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Software Engineering and Architecture

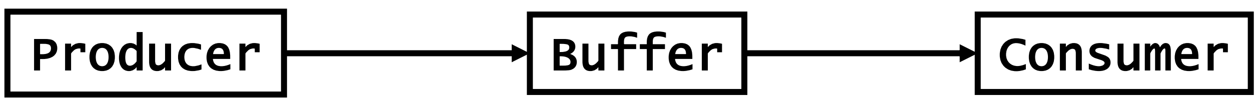
Producer Consumer

Recap

- The three categories of concurrent programs
  - Independent threads
    - Like running your Media player program while coding in IntelliJ
  - Shared resources
    - Like two threads reading/writing to the *same* account object
    - Typical case: web servers handling resources
      - You cannot book the same train seat twice!
  - **Collaborating processes**
    - Like one thread inserting into a buffer and assuming some other thread will remove those items from the buffer

Collaborating Threads

- The last, and most challenging, class of concurrent programs is *collaborating processes*
- The typical example is the *Producer Consumer*



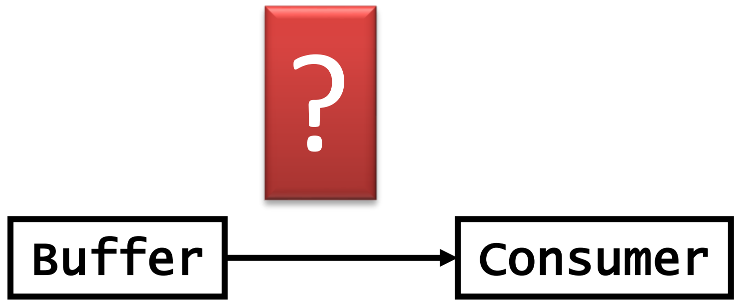
- For instance
  - Printer queue; high volume web traffic; disk read/write; …

Buffer

- Producer(s) and Consumer(s) are threads, and
- Our Buffer (queue) class has methods
  - **synchronized** void **store**(Object o) Insert ‘o’ into buffer
  - **synchronized** Object **retrieve**() Retrieve ‘o’ from buffer
- *Both must be critical regions - guarded by Lock or synchronized*
- Consider the ‘consumer’ that wants to retrieve the next item ‘o’ to process it
  - But if there is no item in the queue, it of course has to *wait* until there is an item available; that is, a producer has stored something into the queue…

Waiting for item to be available

- Waiting for item ‘o’ to become available



- Let us analyze our options…

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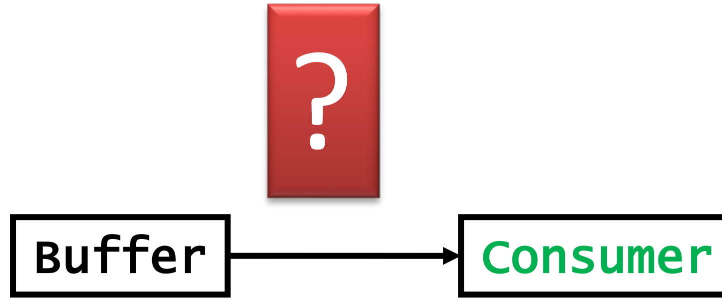
Waiting for ‘o’

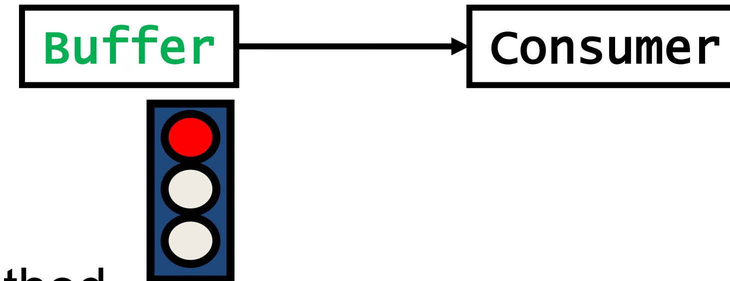
- So, how do we arrange to wait for the item?



  - In the consumer code
    - Call ‘take()’ repeatedly until it returns a non-null value
    - *This is called polling (busy waiting), and wastes a lot of CPU cycles on nothing*
    - *… And there is a waiting time from item available to processing*
- Similar to picking up the phone every 1 minute to see if any has called you …
  - Wasting a lot of time and resources ☹

Waiting for ‘o’

- So, how do we arrange to wait for the item?



