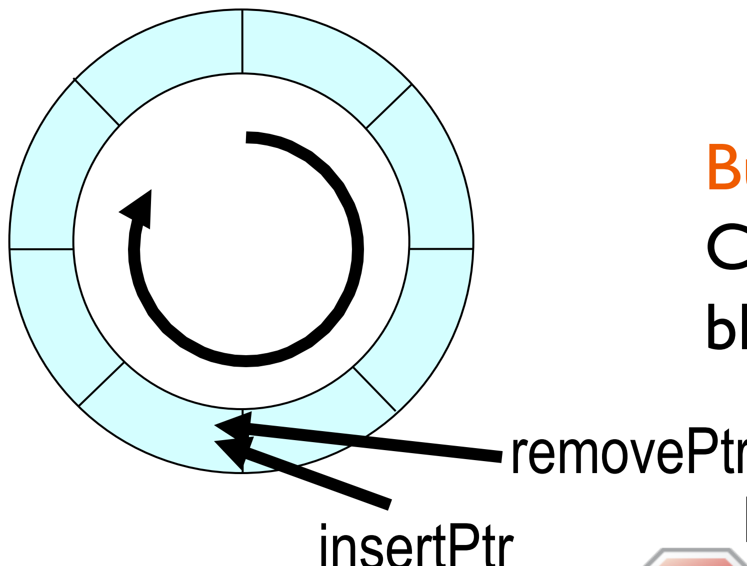
Shared buffer



Shared buffer

Chef (Producer)

Waiter (Consumer)



Buffer empty:
Consumer must be blocked!

Remove pizza

Designing a solution

Chef (Producer)

Waiter (Consumer)

Wait for empty slot
Insert item
Signal item arrival

Wait for item arrival
Remove item
Signal empty slot available

What synchronization do we need?

Designing a solution

Chef (Producer)

Waiter (Consumer)

Wait for empty slot
Insert item
Signal item arrival

Mutex
(shared buffer)

Wait for item arrival
Remove item
Signal empty slot available

What synchronization do we need?

Designing a solution

Chef (Producer)

Waiter (Consumer)

Wait for empty slot
Insert item
Signal item arrival

Semaphore
(# empty slots)

Wait for item arrival
Remove item
Signal empty slot available

What synchronization do we need?

Designing a solution

Chef (Producer)

Waiter (Consumer)

Wait for empty slot
Insert item
Signal item arrival

Semaphore
(# filled slots)

Wait for item arrival
Remove item
Signal empty slot available

What synchronization do we need?

Producer-Consumer Code

Critical Section: move insert pointer

```
buffer[ insertPtr ] =
data;

insertPtr = (insertPtr
+ 1) % N;
```

Critical Section: move remove pointer

```
result =
buffer[removePtr];

removePtr = (removePtr
+1) % N;
```

Producer-Consumer Code

Counting semaphore – check and decrement the number of free slots

Block if there are no free slots

```
sem_wait(&slots);

mutex_lock(&mutex);

buffer[ insertPtr ] = data;

insertPtr = (insertPtr + 1) % N;

mutex_unlock(&mutex);

sem_post(&items);
```

Done – increment the number of available items

Counting semaphore – check and decrement the number of available items

Block if there are no items to take

```
sem_wait(&items);

mutex_lock(&mutex);

result = buffer[removePtr];

removePtr = (removePtr +1) % N;

mutex_unlock(&mutex);

sem_post(&slots);
```

Done – increment the number of free slots

Consumer Pseudocode: getItem()

```
sem_wait(&items);
pthread_mutex_lock(&mutex);
result = buffer[removePtr];
removePtr = (removePtr +1) % N;
pthread_mutex_unlock(&mutex);
sem_signal(&slots);
```

Error checking/EINTR handling not shown

Producer Pseudocode: putItem(data)

```
sem_wait(&slots);
pthread_mutex_lock(&mutex);
buffer[ insertPtr ] = data;
insertPtr = (insertPtr + 1) % N;
pthread_mutex_unlock(&mutex);
sem_signal(&items);
```

Error checking/EINTR handling not shown

Readers-Writers Problem

Readers-Writers Problem

Generalization of the mutual exclusion problem

Problem statement:

- *Reader* threads only read the object
- *Writer* threads modify the object
- Writers must have exclusive access to the object
- Unlimited number of readers can access the object

Occurs frequently in real systems, e.g.,

- Online airline reservation system
- Multithreaded caching Web proxy

A solution

Does it work?
https://www.surveymonkey.com/s/82RYXFT

Shared:

```
int readcnt;    /* Initially = 0 */
sem_t mutex, w; /* Both initially = 1 */
```

Writers:

```
sem_wait(&w);

/* Critical section */
/* Writing here */

sem_post(&w);
```

Readers:

```
sem_wait(&mutex);
readcnt++;
if (readcnt == 1) /* First reader in */
  sem_wait(&w); /* Lock out writers */
sem_post(&mutex);

/* Main critical section */
/* Reading would happen here */

sem_wait(&mutex);
readcnt--;
if (readcnt == 0) /* Last out */
  sem_post(&w); /* Let in writers */
sem_post(&mutex);
```

(full code online)

Variants of Readers-Writers

Favor readers

- No reader waits unless a writer is already in critical section
- A reader that arrives after a waiting writer gets priority over writer

Favor writers

- Once a writer is ready to write, it performs its write as soon as possible
- A reader that arrives after a writer must wait, even if the writer is also waiting

Starvation (thread waits indefinitely) possible in both cases

- Q: How could we fix this?

Summary

Synchronization: more than just locking a critical section

Semaphores useful for counting available resources

- sem_wait(): wait for resource only if none available
- sem_post(): signal availability of another resource

Multiple semaphores / mutexes can work together to solve complex problems

Solution favoring readers

Readers:

```
void reader(void)
{
    while (1) {
        sem_wait(&mutex);
        readcnt++;
        if (readcnt == 1) /* First reader in */
            sem_wait(&w); /* Lock out writers */
        sem_post(&mutex);

        /* Main critical section */
        /* Reading would happen here */

        sem_wait(&mutex);
        readcnt--;
        if (readcnt == 0) /* Last out */
            sem_post(&w); /* Let in writers */
        sem_post(&mutex);
    }
}
```