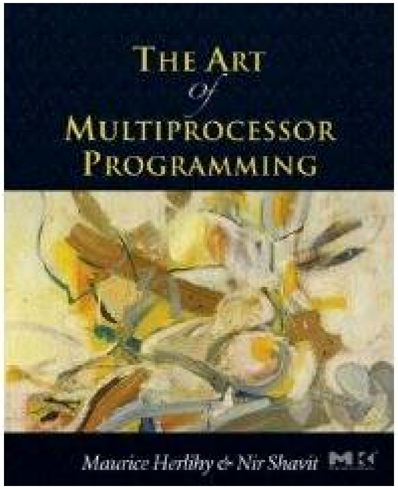
Programming Language Basics



Companion slides for

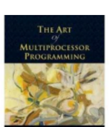
The Art of Multiprocessor Programming

by Maurice Herlihy & Nir Shavit

With some very minor changes by APS

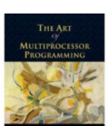
Languages for Multiprocessor Programming

- Java
- PThreads
  - C and C++
- C#
- MPI
- Etc…



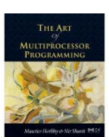
Threads

- Execution of a sequential program
- You can tell a thread
  - What to do
  - When to start
- You can
  - Wait for it to finish
- Other stuff:
  - Interrupt it, give it priority, etc.



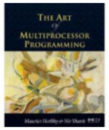
Threads in Java

- Class `java.lang.Thread`
- Each thread has a method
  - `Void run()`
- Executes when it starts
- Thread vanishes when it returns
- You must provide this method



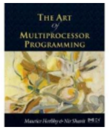
Creating a Thread

- Create a `Runnable` object
  - `Runnable` is an interface
  - Provides `run()` method
- Pass `Runnable` object to thread constructor



A Runnable Class

```java
public class Hello implements Runnable {
  String message;
  public Hello(String m) {
    message = m;
  }
  public void run() {
    System.out.println(message);
  }
}
```



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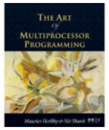
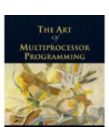
Runnable interface



Creating a Thread

```
String m = “Hello from ” + i;
Runnable h = new Hello(m);
Thread t = new Thread(h);
```



Creating a Thread

```
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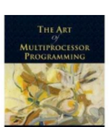
Create a Runnable object



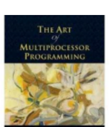
Creating a Thread

```
String m = “Hello from ” + i;
Runnable h = new Hello(m);
Thread t = new Thread(h);
```

Create the thread

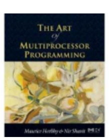
Syntactic Help

- Defining a single-use class like Hello can be a nuisance
- Java provides special syntax
- Anonymous inner classes
  - May be more trouble than it's worth
  - You should recognize it



Anonymous Inner Class

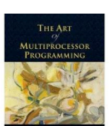
```
t = new Thread(
          new Runnable() {
            public void run() {
              System.out.println(m);
            }
          }
        );
```



Anonymous Inner Class

```
t = new Thread(
      new Runnable() {
        public void run() {
          System.out.println(m);
        }
      }
    );
```

Creates object of anonymous Runnable class



Anonymous Inner Class

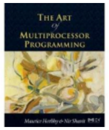
```
t = new Thread(
        new Runnable() {
          public void run() {
            System.out.println(m);
          }
        }
      );
```

Calls Thread constructor with anonymous object

Starting a Thread

```
t.start();
```

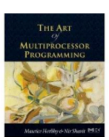
- **Starts the new thread**
- **Caller returns immediately**
- **Caller & thread run in parallel**



Joining a Thread

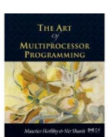
```
t.join();
```

- **Blocks the caller**
- **Waits for the thread to finish**
- **Returns when the thread is done**



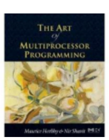
Monitors

- Each object has an implicit lock
- Managed by `synchronized` modifier
  - Methods
  - Code blocks
- OK for easy cases
- Not always for hard cases



Call Center Scenario

- Calls arrive faster than they can be answered
  - Play recorded message
    - "your call is very important to us …"
  - Put call in queue
    - Play insipid music …
  - Operators dequeue call when ready
  - Single enqueuer, multiple dequeuers



Bad Queue Implementation

```
class Queue<T> {
  int head = 0, tail = 0;
  T[] items = new T[QSIZE];
  public enq(T x) {
    items[(tail++) % QSIZE] = x;
  }
  public T deq() {
    return items[(head++) % QSIZE]
  }}
```

In practice, can’t create array of generic type, so use ArrayList<T> instead

Bad Queue Implementation

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class Queue<T> {
  int head = 0, tail = 0;
  T[] items = new T[QSIZE];
  public enq(T x) {
    items[(tail++) % QSIZE] = x;
  }
  public T deq() {
    return items[(head++) % QSIZE]
  }}
```
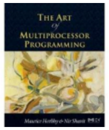

