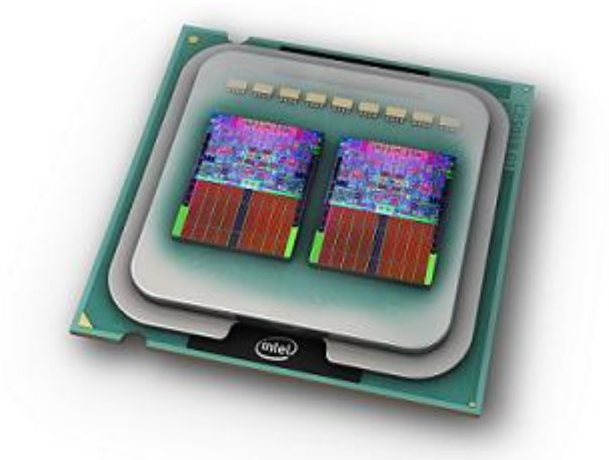
CMSC 330: Organization of Programming Languages

Multithreading

Multiprocessors

- 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

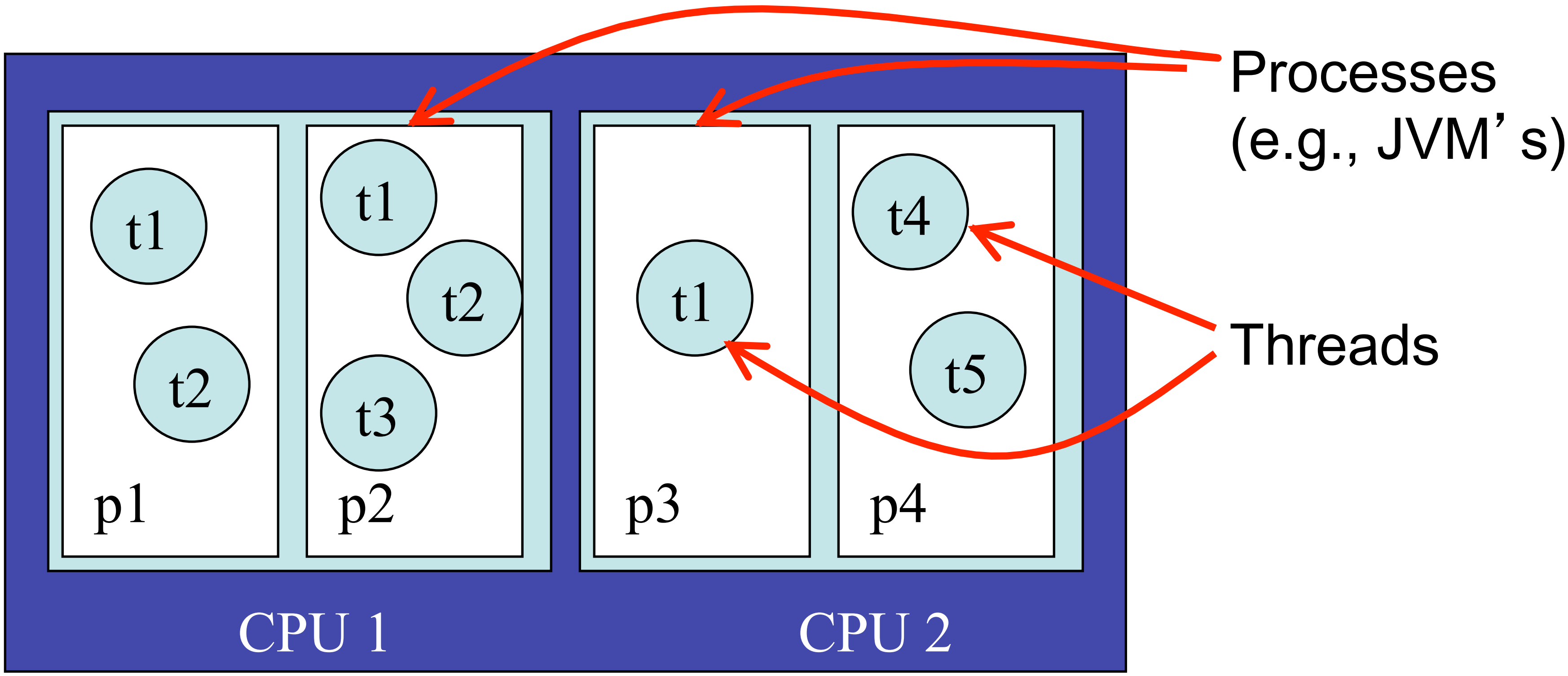
Concurrency

- Important & pervasive topic in CS
- Currently covered in
  - CMSC 132 – object-oriented programming II
    - Java threads, data races, synchronization
  - CMSC 216 – low level programming / computer systems
    - C pthreads
  - CMSC 411/430 – architectures / compilers
    - Instruction level parallelism
  - CMSC 412 – operating systems
    - Concurrent processes
  - CMSC 424 – database design
    - Concurrent transactions