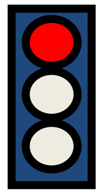
  - In the queue code’s retrieve() method
    - Wait inside – but hey! It is a critical region and thus *no producer can ever enter the ‘store()’ method’s critical region ☹*

- ***Deadlock***
  - *A thread waits infinitely for an event that will never happen*

Deadlock

- Repeat (as it is important!)
- We would *like* to wait in the queue code
  - retrieve() is called and then just returns when there is item available
- But we cannot because
  - retrieve() will take the 'lock' on the object and thus no other thread will ever be able to call the method store()
    - Waiting for the lock outside…

```
public synchronized void store(int item) throws InterruptedException {
public synchronized int retrieve() throws InterruptedException {
```



So We Want…

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- … a mechanism that
  - ***awaits** that a condition becomes true*
  - *Let other threads acquire the lock so they can make that condition true*

Not Java code!

```
class Queue {
  Object p;
  boolean empty = true;

  public synchronized Object retrieve() {
    await (!empty);
    empty = true;
    return p;
  }

  public synchronized void store(Object p) {
    await (empty);
    this.p = p; empty = false;
  }
}
```

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Example

- Scenario
  - C call retrieve()
    - Takes lock
    - Empty == true
    - **Release** lock and
    - **Enter Waiting** state
  - P calls store()
    - Takes lock
    - No wait (empty)
    - Finish and release lock
    - Later: Scheduler force P into ready state (not running)
  - C enters 'running' state
    - Takes lock
    - Empty = false!
    - Finish and release lock

```
class Queue {
  Object p;
  boolean empty = true;

  public synchronized Object retrieve() {
    await (!empty);
    empty = true;
    return p;
  }

  public synchronized void store(Object p) {
    await (empty);
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  }

}
```

! true => 'await'

Example

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    - **Enter Waiting** state
  - P calls store()
    - Takes lock
    - **No await** (empty == true)
    - Toggle empty and release lock
    - Later: Scheduler force P into ready state (not running)
  - C enters 'running' state
    - Takes lock
    - Empty = false!
    - Finish and release lock

```
class Queue {
  Object p;
  boolean empty = true;

  public synchronized Object retrieve() {
    await (!empty);
    empty = true;
    return p;
  }

  public synchronized void store(Object p) {
    await (empty);          true => continue
    this.p = p; empty = false;
  }

}
```

Example

- Scenario
  - C call retrieve()
    - Takes lock
    - empty == true
    - **Release** lock and
    - **Enter Waiting** state
  - P calls store()
    - Takes lock
    - **No await** (empty == true)
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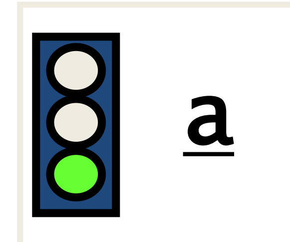
    - Later: Scheduler force P into ready state (not running)
  - C enters 'running' state
    - Takes lock
    - **No await** (empty == false)
    - Finish and release lock

```
class Queue {
  Object p;
  boolean empty = true;

  public synchronized Object retrieve() {
    await (!empty);        true => continue
    empty = true;
    return p;
  }

  public synchronized void store(Object p) {
    await (empty);
    this.p = p; empty = false;
  }

}
```

Java Primitives (Java 1.4)

- Java objects maintain a *wait-set* in addition to the lock
  - a.wait() does *atomically*
    - *Force current thread into waiting state,*
    - *Add current thread in object's wait-set*
    - *Release the lock on the object, a*
  - a.notify() does
    - *Choose one random thread, T, in a's wait-set*
    - *T must take the lock on 'a'*
      - *May fail if another thread has already taken the lock!*
    - *T resumes execution (becomes runnable) from the wait() statement*
  - a.notifyAll() does
    - The same except *all* threads in a's wait-set become 'runnable'…



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Java 1.4 Code

```
class BufferJava14 implements Buffer {
  public BufferJava14() {
    System.out.println("=== Using BufferJava 1.4 ===");
    System.out.println();
  }

  private boolean empty = true;
  private int item;

  // Wait until the buffer is free, then fill it.
  public synchronized void store(int item) throws InterruptedException {
    while(!empty) {
      // Wait to be notified of the buffer being empty.
      wait();
    }
    this.item = item; empty = false;
    notifyAll();
  }

  public synchronized int retrieve() throws InterruptedException {
    while(empty) {
      // Wait to be notified of an item becoming available.
      wait();
    }
    // Retrieve the item before we notify waiting threads.
    int item = this.item; empty = true;
    notifyAll();
    return item;
  }
}
```

