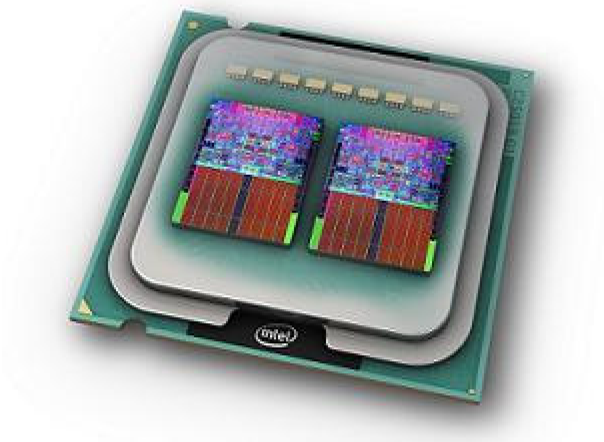
CMSC330

Multithreading

- Description
  - Multiple processing units (multiprocessor)
  - From single microprocessor to large compute clusters
  - Can perform multiple tasks in parallel simultaneously

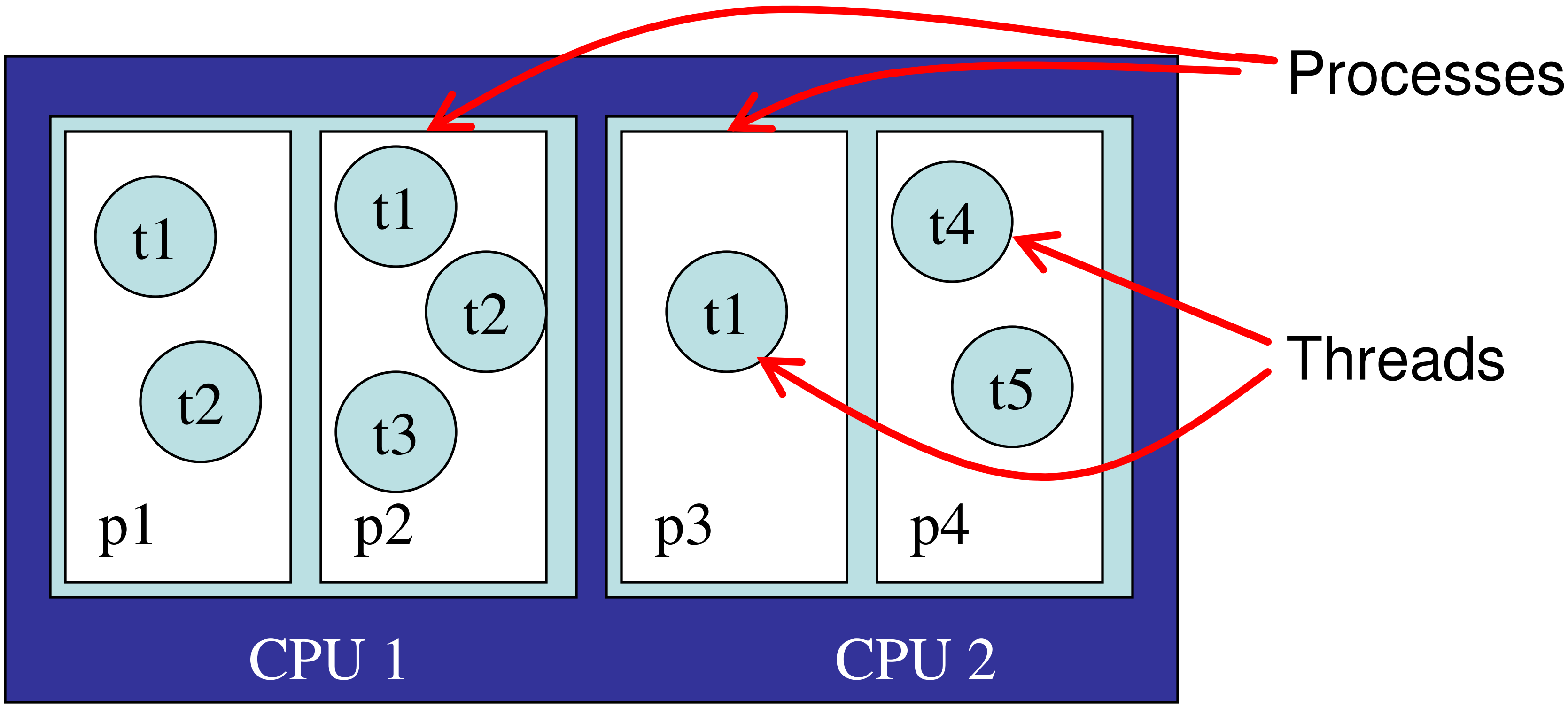


Intel Core 2 Quad 6600

