Patterns based on Semaphores

CS511

Review of Semaphores

- An Abstract Data Type with two operations
  - `acquire`
  - `release`
- Can be used to solve the mutual exclusion problem
- Can be used to synchronize cooperative threads

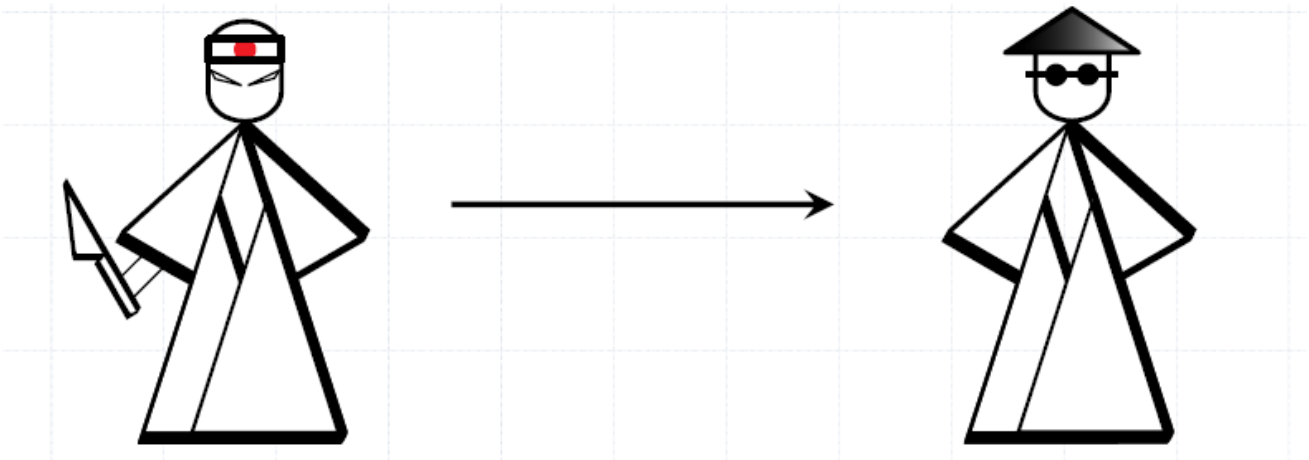
Today

- Recurring problems in the area
- Proven solution templates

Producers/Consumers

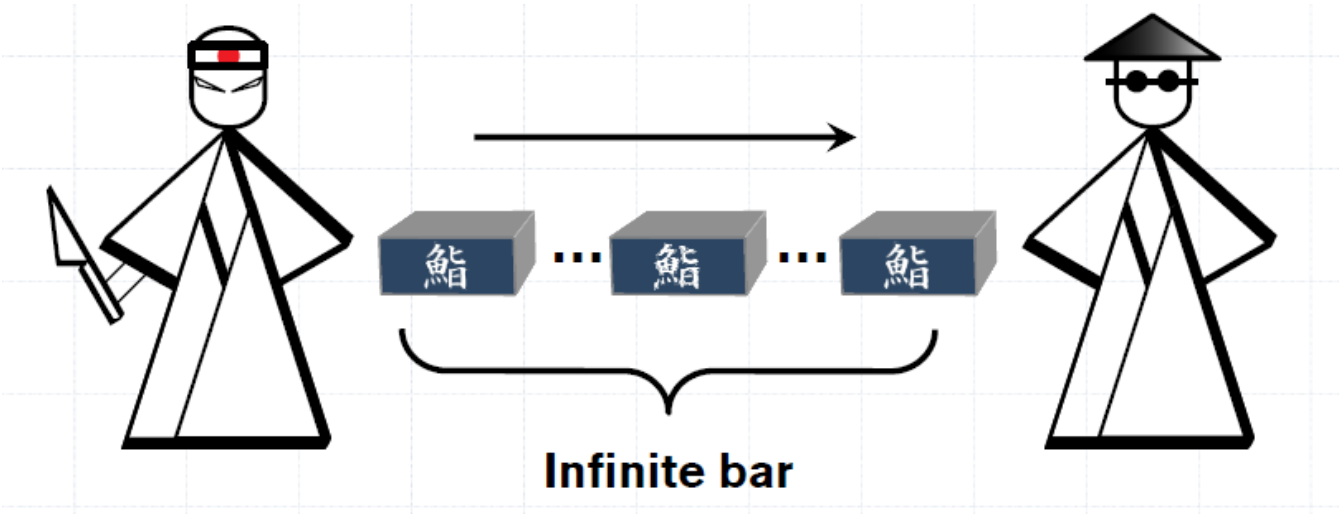
Readers/Writers