Java 1.4 Code

Why a loop around wait() ???

```
class BufferJava14 implements Buffer {
  public BufferJava14() {
    System.out.println("=== Using BufferJava 1.4 ===");
    System.out.println();
  }

  private boolean empty = true;
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  // Wait until the buffer is free, then fill it.
  public synchronized void store(int item) throws InterruptedException {
    while(!empty) {
      // Wait to be notified of the buffer being empty.
      wait();
    }
    this.item = item; empty = false;
    notifyAll();
  }

  public synchronized int retrieve() throws InterruptedException {
    while(empty) {
      // Wait to be notified of an item becoming available.
      wait();
    }
    // Retrieve the item before we notify waiting threads.
    int item = this.item; empty = true;
    notifyAll();
    return item;
  }
}
```

Note

- The wait-set only makes sense inside a critical region
  - You cannot call ‘wait()’ or ‘notify()’ if you are not in a synchronize method / critical region
  - Will throw exceptions at your if you try…

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Demo

```
csdev@m31: ~/proj/frsproject/producerconsumer-j14
File  Edit  Tabs  Help
csdev@m31:~/proj/frsproject/producerconsumer-j14$ java ProducerConsumerMain
=== Using BufferJava14 ===

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78
 79 80 81 82 83 84 85 86 87 88 ^Ccsdev@m31:~/proj/frsproject/producerconsumer-j14$
```

```java
public static void main(String[] args) throws InterruptedException {
  // The buffer shared between the producer and consumer.
  Buffer b =
    new BufferJava14();
    // new BufferBlockingQueue();
    // new BufferJava15Lock();

  Thread producer = new Thread(new Producer(b));
  Thread consumer = new Thread(new Consumer(b));

  consumer.start();
  producer.start();
```

Java 5 Onwards

Critique

- Java was the first mainstream language to have internal threading
- Brink Hansen should have said that all his whole lifelong research into concurrency was a complete waste ☹
- Morale: It had to be improved…
  – Package: java.util.concurrent
  – Much more fine-grained concurrency control
  – A lot of default implementations without bugs!

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Java 1.5 Code

```
class BufferJava15Lock implements Buffer {
  Lock lock = new ReentrantLock();
  Condition isFull = lock.newCondition();
  Condition isEmpty = lock.newCondition();
```

The Lock

Two *different* wait-sets associated…

```
public int retrieve() throws InterruptedException {
  int returnvalue = -1;
  lock.lock();
  try {
    while (empty) {
      isFull.await();
    }
    // Retrieve the item before we notify waiting threads.
    returnvalue = item;
    empty = true;
    // Signal to waiting threads that queue is empty
    isEmpty.signal();
  } finally {
    lock.unlock();
  }
  return returnvalue;
}
```

Now, producers are waiting in one wait-set; while consumers are in another! We are sure to signal the right one!

```
public synchronized void store(int item) throws InterruptedException {
  lock.lock();
  try {
    while (!empty) {
      isEmpty.await();
    }
    // Fill it.
    this.item = item;
    empty = false;
    // Signal to waiting threads that queue is full
    isFull.signal();
  } finally {
    lock.unlock();
  }
}
```

And Even More Easy!

- It is already implemented !

```
class BufferBlockingQueue implements Buffer {

  private BlockingQueue<Integer> buffer =
    new ArrayBlockingQueue<Integer>(1);
```

```
public int retrieve() throws InterruptedException {
  return buffer.take();
}

public void store(int item) throws InterruptedException {
  buffer.put(item);
}
```

A Producer-Consumer Example

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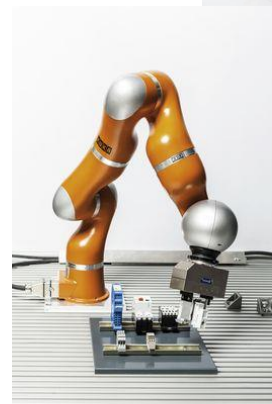
- Robotic Assembly line
  - Set of *manufacturing stations*
    - Programmable
  - Set of *transport robots*
- Challenge
  - *How to orchestrate an optimal processing of a set of products?*
- Solution
  - Model each station/transport as a consumer+producer
    - Consumers ‘trays’ with material, produce ‘trays’ with refined material
  - Buffers/queues orchestrate processing pipeline…



Moving On…

Vast Subject Area

- Lots of properties of concurrent programs
  - Liveliness
  - Fairness
  - Starvation
  - Deadlocks
  - Performance / blocked threads
  - Thread priority
- And library support
  - Java Collection classes are not thread safe ☹
  - But *Decorators* exists
    - List newList = Collections.synchronizedList(oldList);

Vast Subject Area

- And Parallelism – the other side of concurrency
  - Java Stream processing
    - Runs concurrently if you use parallelStream()
- Map-Reduce
  - Why not use 1.000 machines to compute ‘f’?
- *And on, and on, and on…*