32 processor Pentium Xeon

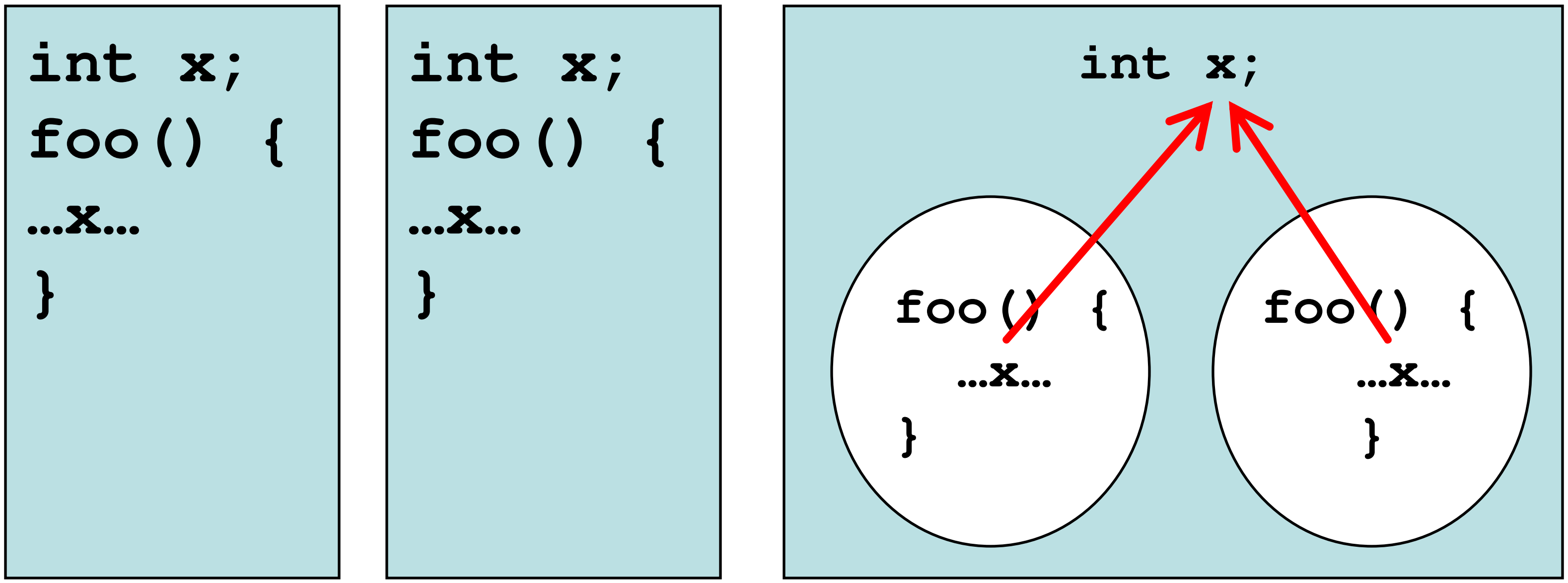
106K processor IBM BlueGene/L

Computation Abstractions



A computer

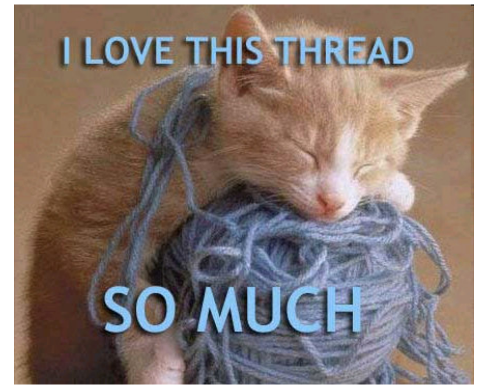
Processes vs. Threads



Processes do not share data

Threads share data within a process

So, What Is a Thread?