Works for generic type T



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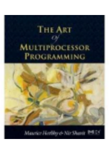
  }
  public T deq() {
    return items[(head++) % QSIZE]
  }}
```

Array of T items



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  public enq(T x) {
    items[(tail++) % QSIZE] = x;
  }
  public T deq() {
    return items[(head++) % QSIZE]
  }}
```
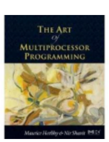

next slot to dequeue, 1st empty slot

#items in queue = tail - head



Bad Queue Implementation

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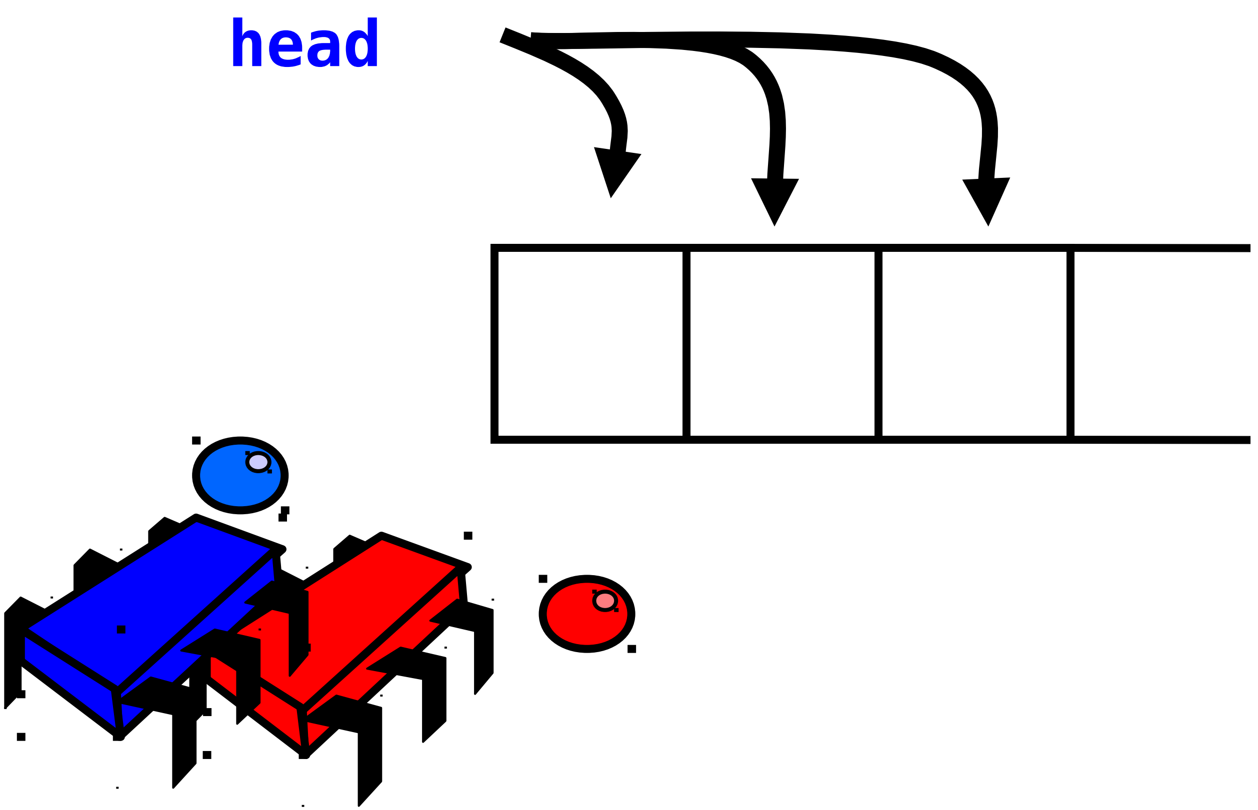
  T[] items = new T[QSIZE];
  public void enq(T x) {
    items[(tail++) % QSIZE] = x;
  }
  public T deq() {
    return items[(head++) % QSIZE]
  }}
```

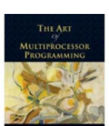
Put in empty slot, advance head

Of course, this doesn’t work

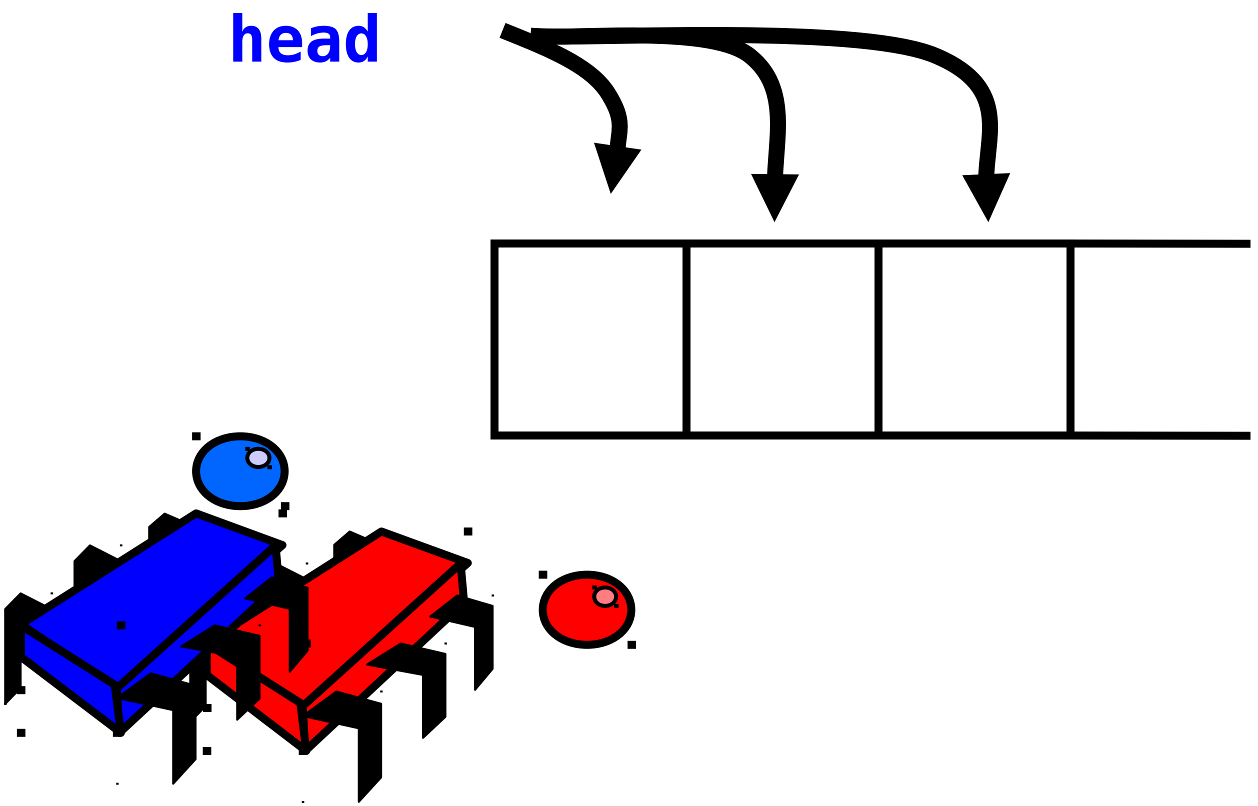


Mutual Exclusion

- **Only one thread modifying queue fields at a time**
- **Use `synchronized` methods**
  - **Locks object on call**
  - **Releases lock on return**



Mutual Exclusion



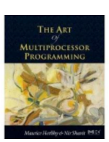
Synchronized Method