  - **CMSC 433 – programming language technologies**
    - Advanced synchronization and parallelization
    - *Moral successor to ideas discussed in this lecture and the next*
  - CMSC 451 – algorithms
    - Parallel algorithms

Parallelizable Applications of Interest

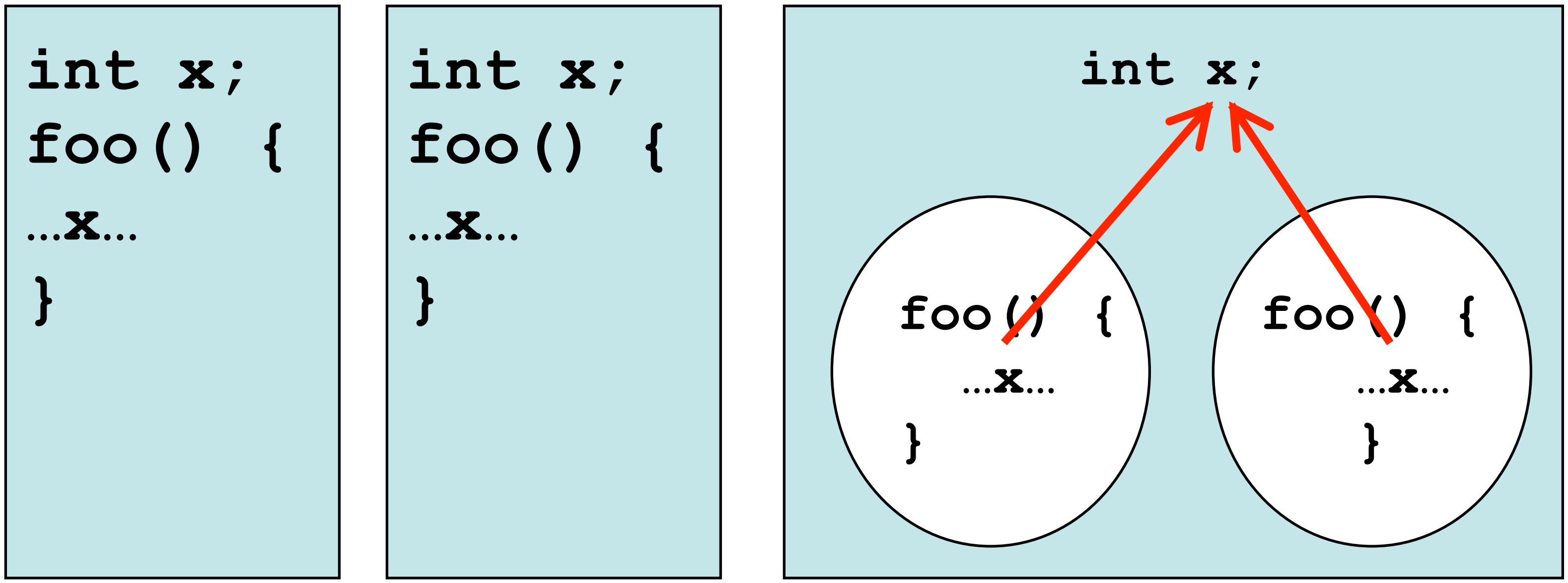
- Knowledge discovery: mine and analyze massive amounts of distributed data
  - Discovering social networks
  - Real-time, highly-accurate common operating picture, on small, power-constrained devices
- Simulations (games?)
- Data processing
  - NLP, vision, rendering, in real-time
- Commodity applications
  - Parallel testing, compilation, typesetting, …