- Conceptually
  - Parallel computation occurring within a process
- Implementation view
  - A program counter and a stack
  - Heap and static area are shared among all threads
- All programs have at least one thread (main)
  - Child threads are forked, and then join with main thread

Programming Threads

- Thread creation is inexpensive
- Threads reside on same physical processor
- Threads share memory, resources
  - Except for local thread variables
- Shared-memory programming paradigm
  - Threads communicate via shared data
  - Synchronization used to avoid data races
- Limited scalability (10's of threads)

Programming Processes

- Process creation is expensive
  - Request to operating system
- Processes may reside on separate processors
- Processes do not share memory
- Message-passing programming paradigm
  - Messages using I/O streams, sockets, network, files
- Processes must cooperate to communicate
  - Actions performed to send and receive data
- Highly scalable (1000’s of processors)

Java Threads Review (from CMSC 132)

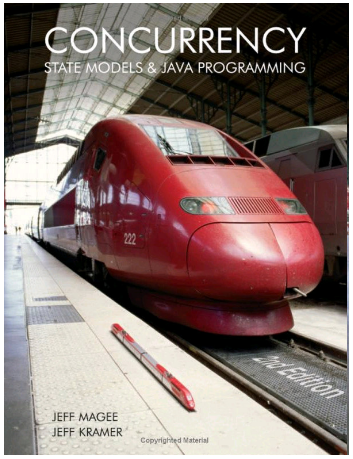
- `Thread` class & `Runnable` interface
  - Used to create / manipulate threads
- Run-time scheduler
  - Preemptive / non-premptive
  - Thread states (new, runnable, blocked, dead)
- Data race
  - Concurrent accesses to same shared object
    - Where at least one access is a write
  - Result may change depending on thread schedule
  - Very difficult to detect & correct

Java Threads Review (cont.)

- Synchronization
  - Locks ensure exclusive access
    - Lock associated w/ every Java object
  - Use synchronized keyword to acquire lock
    - Code blocks – `synchronized (o) { … }` `// lock for Object o`
    - Methods – `synchronized foo( ) { … }` `// lock for this`
  - Thread blocks when trying to acquire locked lock
    - Thread returns when lock is finally acquired
    - May deadlock if threads try to acquire each other's lock

Concurrency

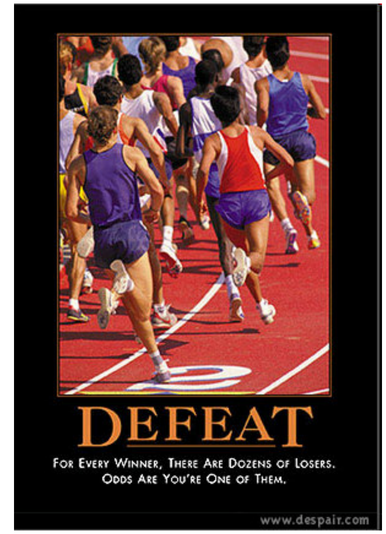
- A concurrent program
  - Program with multiple threads that may be active at the same time
- Might run on one CPU (multi-tasking)
  - The CPU alternates between running different threads
  - The scheduler takes care of the details
    - Switching between threads might happen *at any time*
- Might run in parallel on a multiprocessor machine
  - May have multiple threads per CPU



Concurrency and Shared Data

- Concurrency is easy if threads don't interact
  - Each thread does its own thing, ignoring other threads
  - Typically, however, threads need to communicate with each other
- In multithreaded programs, communication is achieved by sharing data
  - In Java, different threads may access the heap simultaneously
  - But the scheduler might interleave threads arbitrarily
  - Problems can occur if we're not careful

Data Race



- Definition
  - Concurrent accesses to same shared variable, where at least one access is a write
- Properties
  - Order of accesses may change result of program
  - May cause intermittent errors, very hard to debug

Data Race Example

```
public class Example extends Thread {
  private static int cnt = 0;  // shared state
  public void run() {
    int y = cnt;
    cnt = y + 1;
  }
  public static void main(String args[]) {
    Thread t1 = new Example();
    Thread t2 = new Example();
    t1.start();
    t2.start();
  }
}
```

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

Start: both threads ready to run. Each will increment the global cnt.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

y = 0

Shared state cnt = 0

T1 executes, grabbing the global counter value into its own y.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

y = 0

Shared state **cnt = 1**

T1 executes again, storing its value of y + 1 into the counter.

Data Race Example

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

y = 0

y = 1

Shared state cnt = 1

T1 finishes. T2 executes, grabbing the global counter value into its own y.

