Edsger's perspective

"During system conception it transpired that we used the semaphores in two completely different ways. The difference is so marked that, looking back, one wonders whether it was really fair to present the two ways as uses of the very same primitives. On the one hand, we have the semaphores used for mutual exclusion, on the other hand, the private semaphores."

The structure of the 'THE'-Multiprogramming System"
Communications of the ACM v. 11 n. 5 May 1968.

Semaphores considered harmful

- Semaphores are "low-level" primitives. Small errors
  - can introduce incorrect executions or grind the program to a halt
  - very difficult to debug
- Semaphores conflate two distinct uses
  - mutex
  - condition synchronization (e.g., bounded buffer)

Enter Monitors

- Collect shared data into an object/module
- Define methods for accessing shared data
- Separate the concerns of mutual exclusion and condition synchronization
- They are comprised of
  - one lock, and
  - zero or more condition variables for managing concurrent access to shared data

How did Monitors come about?

- First introduced as an OO programming language construct
  - synchronization object + methods
  - calling a method defined in the monitor automatically acquires the lock
    - Mesa, Java (synchronized methods)
- A programming convention
  - can be defined in any language

Condition Variables

- An abstraction for conditional synchronization associated with a monitor
- Enable threads to wait inside a critical section by releasing the monitor lock
- A misnomer
  - can neither be read nor set to a value
  - think of them as a label associated with a condition on a resource and a queue
  - thread can wait in the queue (inside the CS) until they are notified that condition holds

How do I wait for thee? Let me count the ways...

- At the entry of the monitor
  - threads can queue on the mutex that protects the monitor, waiting for the thread that is currently in the monitor to exit (or to release the lock by starting to wait on a condition variable)
- On a condition variable
  - threads can queue waiting on the associated condition

Condition Variables: Operations

- Three operations on condition variable x
  - x.wait(lock)
    - Atomically: Release lock and go to sleep
    - sleep by waiting on the queue associated with x
  - x.notify (historically called x.signal())
    - wake up a waiter if any; otherwise no-op
    - wake up by moving waiter to the ready queue
  - x.notifyall (historically called x.broadcast())
- Only called while holding a lock

Resource Variables

- Condition variables (unlike semaphores) are stateless
- Each condition variable should be associated with a resource variable (RV) tracking the state of that resource
  - It is your job to maintain the RV!
- Check its RV before calling wait() on a condition variable to ensure the resource is truly unavailable
- Once the resource is available, claim it (subtract the amount you are using!)
- Before notifying you are releasing a resource, indicate it has become available by increasing the corresponding RV

Notify() Semantics

- Which thread executed once notify() is called on CV?
  - if no thread is waiting on CV, notifier continues
  - if one or more thread waiting on CV:
    - at least two ready threads: notifier and thread(s) that are moved from the queue of the CV to the ready queue
    - only one can run...
    - ...but which one?

Notify() semantics: Mesa vs. Hoare

- Mesa (or Brinch Hansen) semantics:
  - signaled thread is moved to ready list, but not guaranteed to run right away
- Hoare semantics:
  - signaling thread is suspended and, atomically, ownership of the lock is passed to one of the waiting threads, whose execution is immediately resumed.
  - notifying thread is resumed if former waiter exits crucial section, or if it waits again

What are the implications?

Mesa/Brinch Hansen

- signal() and broadcast() are hints
  - adding them affects performance, never safety
- Shared state must be checked in a loop (could have changed! (tricky tricky...))
  - robust to spurious wakeups
- Simple implementation
- Used in most systems
- Sponsored by a Turing Award
  - Butler Lampson

Hoare

- Signaling is atomic with the resumption of waiting thread
  - shared state cannot change before waiting thread is resumed
- Shared state can be checked using an if statement
- Makes it easier to prove liveness
- Tricky to implement
- Does not support broadcast/notifyAll
- Used in most books (but not yours!)
- Sponsored by a Turing Award
  - Tony Hoare