```
class Queue<T> {
  …
  public synchronized void enq(T x) {
    items[(tail++) % QSIZE];
  }
  ...
}
```

Synchronized Method

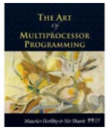
```
class Queue<T> {
  …
  public synchronized enq(T x) {
    items[(tail++) % QSIZE];
  }
  ...
}
```

Lock acquired on entry, released on exit



Syntactic Sugar

```
class Queue<T> {
  …
  public void enq(T x) {
    synchronized (this) {
      items[(tail++) % QSIZE];
    }
  }
  ...
}
```



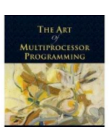
Syntactic Sugar

```
class Queue<T> {
  …
  public void enq(T x) {
    synchronized (this) {
      items[(tail++) % QSIZE];
    }
  }
  ...
}
```

Same meaning, more verbose

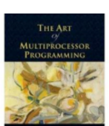
Vocabulary

- A `synchronized` method locks the object
- No other thread can call another `synchronized` method for that same object
- Code in middle is critical section



Re-entrant Locks

- What happens if you lock the same object twice?
  - In Java, no deadlock
  - Keeps track of number of times locked and unlocked
  - Unlock occurs when they balance out



Still Doesn't Work

```
class Queue<T> {
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  public synchronized void enq(T x) {
    items[(tail++) % QSIZE] = x;
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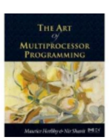
}
```



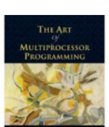
Still Doesn't Work

```
class Queue<T> {
  …
  public synchronized void enq(T x) {
    items[(tail++) % QSIZE] = x;
  }
  ...
}
```

What if the array is full?

Waiting

- What if
  - Enqueuer finds a full array?
  - Dequeuer finds an empty array?
- Throw an exception?
  - What can caller do?
  - Repeated retries wasteful
- **Wait** for something to happen



Waiting Synchronized Method

```
class Queue<T> {

  …
  public synchronized void enq(T x) {
    while (tail - head == QSIZE) {};
    items[(tail++) % QSIZE] = x;
  }
  ...
}
```

Waiting Synchronized Method