Data Race Example

```
static int cnt = 0;
t1.run() {
   int y = cnt;
   cnt = y + 1;
}
t2.run() {
   int y = cnt;
   cnt = y + 1;
}
```

y = 0

y = 1

Shared state **cnt = 2**

T2 executes, storing its incremented cnt value into the global counter.

Data Race Example – 2nd Try

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

Start: both threads ready to run. Each will increment the global count.

Data Race Example – 2^{nd} Try

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

Shared state cnt = 0

y = 0

T1 executes, grabbing the global counter value into its own y.

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

y = 0

y = 0

Shared state cnt = 0

T1 is preempted. T2 executes, grabbing the global counter value into its own y.

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;       y = 0
}
t2.run() {
  int y = cnt;
  cnt = y + 1;       y = 0
}
```

Shared state **cnt = 1**

T2 executes, storing the incremented cnt value.

```
static int cnt = 0;
t1.run() {
  int y = cnt;
  cnt = y + 1;
}
t2.run() {
  int y = cnt;
  cnt = y + 1;
}
```

y = 0

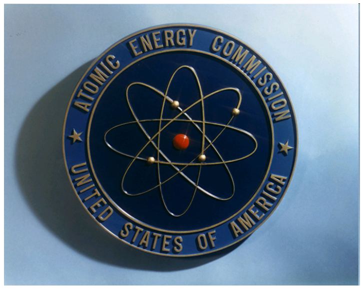
y = 0

Shared state **cnt = 1**

T2 completes. T1 executes again, storing the incremented original counter value (1) rather than what the incremented updated value would have been (2)!

What Happened?

- Different schedules led to different outcomes
  - This is a data race or race condition
- A thread was preempted in the middle of an operation
  - Reading and writing cnt was supposed to be atomic
    - Execute with no interference from other threads
  - But the schedule (interleaving of threads) which was chosen allowed atomicity to be violated



  - These bugs can be extremely hard to reproduce, and so hard to debug
    - Depends on what scheduler chose to do, which is hard to predict

Question

- If instead of

```
int y = cnt;
cnt = y+1;
```

- We had written
  - `cnt++;`
- Would the result be any different?
- Answer: NO!
  - Don't depend on your intuition about atomicity

What's Wrong with the Following?


```
static int cnt = 0;
static int x = 0;
```

```
Thread 1
  while (x != 0);
  x = 1;
  cnt++;
  x = 0;
```

```
Thread 2
  while (x != 0);
  x = 1;
  cnt++;
  x = 0;
```

- Threads may be interrupted after the `while` but before the assignment `x = 1`
  - Both may think they "hold" the lock!
- This approach is called busy waiting
  - Consumes lots of processor cycles

Synchronization

- Definition
  - Coordination of events with respect to time
- Properties
  - Can eliminate data races in multithreaded programs
  - Overhead → excessive use reduces performance
- Mechanisms
  - Different in each programming language
  - Look at examples in Java

Synchronized

- This pattern is really common
  - Acquire lock, do something, release lock under any circumstances after we're done
    - Even if exception was raised etc.

- Java has a language construct for this
  - **`synchronized (obj) { body }`**
    - Every Java object has an implicit associated lock
  - Obtains the lock associated with **`obj`**
  - Executes ***`body`***
  - Release lock when scope is exited
    - Even in cases of exception or method return

Example

```
static Object o = new Object();

void f() throws Exception {
  synchronized (o) {
    FileInputStream f =
       new FileInputStream("file.txt");
    // Do something with f
    f.close();
  }
}
```

– Lock associated with o acquired before body executed
  - Released even if exception thrown

Example: Synchronizing on this

```
class C {
   int cnt;

   void inc() {
     synchronized (this) {
       cnt++;
     }
   }
}
```

```
C c = new C();
```

```
Thread 1
c.inc();
```

```
Thread 2
c.inc();
```

- Does this program have a data race?
  - No, both threads acquire locks on the same object before they access shared data

Example: Synchronizing on this (cont.)