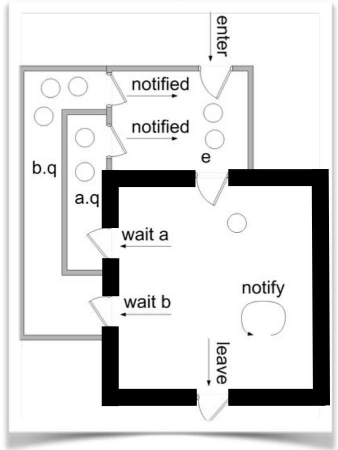
notify() vs notifyall() (signal() vs. broadcast())

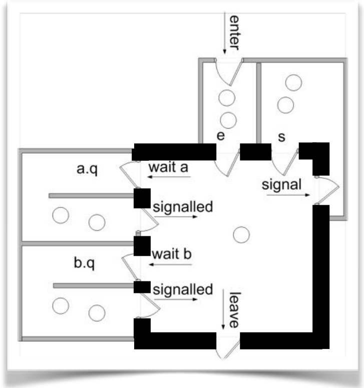
- It is always safe to use notifyall() instead of notify()
  - only performance is affected
- notify() is preferable when
  - at most one waiting thread can make progress (e.g., with mutual exclusion)
  - any thread waiting on the condition variable can make progress
- notifyall() is preferable when
  - multiple waiting thread may be able to make progress
  - some waiting threads can make progress, others can't
    - e.g., if a single CV is used for multiple predicates

Condition Variables vs Semaphores

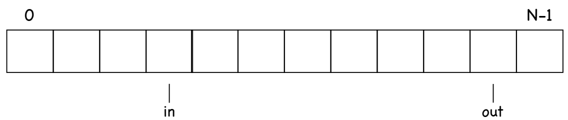
- wait() vs P()
  - P() blocks threads only if value = 0
  - wait() always block and gives up monitor lock
- notify() vs V()
  - V is stateful - if no thread is waiting, V() ensure future thread does not wait on P()
  - if no waiting thread, notify() is a no op
  - condition variables are stateless
- Code that uses monitors is easier to read
  - Conditions for which threads are waiting are explicit

Which is Mesa? Which is Hoare?





Producer-Consumer with Bounded Buffer



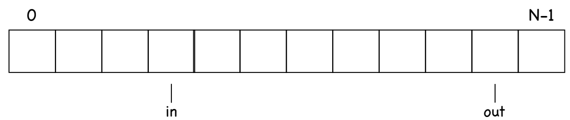

```
// add item to buffer
void produce(int item) {
  empty.P();
  mutex_in.P();
  buf[in%N] := item;
  in := in+1;
  mutex_in.V();
  full.V();
}
```

```
Shared:
int buf[N];
int in := 0, out := 0;
Semaphore mutex_in(1),
              mutex_out(1);
Semaphore empty(N), full(0);
```

Semaphores

```
// remove item from buffer
int consume() {
  full.P();
  mutex_out.P();
  int item := buf[out%N];
  out := out+1;
  mutex_out.V();
  empty.V();
  return(item);
}
```


Producer-Consumer with Bounded Buffer




```
// add item to buffer
void produce(int item) {
  lock.Acquire()
  while (n == N)
    wait(notFull);
  buf[in%N] := item;
  in := in+1;
  n := n+1;
  notify(notEmpty);
  lock.Release()
}
```

```
Monitor Producer Consumer {
char buf[N];
Lock lock;
int n := 0, in := 0, out := 0;
Condition notEmpty, notFull;
```

Monitor

```
// remove item from buffer
int consume() {
  lock.Acquire();
  while (n == 0)
    wait(nonEmpty);
  int item := buf[out%N];
  out := out+1;
  n := n-1
  notify(notFull);
  lock.Release();
  return(item);
}
```

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;

  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
kid_main() {
   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();
}
```

Ready
inside Monitor

Ready