Computation Abstractions



A computer

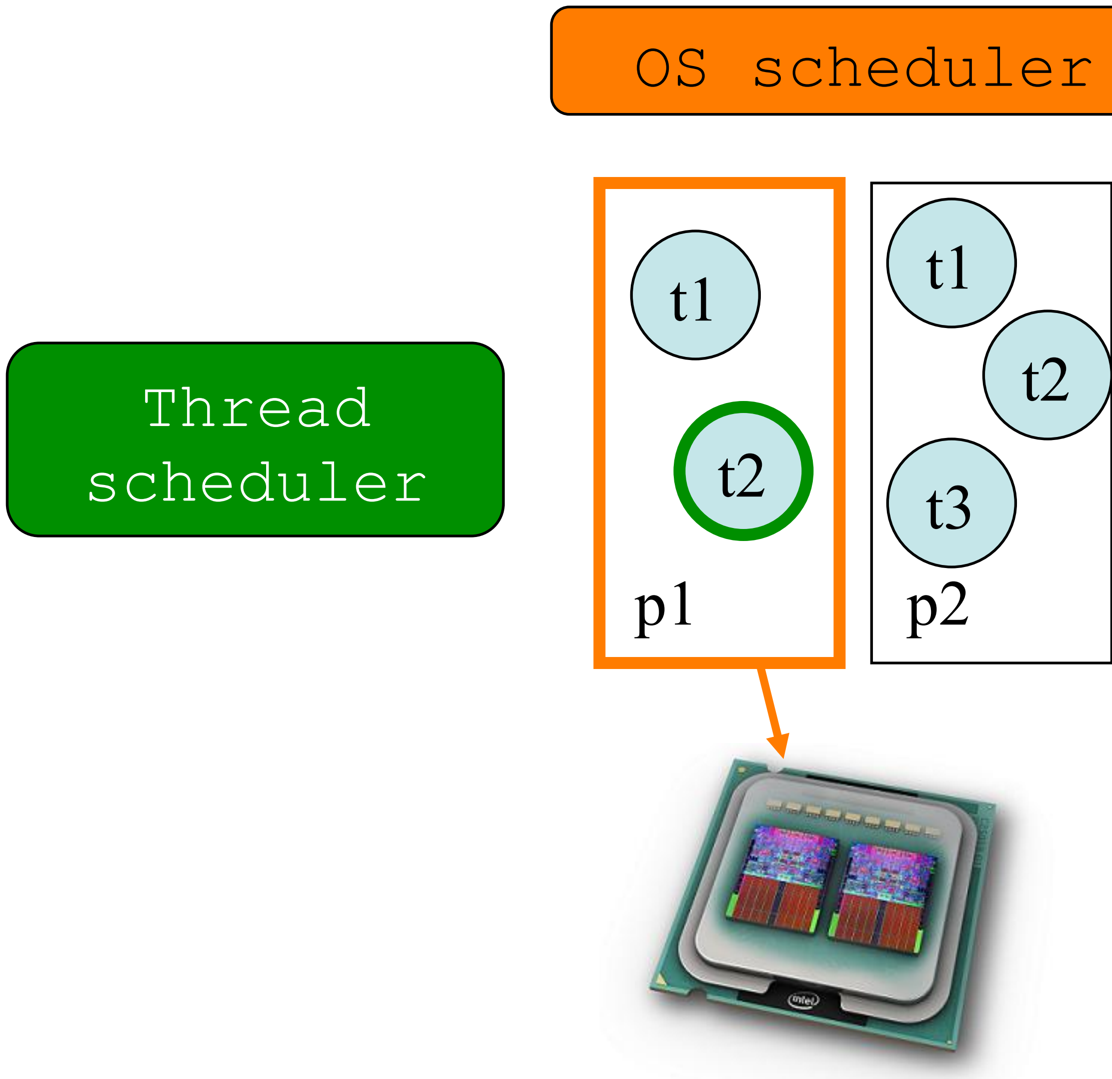
Processes vs. Threads



Processes do not share data

Threads share data within a process

Scheduling



The schedulers do most of the heavy lifting.