```
class C {
   int cnt;

   void inc() {
     synchronized (this) {
       cnt++;
     }
   }

   void dec() {
     synchronized (this) {
       cnt--;
     }
   }
}
```

```
C c = new C();
```

Thread 1

```
c.inc();
```

Thread 2

```
c.dec();
```

- Data race?
  - No, threads acquire locks on the same object before they access shared data

Synchronized Methods

- Marking method as synchronized same as synchronizing on this in body of the method
  - The following two programs are the same

```
class C {
   int cnt;

   void inc() {
     synchronized (this) {
       cnt++;
     }
   }
}
```

```
class C {
  int cnt;

  synchronized void inc(){
    cnt++;
  }
}
```

New Java Thread Topics

- Lock interface
  - lock( )
  - unlock( )
- ReentrantLock class
- Condition interface
  - await( )
  - signalAll( )

Lock Interface (Java 1.5)

```
interface Lock {
  void lock();
  void unlock();
  ... /* Some more stuff, also */
}
class ReentrantLock implements Lock { ... }
```

- Explicit **`Lock`** objects
  - Same as implicit lock used by **`synchronized`**
- Only one thread can hold a lock at once
  - **`lock()`** causes thread to block (become suspended) until lock can be acquired
  - **`unlock()`** allows lock to be acquired by different thread

Lock Synchronization Example

```
public class Example extends Thread {
  private static int cnt = 0;
  static Lock lock = new ReentrantLock();
  public void run() {
    lock.lock();
    int y = cnt;
    cnt = y + 1;
    lock.unlock();
    }
  }
  …
}
```

***Lock**, for protecting the shared state*

***Acquires** the lock; Only succeeds if not held by another thread*

***Releases** the lock*

ReentrantLock Class (Java 1.5)

```
class ReentrantLock implements Lock { ... }
```

- Reentrant lock
  - Can be reacquired by same thread by invoking `lock()`
  - To release lock, must invoke `unlock()`
    - The same number of times `lock()` was invoked
- Reentrancy is useful
  - Each method can acquire/release locks as necessary
    - No need to worry about whether callers already have locks
  - Discourages complicated coding practices
    - To determine whether lock has already been acquired

Reentrant Lock Example

```
static int count = 0;
static Lock l =
    new ReentrantLock();

void inc() {
  l.lock();
  count++;
  l.unlock();
}
```

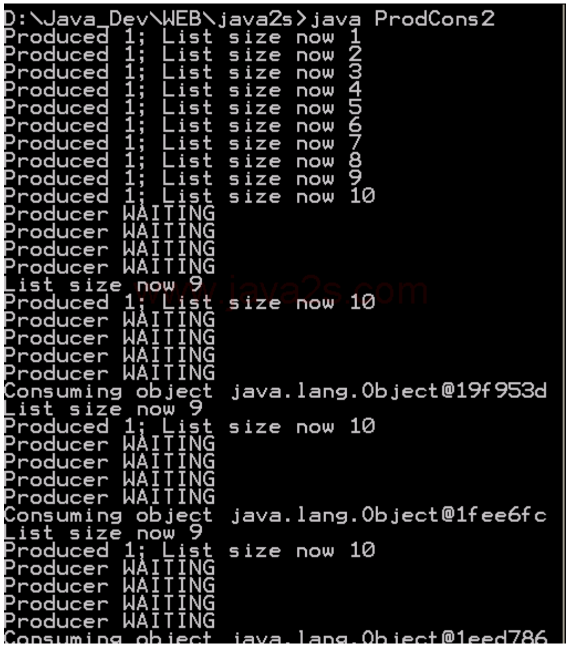
```
void returnAndInc() {
  int temp;