```
cook_main() {
   wake();
   shower();
   drive_to_work();
   while(not_5pm)
     BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();
}
```

Running

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;

  int numburgers = 0
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  void kid_eat() {
     mlock.acquire()
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}
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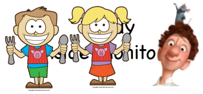

Ready

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cook_main() {
   wake();
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Running

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     BK.makeburger();
   drive_to_home();
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```

Running

girl swapped in

Kid and Cook Threads

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   drive_to_home();
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}
```

Running

girl executes

Kid and Cook Threads

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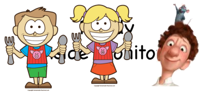

Ready

Running

girl swapped out

Kid and Cook Threads

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kid_main() {

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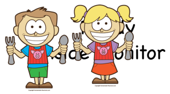

Ready

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cook swapped in

Kid and Cook Threads

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Ready

Running

cook executes

Kid and Cook Threads

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  sleep();

}
```

Ready

Running

cook swapped out

Kid and Cook Threads

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   shower();
   drive_to_work();
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     BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Running

boy swapped in

Kid and Cook Threads

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}
```

Ready

```
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   wake();
   shower();
   drive_to_work();
   while(not_5pm)
     BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Running

boy executes

Kid and Cook Threads

```
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  Lock mlock;

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}
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}
```

Running

boy tries to enter monitor

Kid and Cook Threads

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   BK.kid_eat();

}
```

Ready

```
cook_main() {

   wake();
   shower();
   drive_to_work();
   while(not_5pm)
     BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Running

boy gets monitor lock

Kid and Cook Threads

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Monitor BurgerKing {
  Lock mlock;

  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
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     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
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cook_main() {

  wake();
  shower();
  drive_to_work();
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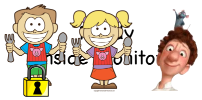
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```



Ready

Running

boy swapped out

Kid and Cook Threads

```
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  Lock mlock;

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   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready

Running

girl swapped in

Kid and Cook Threads

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  Lock mlock;

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cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready

Running

girl tries to enter monitor

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
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     mlock.release()
  }
}
```

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kid_main() {

   dig_in_mud();
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}
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```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready

Running

monitor has lock Queue

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
    mlock.acquire()
    while (numburgers==0)
       burgerReady.wait()
    numburgers -= 1
    mlock.release()
  }

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    mlock.acquire()
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    mlock.release()
  }
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kid_main() {

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   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```


Ready
Inside Monitor


Ready

Running

girl placed on lock Q

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
    mlock.acquire()
    while (numburgers==0)
       burgerReady.wait()
    numburgers -= 1
    mlock.release()
  }

  void makeburger() {
    mlock.acquire()
    ++numburger;
    burgerReady.signal();
    mlock.release()
  }
}
```

```
kid_main() {

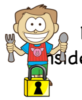
   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```


Ready
Inside Monitor


Ready

Running

cook swapped in

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
    mlock.acquire()
    while (numburgers==0)
       burgerReady.wait()
    numburgers -= 1
    mlock.release()
  }

  void makeburger() {
    mlock.acquire()
    ++numburger;
    burgerReady.signal();
    mlock.release()
  }
}
```

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```


Ready
Inside Monitor


Ready

Running

cook executes

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
    mlock.acquire()
    while (numburgers==0)
       burgerReady.wait()
    numburgers -= 1
    mlock.release()
  }

  void makeburger() {
    mlock.acquire()
    ++numburger;
    burgerReady.signal();
    mlock.release()
  }
}
```

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```


Ready
Inside Monitor


Ready

Running

cook tries to enter monitor

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

cook placed on lock Q

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

boy swapped in w/lock

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

no burgers!

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0
  condition burgerReady;
   Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

boy releases monitor lock & waits for hungrykid signal

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0;
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
     BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Re dy
inside nitor

Ready

Running

cook made Ready with release of monitor lock

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0;
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
     BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready
inside Monitor

Ready

Running

cook swapped in

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0;
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
     BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready
inside Monitor

Ready

Running

cook acquires monitor lock

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0; 1
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
     BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready
inside Monitor

Ready

Running

cook makes a burger

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0; 1
  condition burgerReady;
   Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready
inside Monitor

Ready

Running

cook signals a hungry kid

145

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0; 1
  condition burgerReady;
   Q:

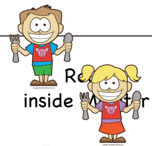
  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```



Ready

Running

cook releases monitor lock, girl made Ready

146

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0; 1
  condition burgerReady;
   Q:

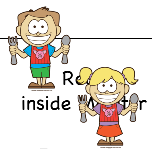
  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```



Ready

Running

cook leaves monitor

147

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0; 1
  condition burgerReady;
   Q:

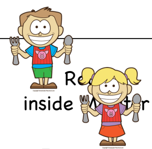
  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```



Ready

Running

cook executes

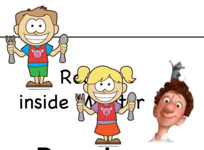
148

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```



Ready