```
class Queue<T> {
  …
  public synchronized enq(T x) {
    while (tail - head == QSIZE) {};
    items[(tail++) % QSIZE] = x;
  }
  ...
}
```

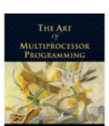
Spin while the array is full

Deadlock

- Enqueuer is
  - Waiting for a dequeuer
  - While holding the lock
- Dequeuer
  - Waiting for enqueuer to release lock
- Nothing will ever happen

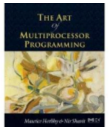
Waiting Thread

- Release lock while waiting
- When “something happens”
  - Re-acquire lock
  - Either
    - Re-release lock & resume waiting
    - Finish up and return



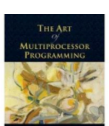
Styles of Waiting

- **Spinning**
  - **Repeatedly retest condition**
- **Blocking**
  - **Ask OS to run someone else**



Styles of Waiting

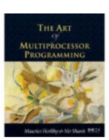
- Spinning
  - Good for very short intervals
  - Expensive to call OS
  - Works only on multiprocessors!
- Blocking
  - Good for longer intervals
  - Processor can do work
- Clever libraries sometimes mix



The wait() Method

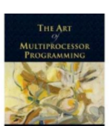
```
q.wait();
```

- Releases lock on q
- Sleeps (gives up processor)
- Awakens (resumes running)
- Reacquires lock & returns
- (note: wait() throws InterruptedException)



The wait() Method

```
class Queue<T> {
  …
  public synchronized void enq(T x) {
    while (tail - head == QSIZE) {
      wait();
    };
    items[(tail++) % QSIZE] = x;
  }
  ...
}
```



Waiting Synchronized Method

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  ...
}
```

Keep retesting condition

Waiting Synchronized Method

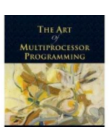
```
class Queue<T> {

  …
  public synchronized enq(T x) {
    while (tail - head == QSIZE) {
      wait();
    };
    items[(head++) % QSIZE] = x;
  }
  ...
}
```

Keep retesting condition

Release lock & sleep

Wake up and Smell the Coffee

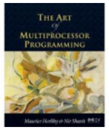
- When does a waiting thread awaken?
  - Must be **notified** by another thread
  - when something has happened
- Failure to notify in a timely way is called a “**lost wakeup**”



The wait() Method

```
q.notify();
```

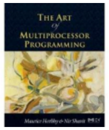
- **Awakens one waiting thread**
- **Which will reacquire lock & returns**



The wait() Method

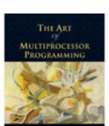
```
q.notifyAll();
```

- Awakens **all** waiting threads
- Which will reacquire lock & return



The wait() Method with Problem

```
public synchronized enq(T x) {
  while (tail - head == QSIZE) {
    wait();
  };
  items[(tail++) % QSIZE] = x;
  if (tail - head == QSIZE - 1) {
    notify();
  }
}
```



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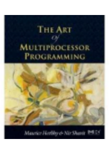
  if (tail - head == QSIZE - 1) {
    notify();
  }
}
```

Wait for empty slot

The wait() Method with Problem

```
public synchronized enq(T x) {
  while (tail - head == QSIZE) {
    wait();
  };
  items[(tail++) % QSIZE] = x;
  if (tail - head == QSIZE - 1) {
    notify();
  }
}
```

Stuff item into array



The wait() Method with Problem