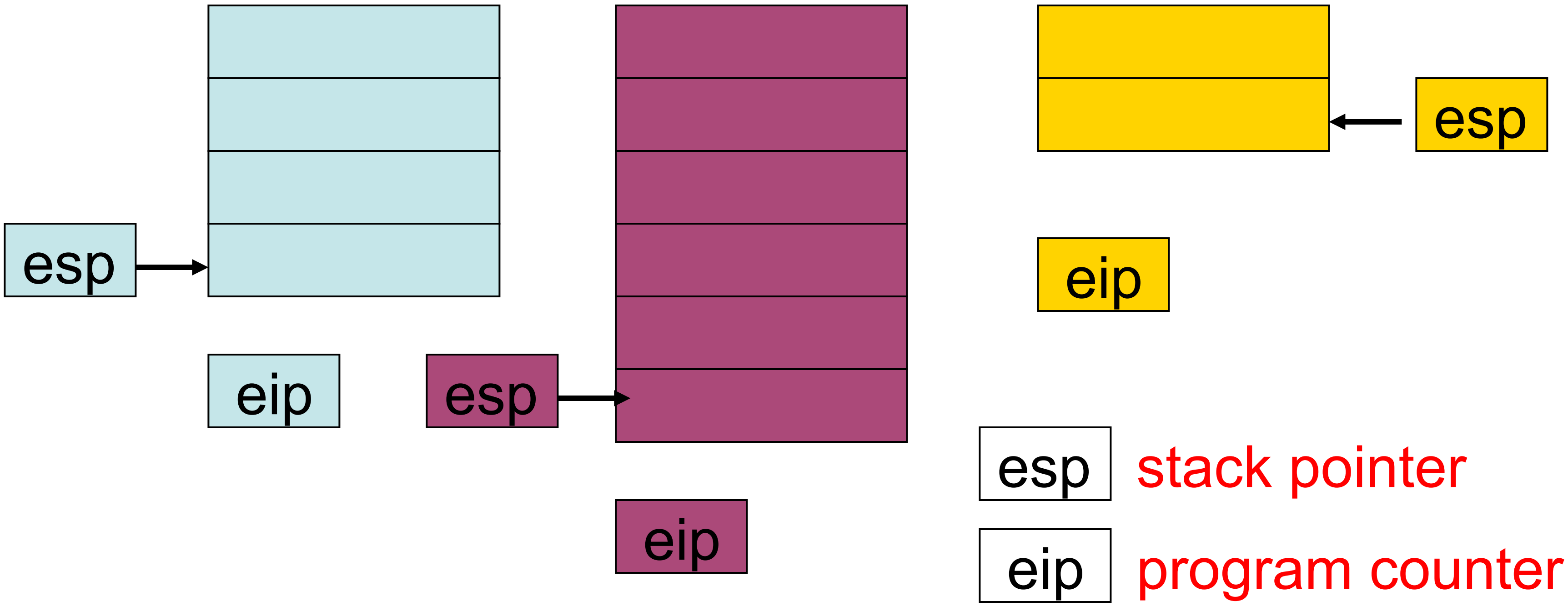
But they don't know the semantics of what the threads are actually doing.

So, What Is a Thread?

- Fundamental unit of execution
  - All programs have at least one thread (main)

- Implementation view
  - A program counter and a stack
  - Heap and static area are shared among all threads

Implementation View



- Per-thread stack and instruction pointer
  - Saved in memory when thread suspended
  - Put in hardware esp/eip when thread resumes

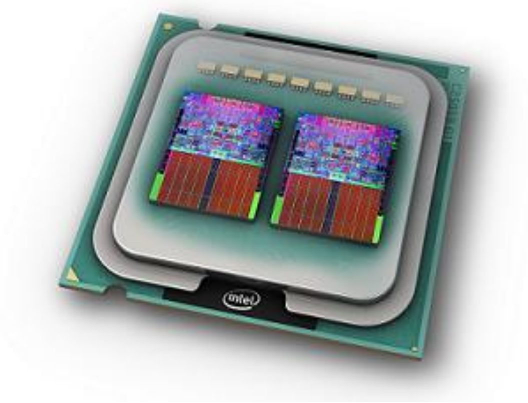
Programming Languages & Threads

- Old: libraries
  - pthreads
  - Could use different libraries for different properties
- New: primitives
  - Java, Ruby, OCaml
  - Can utilize special keywords, syntax
  - Better integration into assumptions of the language