```
Monitor BurgerKing {
  Lock mlock;
    Q:
  int numburgers = 0; 1
  condition burgerReady;
    Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

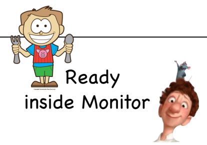
cook swapped out

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```



Ready

```
Monitor BurgerKing {
  Lock mlock;
    Q:
  int numburgers = 0; 1
  condition burgerReady;
    Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

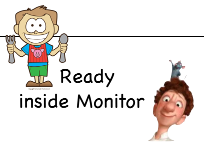
girl swapped in

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```



Ready

```
Monitor BurgerKing {
  Lock mlock;
    Q:
  int numburgers = 0; 1
  condition burgerReady;
    Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

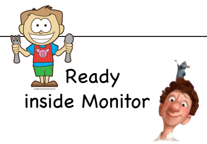
girl acquires monitor lock

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```



Ready

```
Monitor BurgerKing {
  Lock mlock;
    Q:
  int numburgers = 0; 1
  condition burgerReady;
    Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

girl executes

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0; 1
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

Mmmm... burgers....

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0; 0
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

girl eats burger

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0; 0
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

girl releases monitor lock

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

Ready
inside Monitor

Ready

```
Monitor BurgerKing {
  Lock mlock;
  Q:
  int numburgers = 0; 0
  condition burgerReady;
  Q:

  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Running

girl leaves monitor

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0;
  condition burgerReady;
   Q:
  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready
inside Monitor

Ready

Running

girl executes

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0;
  condition burgerReady;
   Q:
  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready

Running

girl swapped out

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0;
  condition burgerReady;
   Q:
  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready

Running

boy swapped in

Kid and Cook Threads

```
Monitor BurgerKing {
  Lock mlock;
   Q:
  int numburgers = 0;
  condition burgerReady;
   Q:
  void kid_eat() {
     mlock.acquire()
     while (numburgers==0)
        burgerReady.wait()
     numburgers -= 1
     mlock.release()
  }

  void makeburger() {
     mlock.acquire()
     ++numburger;
     burgerReady.signal();
     mlock.release()
  }
}
```

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
cook_main() {

  wake();
  shower();
  drive_to_work();
  while(not_5pm)
    BK.makeburger();
  drive_to_home();
  watch_got();
  sleep();