Producers/consumers



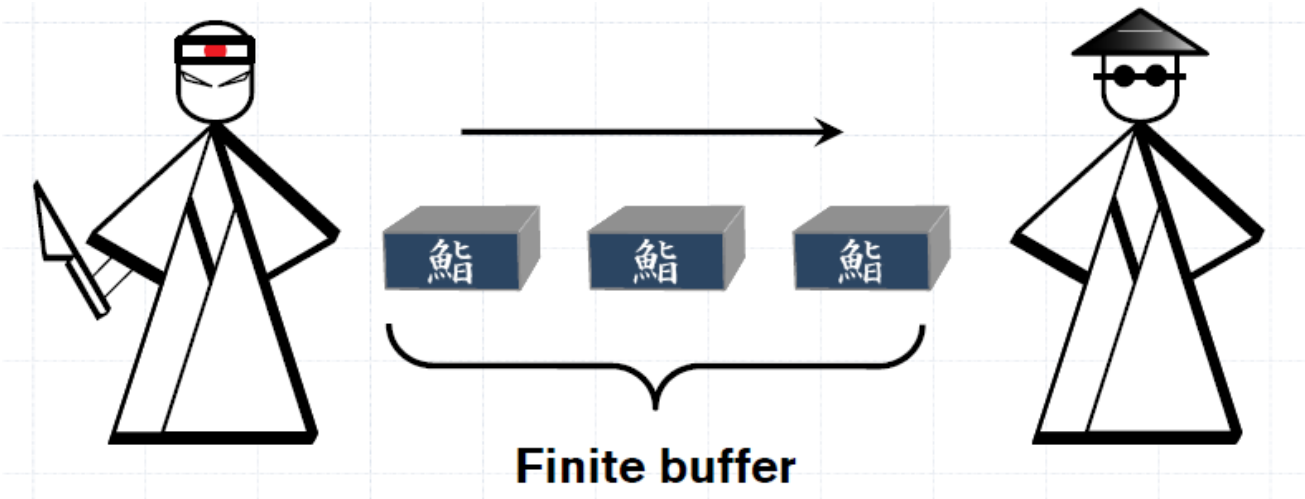
- A commmon pattern of interaction
- Must cater for difference in speed between each party

Unbounded Buffer



- The producer can work freely
- The consumer must wait for the producer to produce

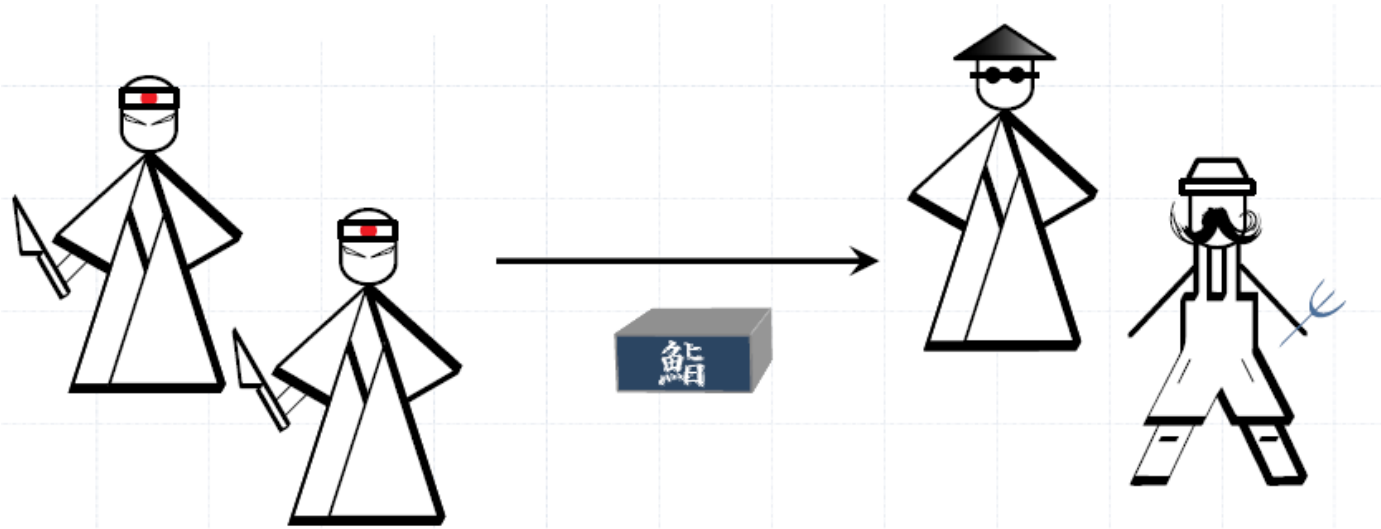
Bounded Buffer



- The producer must wait when the buffer is full
- The consumer must wait for the producer to produce