```
public synchronized enq(T x) {
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    wait();
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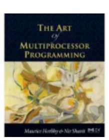
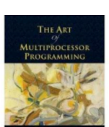
  items[(tail++) % QSIZE] = x;
  if (tail - head == QSIZE - 1) {
    notify();
  }
}
```

If the queue was empty, wake up a dequeuer

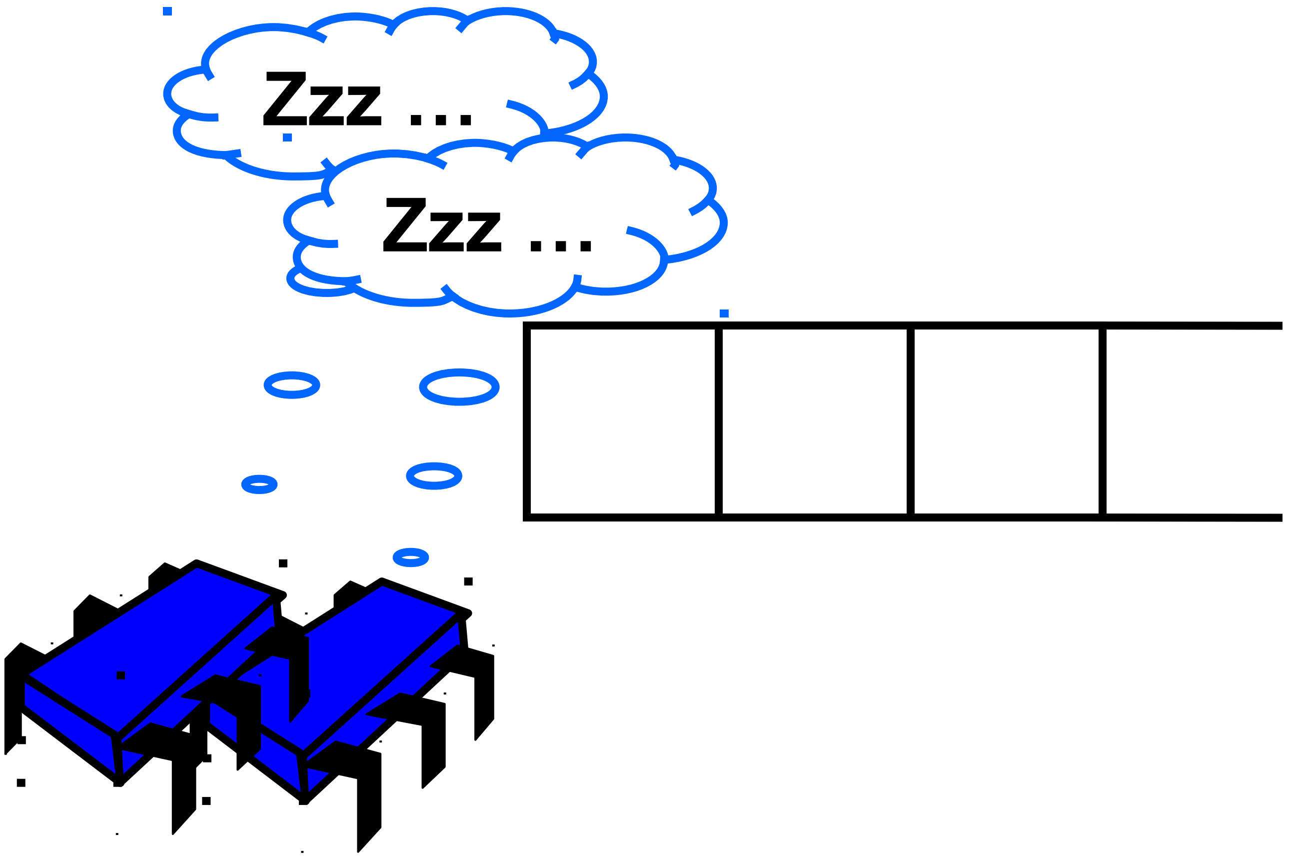