}
```

Ready

Running

boy acquires monitor lock

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
   Lock mlock;
    Q:
   int numburgers = 0;
   condition burgerReady;
    Q:

   void kid_eat() {
      mlock.acquire()
      while (numburgers==0)
         burgerReady.wait()
      numburgers -= 1
      mlock.release()
   }

   void makeburger() {
      mlock.acquire()
      ++numburger;
      burgerReady.signal();
      mlock.release()
   }
}
```

```
cook_main() {

   wake();
   shower();
   drive_to_work();
   while(not_5pm)
      BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Ready

Running

boy returns from wait

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
   Lock mlock;
    Q:
   int numburgers = 0;
   condition burgerReady;
    Q:

   void kid_eat() {
      mlock.acquire()
      while (numburgers==0)
         burgerReady.wait()
      numburgers -= 1
      mlock.release()
   }

   void makeburger() {
      mlock.acquire()
      ++numburger;
      burgerReady.signal();
      mlock.release()
   }
}
```

```
cook_main() {

   wake();
   shower();
   drive_to_work();
   while(not_5pm)
      BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Ready

Running

boy executes

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
   Lock mlock;
    Q:
   int numburgers = 0;
   condition burgerReady;
    Q:

   void kid_eat() {
      mlock.acquire()
      while (numburgers==0)
         burgerReady.wait()
      numburgers -= 1
      mlock.release()
   }

   void makeburger() {
      mlock.acquire()
      ++numburger;
      burgerReady.signal();
      mlock.release()
   }
}
```

```
cook_main() {

   wake();
   shower();
   drive_to_work();
   while(not_5pm)
      BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Ready

Running

no burgers!

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
   Lock mlock;
    Q:
   int numburgers = 0;
   condition burgerReady;
    Q:

   void kid_eat() {
      mlock.acquire()
      while (numburgers==0)
         burgerReady.wait()
      numburgers -= 1
      mlock.release()
   }

   void makeburger() {
      mlock.acquire()
      ++numburger;
      burgerReady.signal();
      mlock.release()
   }
}
```

```
cook_main() {

   wake();
   shower();
   drive_to_work();
   while(not_5pm)
      BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Ready

Running

boy releases monitor lock & waits for hungrykid signal

Kid and Cook Threads

```
kid_main() {

   dig_in_mud();
   BK.kid_eat();
   bathe();
   draw_on_walls();
   BK.kid_eat();
   facetime_Karthik();
   facetime_oma();
   BK.kid_eat();

}
```

```
Monitor BurgerKing {
   Lock mlock;
     Q:
   int numburgers = 0;
   condition burgerReady;
     Q:

   void kid_eat() {
      mlock.acquire()
      while (numburgers==0)
         burgerReady.wait()
      numburgers -= 1
      mlock.release()
   }

   void makeburger() {
      mlock.acquire()
      ++numburger;
      burgerReady.signal();
      mlock.release()
   }
}
```

```
cook_main() {

   wake();
   shower();
   drive_to_work();
   while(not_5pm)
      BK.makeburger();
   drive_to_home();
   watch_got();
   sleep();

}
```

Ready

Running

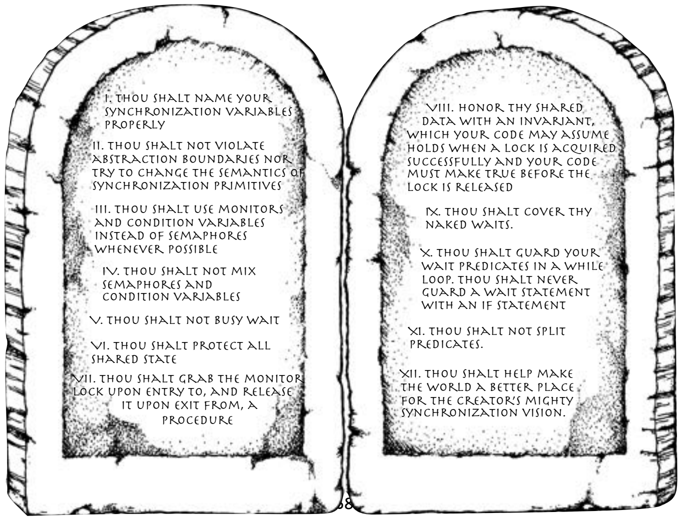
cook swapped in

and so forth…

Designing multithreaded programs

- Familiar steps
  - Decompose problem into objects; for each object:
    - define a clear interface
    - implement methods that manipulate state appropriately
- New steps
  - Add a lock, and code to acquire and release the lock
    - acquire a lock at the start of each public method
    - release the lock at the end of each public method
  - Identify synchronization points and add condition variables
  - add loops to check resource status and wait using condition variables
  - Add notify(), notifyall() calls

12 Commandments of Synchronization



Readers/Writers

- Safety
- What about fairness?
  - the last thread to live the critical section will give priority to writers
  - To implement this policy, one needs to keep track of waitingWriters, waitingReaders, activeWriters, and activeReaders

Readers/Writers