Buffer using Semaphores

- Capacity 1



- Various producers
- Various consumers
- Semaphores

Buffer using Semaphores – 1 producer and 1 consumer

```
1 Object buffer;
2 ...
3 ...
```

```
4 Thread.start { // Prod
5   while (true) {
6     ...
7     buffer = produce();
8     ...
9   }
```

```
4 Thread.start { // Cons
5   while (true) {
6     ...
7     consume(buffer);
8     ...
9   }
```

Split Binary Semaphores

- Two semaphores
  - one to hold permissions to produce
  - one to hold permissions to consume
- Initialization
  - `produce = 1`
  - `consume = 0`
- Invariant
  - `produce + consume <= 1`

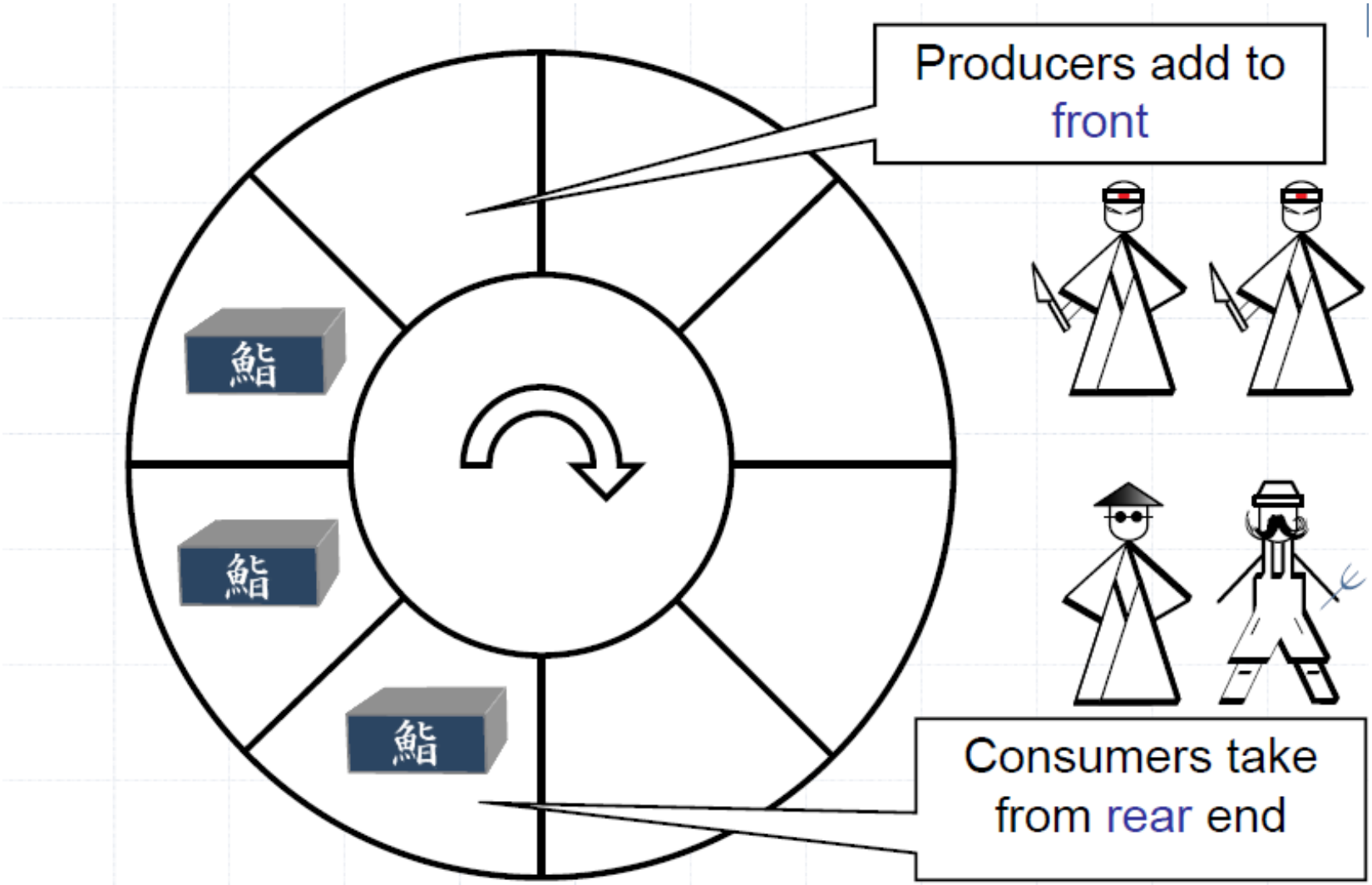
Split Binary Semaphores

```
1 Object buffer;
2 Semaphore produce = new Semaphore(1);
3 Semaphore consume  = new Semaphore(0);

4 Thread.start { // Prod
5   while (true) {
6     produce.acquire();
7     buffer = produce();
8     consume.release();
9   }
```

```
4 Thread.start { // Cons
5   while (true) {
6     consume.acquire();
7     consume(buffer);
8     produce.release();
9   }
```