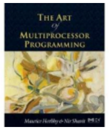
Lost Wakeup

- This code has a lost wakeup bug
- Possible to have
  - Waiting dequeuer
  - Non-empty queue
- Because not enough threads awakened

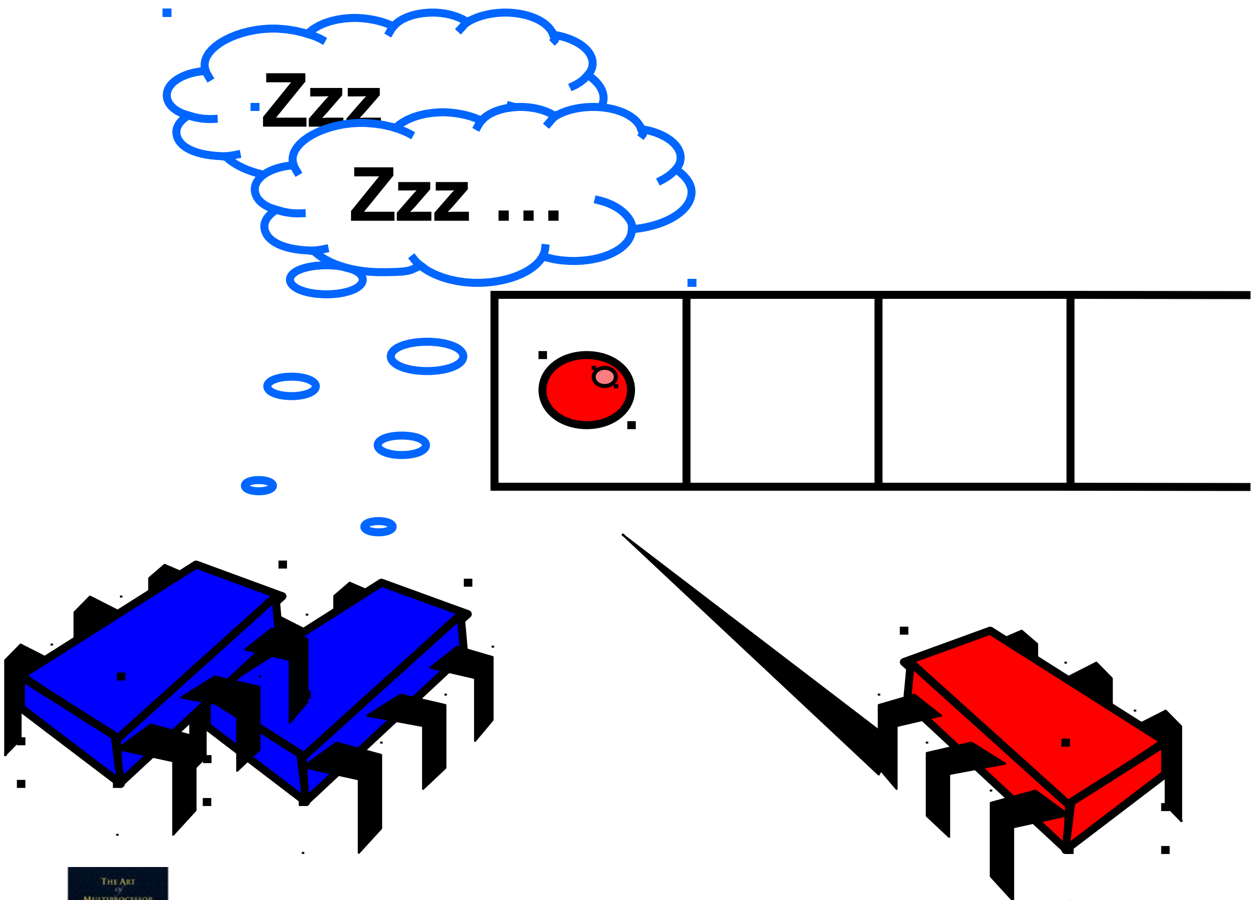


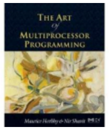
Empty queue, waiting dequeuers



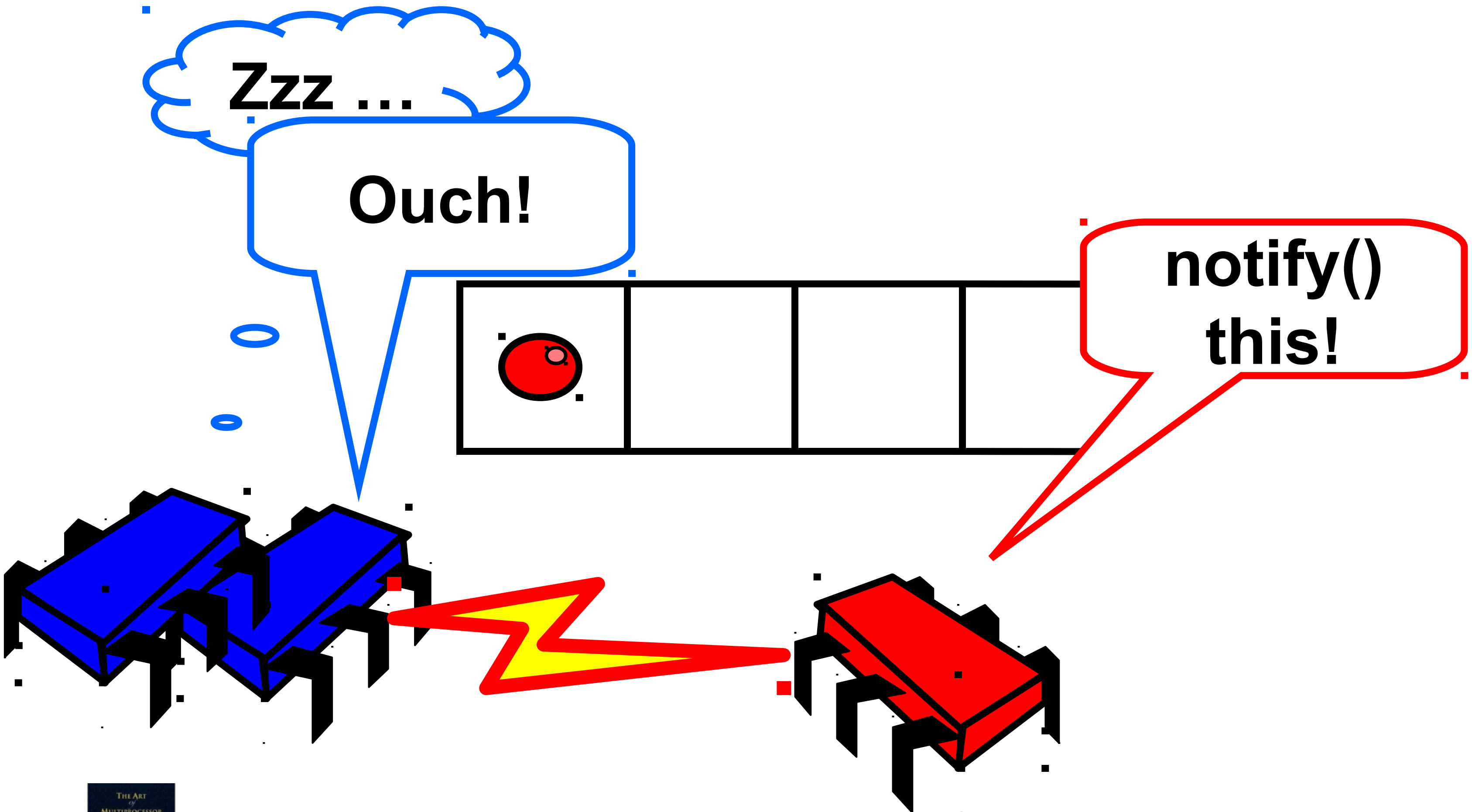


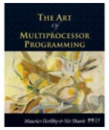
Enqueuer puts item in queue