```
Monitor ReadersNWriters {

 int waitingWriters=0, waitingReaders=0, activeReaders=0, activeWriters=0;
 Condition canRead, canWrite;

void BeginWrite()
  with monitor.lock:
    ++waitingWriters
    while (activeWriters > 0 or activeReaders > 0)
      canWrite.wait();
    --waitingWriters
    activeWriters = 1;


}
```


Readers/Writers

```
Monitor ReadersNWriters {

 int waitingWriters=0, waitingReaders=0, activeReaders=0, activeWriters=0;
 Condition canRead, canWrite;

void BeginWrite()
  with monitor.lock:
    ++waitingWriters
    while (activeWriters > 0 or activeReaders > 0)
      canWrite.wait();
    --waitingWriters
    activeWriters = 1;

void EndWrite()
  with monitor.lock:
    activeWriters = 0
    if waitingWriters > 0
      canWrite.signal();
    else if waitingReaders > 0
      canRead.broadcast();
}
```


Readers/Writers

```
Monitor ReadersNWriters {

 int waitingWriters=0, waitingReaders=0, activeReaders=0, activeWriters=0;
 Condition canRead, canWrite;

void BeginWrite()
  with monitor.lock:
    ++waitingWriters
    while (activeWriters > 0 or activeReaders > 0)
      canWrite.wait();
    --waitingWriters
    activeWriters = 1;

void EndWrite()
  with monitor.lock:
    activeWriters = 0
    if waitingWriters > 0
      canWrite.signal();
    else if waitingReaders > 0
      canRead.broadcast();
}
```

```
void BeginRead()
  with monitor.lock:
    ++waitingReaders
    while (activeWriters > 0 or waitingWriters > 0)
      canRead.wait();
    --waitingReaders
    ++activeReaders
```

Readers/Writers

```
Monitor ReadersNWriters {

 int waitingWriters=0, waitingReaders=0, activeReaders=0, activeWriters=0;
 Condition canRead, canWrite;

void BeginWrite()
  with monitor.lock:
    ++waitingWriters
    while (activeWriters > 0 or activeReaders > 0)
      canWrite.wait();
    --waitingWriters
    activeWriters = 1;

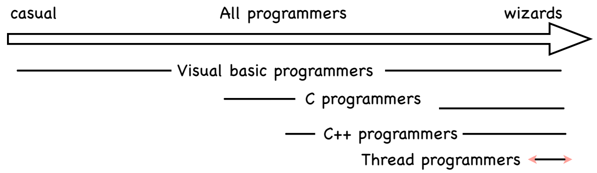
void EndWrite()
  with monitor.lock:
    activeWriters = 0
    if waitingWriters > 0
      canWrite.signal();
    else if waitingReaders > 0
      canRead.broadcast();
}

void BeginRead()
  with monitor.lock:
    ++waitingReaders
    while (activeWriters > 0 or waitingWriters > 0)
      canRead.wait();
    --waitingReaders
    ++activeReaders

void EndRead()
  with monitor.lock:
    --activeReaders;
    if (activeReaders == 0 and waitingWriters > 0)
      canWrite.signal();
```

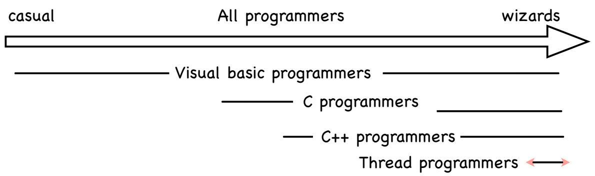

Contra Threads: Events

- John Ousterhout: “Why Threads Are a Bad Idea (for most purposes)”



Contra Threads: Events

- John Ousterhout: “Why Threads Are a Bad Idea (for most purposes)”



Event-driven Programming

- No concurrency: one execution stream
- Register interest in events (callbacks)
- Wait for events; invoke (short-lived) handlers
- Complicated only for unusual cases
- Easier to debug