N Size Buffer



General Semaphores

- Semaphores count the number of empty slots in the buffer
- Initialization
  - There are N empty slots
  - There are 0 full slots
- Invariant
  - `produce + consume <= N`

Unique Producer/Consumer

```
1  Object[]  buffer  = new Object[N];
2  Semaphore produce = new Semaphore(N);
3  Semaphore consume = new Sempahore(0);
4  int start = 0;
5  int end   = 0;
```

```
6  Thread.start { // Prod
7    while (true) {
8      ...
9      buffer[start] = produce();
10     start = (start+1) % N;
11     ...
12   }
```

```
6  Thread.start{ // Cons
7    while (true) {
8      ...
9      consume(buffer[end]);
10     end = (end+1) % N;
11     ...
12   }
```

Unique Producer/Consumer

```
1  Object[]  buffer = new Object[N];
2  Semaphore produce  = new Semaphore(N);
3  Semaphore consume   = new Sempahore(0);
4  int start = 0;
5  int end   = 0;
```

```
6  Thread.start{ // Prod
7    while (true) {
8      produce.acquire();
9      buffer[start] = produce();
10     start = (start+1) % N;
11     consume.release();
12   }
```

```
6  Thread.start { // Cons
7    while (true) {
8      consume.acquire();
9      consume(buffer[end]);
10     end = (end+1) % N;
11     produce.release();
12   }
```

Multiple Producers

- We cannot simply add multiple instances of the producer
- Why? Justify with a trace
- What can we do about it?

```
1  // declarations: same as above...
```

```
6  Thread.start{ // ProdA
7    while (true) {
8      produce.acquire();
9      buffer[start] = produce();
10     start = (start+1) % N;
11     consume.release();
12   }
```

```
6  Thread.start { // ProdB
7    while (true) {
8      produce.acquire();
9      buffer[start] = produce();
10     start = (start+1) % N;
11     consume.release();
12   }
```

Multiple Producers

- Must guarantee mutual exclusion between producers:
  - We add a new semaphore

```
1  Semaphore mutexP = new Semaphore(1);
2
3  Thread.start { // Prod
4    while (true) {
5      produce.acquire();
6      mutexP.acquire();
7      buffer[start] = produce();
8      start = (start+1) % N;
9      mutexP.release();
10     consume.release();
11   }
12 }
```

Multiple Consumers

- Must guarantee mutual exclusion between consumers

```
1  Semaphore mutexC = new Semaphore(1);
2
3  Thread.start { // Cons
4    while (true) {
5      consume.acquire();
6      mutexC.acquire();
7      consume(buffer[end]);
8      end = (end+1) % N;
9      mutexC.release();
10     produce.release();
11   }
12 }
```

Putting it all together

```
1  int N = 10;
2  int[]  buffer = new int[N];
3  Semaphore produce  = new Semaphore(N);
4  Semaphore consume   = new Semaphore(0);
5  int start = 0;
6  int end   = 0;
7  int counter = 0;
8
9  void consume(int i) { }
10
11 int produce () { return counter++; }
12
13 Semaphore mutexP = new Semaphore(1);
14 Semaphore mutexC = new Semaphore(1);
15
16 // continues in next slide
```