Programming Processes

- Process creation is expensive
  - Stack, heap, PC, code, OS state
- Highly scalable
  - Virtually unlimited
- Processes may reside on separate processors
  - Sharing memory typically too expensive
- Message-passing programming paradigm
  - I/O streams, sockets, network, files
  - Cooperation key to communication (send/recv)

Programming Threads



- Thread creation is less expensive
  - Stack, program counter, scheduler state
- Threads may reside on same physical processor
  - So memory sharing is cheap
- Modern architectures can scale threads well
  - Depends on implementation; e.g., hundreds of thousands of Erlang threads
- Shared-memory programming paradigm
  - Everything except thread local variables are shared
  - Threads communicate via shared data
  - Synchronization used to avoid data races

What Is the Big Deal About Threads?

- Conventional wisdom: threads are hard
- Main reason: non-determinism of scheduling
  - Different threads execute at different speeds
    - Actions on memory are interleaved
  - This leads to unpredictable results
  - When you program with threads, you have to consider all possible ways that threads can interact
- The goal of the PL designer is to make this easier

Example

- x = 0 initially. Then these threads are executed:

```
T1   y = x;          T2   z = x;
     x = y+1;             x = z+2;
```

- What is the value of x afterward   3   1   2

```
T1   y = x;     T2
     x = y+1;
                     z = x;
                     x = z+2;
```

```
T1              T2   z = x;
                     x = z+2;
     y = x;
     x = y+1;
```

```
T1   y = x;     T2
                     z = x;
                     x = z+2;
     x = y+1;
```

```
T1              T2   z = x;
     y = x;
     x = y+1;
                     x = z+2;
```

Data Races

- That was an example of a data race
  - Threads are "racing" to read, write x
  - The value of x depends on who "wins" (3, 1, 2)
- Languages rarely specify who wins data races
  - The outcome is nondeterministic
- So programmers restrict certain outcomes
  - Synchronization with locks, condition variables
- And they often mess up
  - Leading to bugs that are hard to track down…

Thread API Concepts

- Thread management
  - Creating, killing, joining (waiting for) threads
  - Sleeping, yielding, prioritizing
- Synchronization
  - Controlling order of execution, visibility, atomicity
  - Locks: Can prevent data races, but watch out for deadlock!
  - Condition variables: supports communication between threads
- Most languages have similar APIs, details differ

Java – Creating Threads

- Thread.create(Runnable r)
  - Or subclass the Thread class
  - Java makes it hard to create threads that access local variables (since it does not have closures)
- In practice, there are better ways
  - Use thread pools, to separate the idea of creating a thread from creating a (Runnable) task
    - May have N threads execute M > N jobs
- We'll stick with the simple idea here

Thread Creation Example

```
public class MyT implements Runnable {
    public void run( ) {
        …       // particular work for this thread
    }
}

Thread t = new Thread(new MyT( ));  // create thread
t.start();       // begin running thread
…                // thread executing in parallel
t.join();        // waits for thread to exit
```

Locks

- Language designers limit non-determinism by introducing concurrency-control constructs
  - Make some parts deterministic = more predictable
  - Trade-off: reducing concurrency can reduce performance
- Common concurrency-control feature: locks
  - They “guard” shared resources that shouldn’t be accessed by more than one thread at a time
- The gist
  - At most one owner at a time
  - If someone else owns it, you block
  - When you’re done with it, release ownership

Java Intrinsic Locks

- Objects each have an associated intrinsic lock
- Use synchronized keyword to acquire lock
  - Code blocks – synchronized (o) { … } // lock for Object o
  - Methods – synchronized foo( ) { … } // lock for this
- Thread blocks when lock held
  - Thread returns when lock is finally acquired
  - May deadlock if threads try to acquire each other's lock
- Locks sometimes referred to as mutexes

Why Locks?