  l.lock();
  temp = count;
  inc();
  l.unlock();
}
```

- **`returnAndInc()`** can acquire lock and invoke **`inc()`**
- **`inc()`** can acquire lock without having to worry about whether thread already has lock

Producer / Consumer Problem

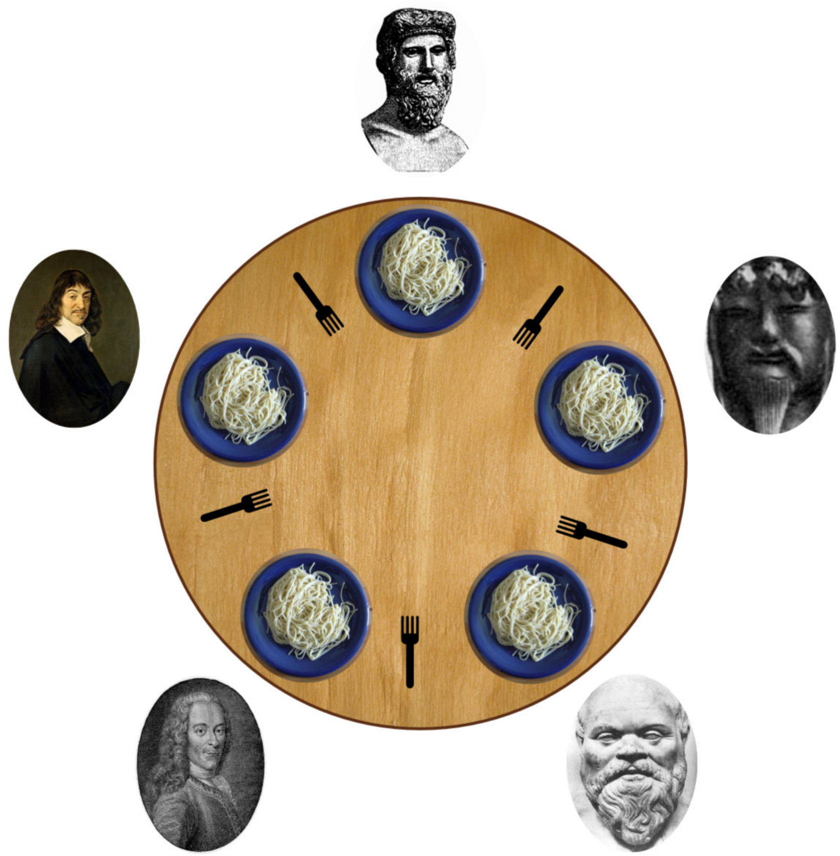
- Suppose we are communicating with a shared variable
  - E.g., a fixed size buffer holding messages



- One thread produces input to the buffer
- One thread consumes data from the buffer

- Rules
  - Producer can't add input to the buffer if it's full
  - Consumer can't take input from the buffer if it's empty

The Dining Philosophers Problem



- Philosopher
  - Thinks & eats
- To eat
  - Must have two forks
  - Can only use forks on either side of plate
- Goal
  - Avoid deadlock
  - Avoid starvation
- Fancy version of producer / consumer

Broken Producer / Consumer Code

```
Lock lock = new ReentrantLock();
boolean valueReady = false;
Object value;
```

```
void produce(Object o) {
  lock.lock();
  while (valueReady);
  value = o;
  valueReady = true;
  lock.unlock();
}
```

```
Object consume() {
  lock.lock();
  while (!valueReady);
  Object o = value;
  valueReady = false;
  lock.unlock();
}
```

- Threads wait with lock held – deadlock

Broken Producer / Consumer Code

```
Lock lock = new ReentrantLock();
boolean valueReady = false;
Object value;
```

```
void produce(Object o) {
  while (valueReady);
  lock.lock();
  value = o;
  valueReady = true;
  lock.unlock();
}
```

```
Object consume() {
  while (!valueReady);
  lock.lock();
  Object o = value;
  valueReady = false;
  lock.unlock();
}
```

- valueReady accessed without a lock held – data race

Bad Producer / Consumer Code

```
Lock lock = new ReentrantLock();
boolean valueReady = false;
Object value;
```

```
void produce(Object o) {
  while (true) {
    lock.lock();
    if (!valueReady){
      value = o;
      valueReady = true;
    }
    lock.unlock();
} }
```

```
Object consume() {
  while (true) {
    lock.lock();
    if (valueReady){
      Object o = value;
      valueReady = false;
    }
    lock.unlock();
} }
```

- Constantly acquiring / releasing lock – busy wait

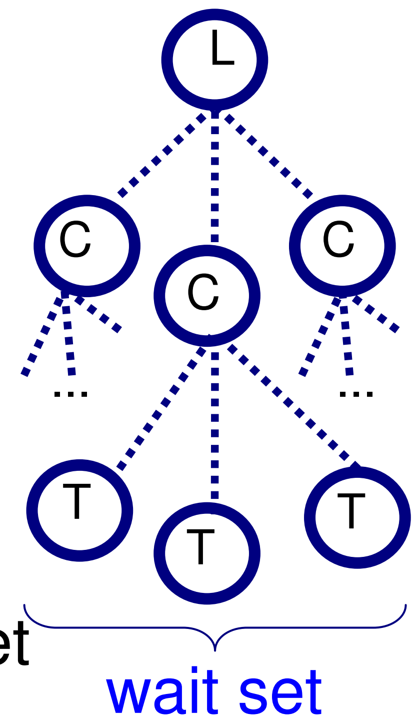
Solving Producer / Consumer Problem

- Difficult to use locks directly
  - Very hard to get right
  - Problems often very subtle
- Another approach – use Condition interface
  - Condition is created from `Lock` object
  - Allows threads to sleep while waiting to acquire lock
  - Can wake up sleeping threads before releasing lock