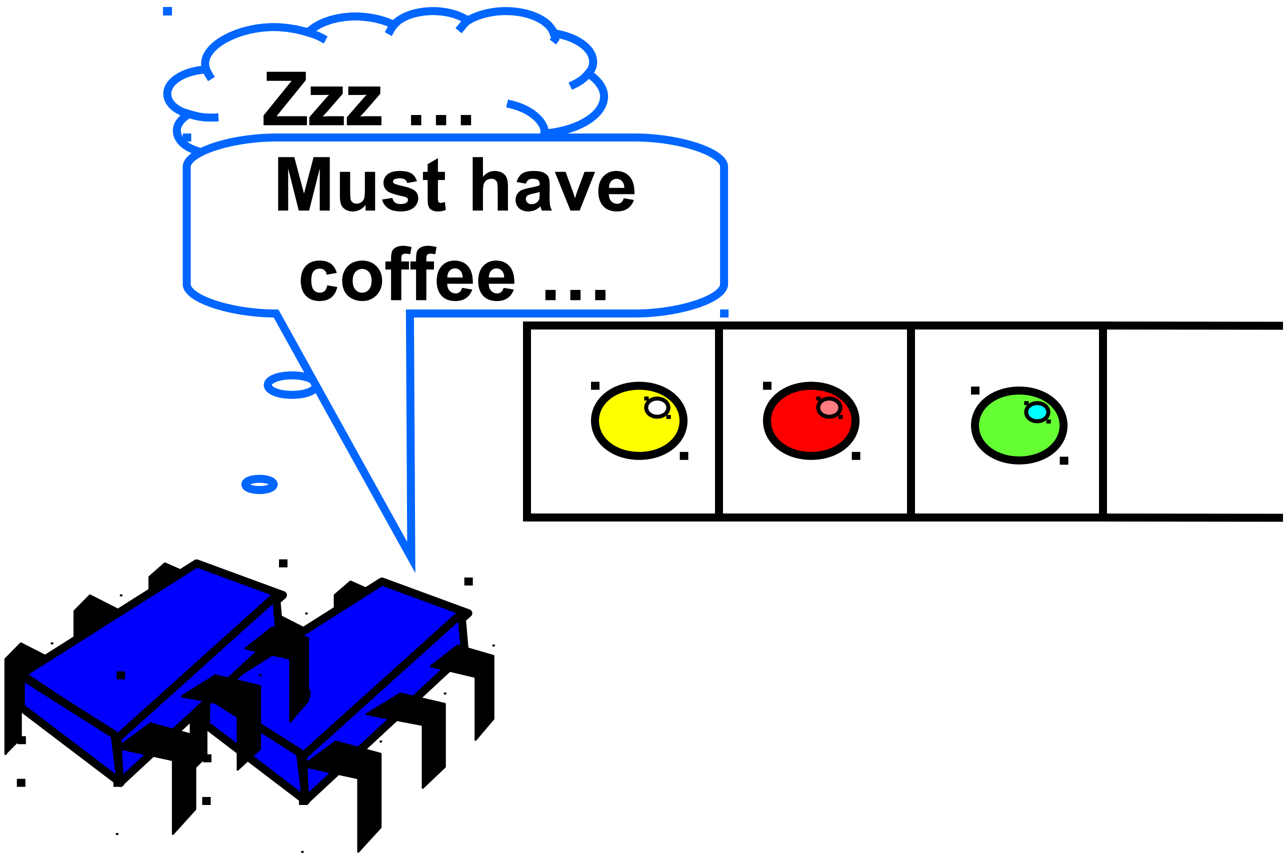


Since queue was empty, wakes dequeuer

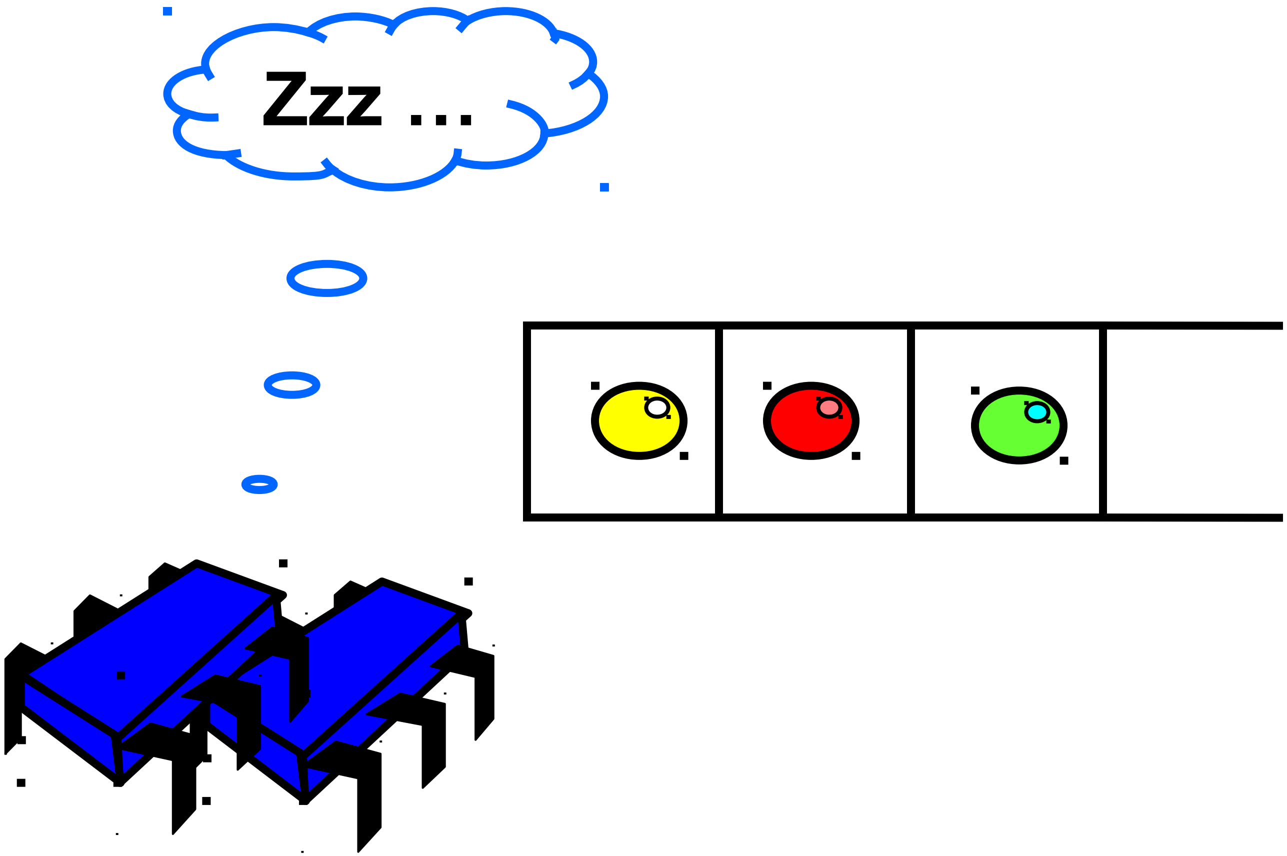




1st Dequeuer slow, overtaken by enqueuers



1st Dequeuer finishes

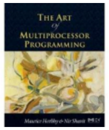


Solutions

- Don't write buggy code d'oh!
- Always call `notifyAll()`
- Can also use timed waits
  - Wake up after specified time

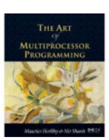
The wait() Method Solution