- #1 concern: prevent data races
- Patterns of use:
  - Enforce atomicity of shared data
    - 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 held at a time
- Synchronization also used to ensure ordering and visibility
  - The last is due to memory models in modern arch's

Synchronization Example

```
public class Example {
  private int cnt = 0;
  public void increment() {
    synchronized (this) {
      int y = cnt;
      cnt = y + 1;
    }
  }
  ...
}
```

Acquires *the lock associated w/ current object; only succeeds if lock not held by another thread, otherwise blocks*

Releases *the lock*

Synchronization Example, retold

```
public class Example {
  private int cnt = 0;
  public synchronized void increment() {
    int y = cnt;
    cnt = y + 1;
  }
  ...
}
```

***Acquires** the lock associated w/ current object on entering the method*

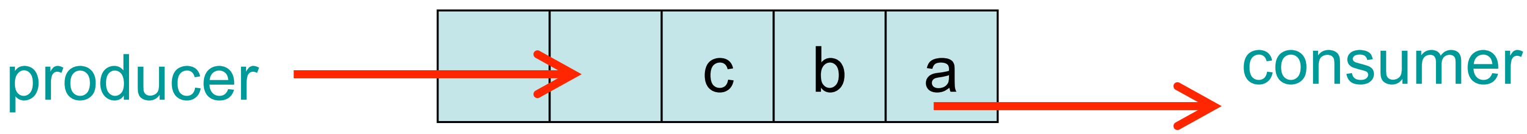
***Releases** the lock on method exit*

Producer / Consumer Problem

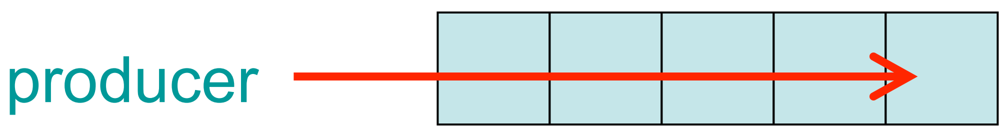
- Suppose we are communicating with a shared variable
  - E.g., a fixed size buffer holding messages
- One thread produces input to the buffer
- One thread consumes data from the buffer
- Rules
  - Producer can't add input to the buffer if it's full
  - Consumer can't take input from the buffer if it's empty

Producer / Consumer Idea

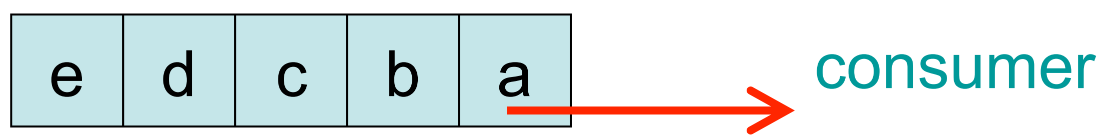
- If buffer is partially full, producer or consumer can run



- If buffer is empty, only producer can run



- If buffer is full, only consumer can run



Broken Producer/Consumer Example

```
boolean valueReady = false;
Object value; // one-place buffer
```

```
void produce(object o) {
  synchronized (this) {
    while (valueReady)
      ;
    value = o;
    valueReady = true;
  }
}
```

```
Object consume() {
  synchronized (this) {
    while (!valueReady)
      ;
    Object o = value;
    valueReady = false;
    return o;
  }
}
```

Threads wait with lock held – no way to make progress

Broken Producer/Consumer Example

```
boolean valueReady = false;
Object value;
```

```
void produce(object o) {
  while (valueReady)
    ;
  synchronized (this) {
    value = o;
    valueReady = true;
  }
}
```

```
Object consume() {
  while (!valueReady)
    ;
  synchronized (this) {
    Object o = value;
    valueReady = false;
    return o;
  }
}
```

valueReady accessed without a lock held – data race

Inefficient Producer/Consumer Example

```
boolean valueReady = false;
Object value;
```

Constantly acquiring / releasing lock — busy wait

```
void produce(Object o) {
  boolean done = false;
  while (!done) {
    synchronized (this) {
      if (!valueReady) {
        value = o;
        valueReady = true;
        done = true;
      }
    }
  }
}
```

```
Object consume() {
  Object o = null;
  boolean done = false;
  while (!done) {
    synchronized (this) {
      if (valueReady) {
        o = value;
        valueReady = false;
        done = true;
      }
  } }
  return o;
}
```