Putting it all together

```
1  Consumer(int id) {
2    while (true) {
3      consume.acquire();
4      mutexC.acquire();
5      consume(buffer[end]);
6      print(id+" consumed product "+ buffer[end] + " at "+ end);
7      end = (end+1) % N;
8      mutexC.release();
9      produce.release();
10   }
11 }
12
13
14 Producer(int id) {
15   while (true) {
16     produce.acquire();
17     mutexP.acquire();
18     buffer[start] = produce();
19     print(id+" add product "+ buffer[start]+ " at "+ start);
20     start = (start+1) % N;
21     mutexP.release();
22     consume.release();
23   }
24 }
```

Putting it all together

```
1
2 for (i=0; i<5; i++) {
3     int id = i;
4     thread Producer(id);
5     thread Consumer(id);
6     }
```

Producers/Consumers

Readers/Writers

Readers/Writers

- There are shared resources between two types of threads
  - Readers: access the resource without modifying it
  - Writers: access the resource and may modify it
- Mutual exclusion is too restrictive
  - Readers: can access simultaneously
  - Writers: at most one at any given time

Properties a Solution should Possess

- Each read/write operation should occur inside the critical region
- Must guarantee mutual exclusion between the writers
- Must allow multiple readers to execute inside the critical region simultaneously

First Solution: Priority Readers

```
1 Writer() {
2
3   ...
4   write();
5   ...
6
7 }
```

```
1 Reader() {
2
3   ...
4   read();
5   ...
6
7 }
```

First Solution: Priority to Readers

- One semaphore for controlling write access
- Before writing, the permission must be obtained and then released when done
- The first reader must "steal" the permission to write and the last one must return it
  - We must count the number of readers inside the CS
  - This must be done inside its own CS

First Solution: Prioity Readers

```
1 Semaphore resource = new Semaphore(1);
2 Semaphore numReadersMutex  = new Semaphore(1);
3 int numReaders = 0;
```

```
1 Writer() {
2   resource.acquire();
3   write();
4   resource.release();
5 }
```

```
1  Reader() {
2    numReadersMutex.acquire();
3    numReaders++;
4    if (numReaders == 1)
5      resource.acquire();
6    numReadersMutex.release();
7
8    read();
9
10   numReadersMutex.acquire();
11   numReaders--;
12   if (numReaders == 0)
13     resource.release();
14   numReadersMutex.release();
15 }
```

Note: Is this solution free from starvation?

Second Solution: Priority Writers

- The readers can potentially lock out all the writers
  - We need to count the number of writers that are waiting
  - Also, this counter requires its own CS
- Before reading the readers must obtain a permission to do so

Second Solution: Priority Writers

```
1  Writer() {
2    numWritersMutex.acquire();
3    numWriters++;
4    if (numWriters == 1)
5      readTry.acquire();
6    numWritersMutex.release();
7
8    resource.acquire();
9    write();
10   resource.release();
11
12   numWritersMutex.acquire();
13   numWriters--;
14   if (numWriters == 0)
15     readTry.release();
16   numWritersMutex.release();
17 }
```

```
1  Reader() {
2    readTry.acquire();
3    numReadersMutex.acquire();
4    numReaders++;
5    if (numReaders == 1)
6      resource.acquire();
7    numReadersMutex.release();
8    readTry.release();
9
10   read();
11
12   numReadersMutex.acquire();
13   numReaders--;
14   if (numReaders == 0)
15     resource.release();
16   numReadersMutex.release();
17 }
```

- Readers might starve
- Solution in which neither readers nor writers starve?
  - Hint: Common service queue for both readers and writers

Third Solution

```
1  int numReaders;
2  Semaphore resource = new Semaphore(1);
3  Semaphore readCountAccess = new Semaphore(1);
4  Semaphore serviceQueue = new Semaphore(1);
```

```
1  Writer() {
2
3
4    serviceQueue.acquire();
5    resource.acquire();
6    serviceQueue.release();
7
8
9    writeResource();
10
11   resource.release();
12 }
```

```
1  Reader() {
2    serviceQueue.acquire();
3    readCountAccess.acquire();
4    readCount++;
5    if (readCount == 1)
6        resource.acquire();
7    readCountAccess.release();
8    serviceQueue.release();
9
10   readResource();
11
12   readCountAccess.acquire();
13   readCount--;
14   if (readCount == 0)
15       resource.release();
16   readCountAccess.release();
17 }
```

Summary

1. Semaphores are elegant and efficient for solving problems in concurrent programs
2. Still, they are low-level constructs since they are not structured
3. Monitors will provide synchronization by encapsulation