```
public synchronized enq(T x) {
  while (tail - head == QSIZE) {
    wait();
  };
  items[(tail++) % QSIZE] = x;
  if (tail - head == QSIZE - 1) {
    notifyAll();
  }
}
```



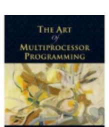
Thread-Local Data

- In many of our examples we assume
  - Threads have unique ids
  - In range 0, … , n-1
- Where do they come from?
  - Passed in to Runner Constructor?
  - Many threads from same Runner?
  - Long-lived data
  - Unique to a thread



Thread-Local Data in Java

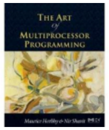
- ThreadLocal<T> class
- No built-in language support
- Library classes
  - Syntax is awkward
  - Very useful anyway
- Note: for instance variables
  - Local variables in methods are on the thread's stack, so not shared



ThreadLocal methods

```
ThreadLocal<T> local;
T x = …;
local.set(x);
```

- **Changes calling thread's version of object**
- **Other threads' versions unaffected**



ThreadLocal methods

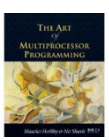
```
ThreadLocal<T> local;
T x = local.get();
```

- **Returns calling thread's version of object**

Initializing ThreadLocals

```
T x = local.initialValue();
```

- **Called by `get()` method the first time the thread-local variable is accessed.**



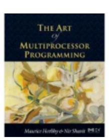
Example

```
int me = ThreadID.get()
```

- **Return unique thread id**
- **Take a number first time called**

Thread-Local IDs

```
public class ThreadID {
 private static volatile int nextID = 0;
 private static LocalID threadID =
    new LocalID();
  public static int get() {
    return threadID.get();
  }
  … // define LocalID here
}
```



Thread-Local IDs

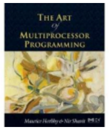
```
public class ThreadID {
  private static volatile int nextID = 0;
  private static LocalID threadID =
      new LocalID();
   public static int get() {
      return threadID.get();
   }
   … // define LocalID here
}
```

Next ID to assign

Thread-Local IDs

```
public class ThreadID {
 private static volatile int nextID = 0;
 private static LocalID threadID =
    new LocalID();
  public static int get() {
    return threadID.get();
  }
  … // define LocalID here
}
```

Declare & initialize thead-local ID



Thread-Local IDs

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public class ThreadID {
 private static volatile int nextID = 0;
 private static LocalID threadID =
    new LocalID();
  public static int get() {
    return threadID.get();
  }
  … // define LocalID here
}
```
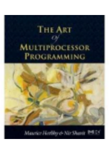

Return value of thread-local ID

The Inner Class

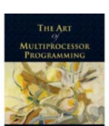
```
private static class LocalID
    extends ThreadLocal<Integer> {
      protected synchronized Integer
        initialValue() {
          return nextID++;
        }
}
```



The Inner Class

```
private static class LocalID
    extends ThreadLocal<Integer> {
      protected synchronized Integer
        initialValue() {
          return nextID++;
        }
}
```

Subclass of ThreadLocal<Integer>



The Inner Class

```
private static class LocalID
    extends ThreadLocal<Integer> {
      protected synchronized Integer
        initialValue() {
          return nextID++;
        }
}
```

Overrides initialValue()

Summary

- Threads
  - And how to control them
- Synchronized methods
  - Wait, notify, and NotifyAll
- Thread-Local objects