Solving Producer / Consumer Problem

- Difficult to use locks only
  - Very hard to get correct (or efficient) solution
  - Problems very subtle
- Proper approach – use signaling
- Common signaling scenario
  1. You get the lock
  2. You realize it's no good to you yet (buffer is empty)
  3. Go to sleep: "wake me up when there's work to do"
- Virtually every threading model supports this
  - Condition variables
    - Operations: *Wait* and *notify*

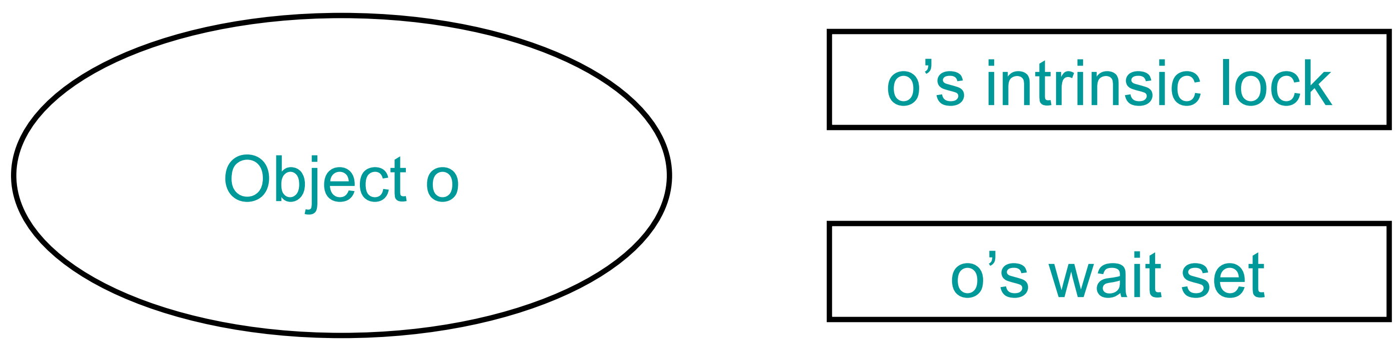
Condition Variables

- A condition variable represents a set of threads waiting for a condition to become true
  - Implemented, at least conceptually, as a wait set

- Since different threads may access the variable at once, we protect the wait set with a lock
  - Thus avoiding possible data races

Condition Variables and Intrinsic Locks

- synchronized accesses intrinsic lock



- Objects also have an intrinsic condition variable (and thus a wait set)

Wait and NotifyAll

- o.wait()
  - Must hold o's intrinsic lock
  - Release that lock
    - And no other locks
  - Adds this thread to wait set for o
  - Blocks the thread
- o.notifyAll()
  - Must hold o's intrinsic lock
  - Resumes all threads on o's wait set
  - Those threads will reacquire lock before continuing
    - This is part of the function; you don't need to do it explicitly

Producer/Consumer Example

```
boolean valueReady = false;
Object value;
```

```
void produce(Object o) {
  synchronized (this) {
    while (valueReady)
      this.wait();
    value = o;
    valueReady = true;
    this.notifyAll();
  }
}
```

```
Object consume() {
  synchronized (this) {
    while (!valueReady)
      this.wait();
    Object o = value;
    valueReady = false;
    this.notifyAll();
    return o;
  }
}
```

Using Conditions Correctly

- wait( ) must be called in a while loop
  - Conditions may not be met when wait returns
  - Some other thread may have awoken first
    - …and changed condition (e.g., consumed item in buffer)
- Prefer notifyAll( ) to the alternative, notify( )
- Avoid holding (other) locks when waiting
  - wait( ) only gives up lock on object you are waiting on
  - Reduces possibility of deadlock
    - Called Nested Monitor Lockout

Broken Producer/Consumer Example

```
boolean valueReady = false;
Object value;
```

```
void produce(Object o) {
  synchronized (this) {
    if (valueReady)
      wait();
    value = o;
    valueReady = true;
    notifyAll();
  }
}
```

```
Object consume() {
  synchronized (this) {
    if (!valueReady)
      wait();
    Object o = value;
    valueReady = false;
    notifyAll();
    return o;
  }
}
```