```
interface Lock { Condition newCondition(); ... }
interface Condition {
  void await();
  void signalAll(); ... }
```

Condition (Java 1.5)

- Calling **`await()`** w/ lock held
  - Releases the lock
    - But not any other locks held by this thread
  - Adds this thread to wait set for condition
  - Blocks the thread



- Calling **`signalAll()`** w/ lock held
  - Resumes all threads in condition's wait set
  - Threads must reacquire lock
    - Before continuing (returning from await)
    - Enforced automatically; you don't have to do it

Producer / Consumer Solution

```
Lock lock = new ReentrantLock();
Condition ready = lock.newCondition();
boolean bufferReady = false;
Object buffer;
```

```
void produce(Object o) {
    lock.lock();
    while (bufferReady){
      ready.await(); }
    buffer = o;
    bufferReady = true;
    ready.signalAll();
    lock.unlock();
  }
```

```
Object consume() {
    lock.lock();
    while (!bufferReady){
      ready.await(); }
    Object o = buffer;
    bufferReady = false;
    ready.signalAll();
    lock.unlock();
  }
```

`Await` and `SignalAll` Gotcha's

- `await()` must be called in a while loop
  - Conditions may not be met when await returns
  - Some other thread may have awoken first
    - And changed condition (e.g., consumed item in buffer)

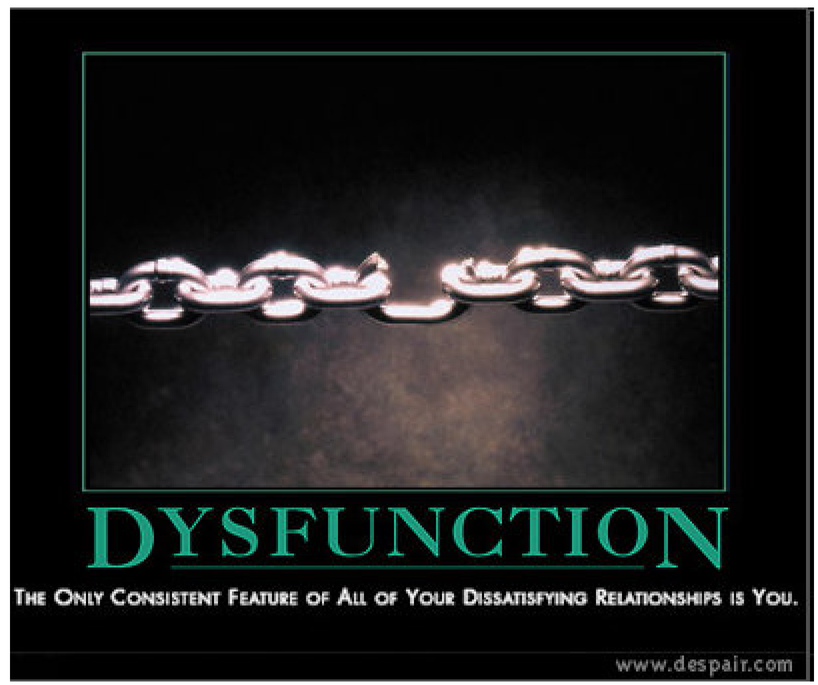
- Avoid holding other locks when waiting
  - `await()` only gives up lock on the object you are waiting on
  - Reduces possibility of deadlock

Key Ideas

- Multiple threads can run simultaneously
  - Either truly in parallel on a multiprocessor
  - Or can be scheduled on a single processor
    - A running thread can be pre-empted at any time
- Threads can share data
  - In Java, only fields can be shared
  - Need to prevent data races
    - Rule of thumb 1: You must hold a lock when accessing shared data
    - Rule of thumb 2: You must not release a lock until shared data is in a valid state
  - Overuse use of synchronization can create deadlock
    - Rule of thumb: No deadlock if only one lock

Deadlock theory

- 4 necessary conditions:
  - Mutual exclusion of a resource
  - Hold and wait
  - No preemption
  - Circular wait



Deadlock and Halting Problem

- Detecting the possibility of a deadlock before it occurs is generally undecidable!
  - Epic fail!
- What can we do?
  - Deadlock prevention
  - Deadlock avoidance
    - Only grant resources if going to be in safe state