- Illegal access if multiple producers or consumers

Notify vs. NotifyAll

- Notify( ) is like notifyAll( ), but wakes up a single thread on the wait set, not all threads
  - Can be more efficient, since if you have a lot of threads waiting, most will simply fail to reacquire the lock, wasting effort
- But, easy to use notify( ) incorrectly
  - Leading to a kind of deadlock

Broken Producer/Consumer Example

```
boolean valueReady = false;
Object value;
```

```
void produce(Object o) {
  synchronized (this) {
    while (valueReady)
      wait();
    value = o;
    valueReady = true;
    notify ();
  }
}
```

BAD: Could wake up another ***producer***

```
Object consume() {
  synchronized (this) {
    while (!valueReady)
      wait();
    Object o = value;
    valueReady = false;
    notify ();
    return o;
  }
}
```

BAD: Could wake up another ***consumer***

- Notify only wakes up one thread – could be wrong kind

Lock Interface (Java 1.5 and later)

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

- Explicit Lock objects
  - ReentrantLock implements Lock
    - same behavior as an intrinsic lock
- 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

Synchronization, the traditional way

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

*Object uses as a **Lock***

***Acquires** the intrinsic lock; only succeeds if lock not held by another thread, otherwise blocks*

***Releases** the lock when exiting block*

Synchronization, with explicit Locks

```
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 lock not held by another thread, otherwise blocks*

Releases *the lock*

ReentrantLock Class

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

- Reentrant lock
  - Can be reacquired by same thread by invoking lock( )
    - Up to 2147483648 times
  - 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();
}
```

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

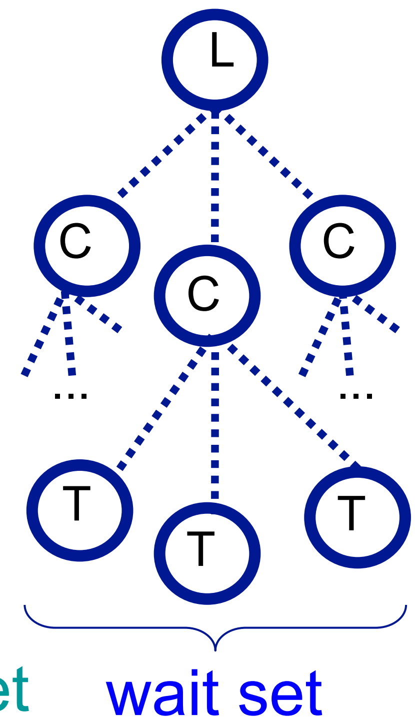
Condition Interface (Java 1.5 and later)

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

- Explicit condition variable objects
  - Condition variable C is created from a Lock object L by calling L.newCondition( )
  - Condition variable C is then associated with L
- Multiple condition objects per lock
  - Allows different wait sets to be created for lock
  - Can wake up different threads depending on condition

Condition – await() and signalAll()

- 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();
    return o;  }
```

- Uses single condition per lock (like intrinsics)

Producer / Consumer Solution

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

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

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

- Uses 2 conditions per lock for greater efficiency

Producer / Consumer Solution

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

```
void produce(Object o) {
    lock.lock();
    if(bufferReady)
      producers.await();
    buffer = o;
    bufferReady = true;
    consumers.signal ();
    lock.unlock();
  }
```

```
Object consume() {
    lock.lock();
    if(!bufferReady)
      consumers.await();
    Object o = buffer;
    bufferReady = false;
    producers.signal ();
    lock.unlock();
    return o; }
```

- Wakes up only one thread: More efficient, still!

Note about unlock

- The prior examples were slightly simplified

```
void produce(Object o) {
  lock.lock();
  try {
    if(bufferReady)
      producers.await();
    buffer = o;
    bufferReady = true;
    consumers.signal ();
  } finally {
    lock.unlock();
  }
}
```

- Need to consider the possibility of exceptional exit
  - Handled automatically for intrinsic locks, when leaving synchronized blocks
- Use finally to ensure that lock is released