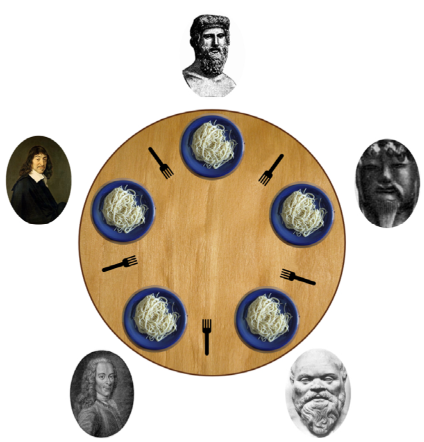
CMSC 330: Organization of Programming Languages

Threads

Classic Concurrency Problems

The Dining Philosophers Problem



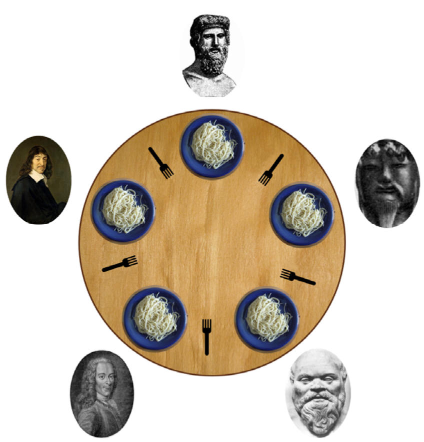
- Philosophers either eat or think
- They must have two forks to eat
- Can only use forks on either side of their plate

- Avoid deadlock and starvation!

Bad Dining Philosophers Solution 1

- Philosophers all pick up the left fork first
- Deadlock!
  - all are holding the left fork and waiting for the right fork

Bad Dining Philosophers Solution 2



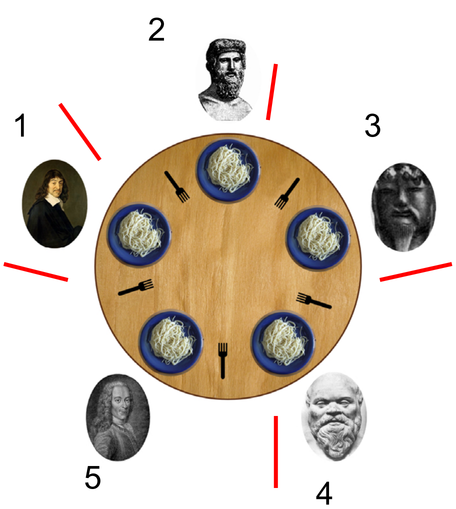
- Philosophers all pick up the left fork first
- Philosophers put down a fork after waiting for 5 minutes, then wait 5 minutes before picking it up again
- Starvation!

Dining Philosophers Solution

you try!

- Number the philosophers
- Start by giving the fork to the philosopher with lower number. Initially, all forks are dirty.
- When a philosopher wants both forks, he sends a message to his neighbors
- When a philosopher with a fork receives a message if his fork is clean, he keeps it, otherwise he cleans it and gives it up.
- After a philosopher eats, his forks are dirty. If a philosopher had requested his fork, he cleans it and sends it.

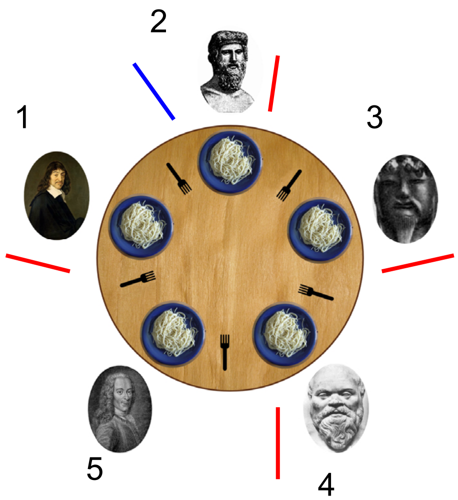
Dining Philosophers Example



Each philosopher begins with the forks shown.

All are dirty.

Dining Philosophers Example

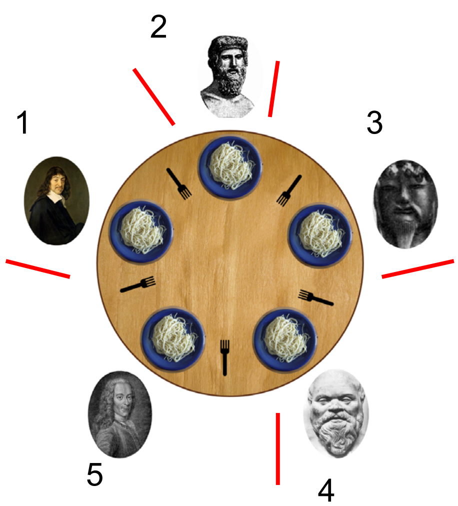


Philosopher 2 sends a message to philosopher 1 that he wants his fork.

Their shared fork is dirty, so philosopher 1 cleans it and sends it.

CMSC 330 7

Dining Philosophers Example



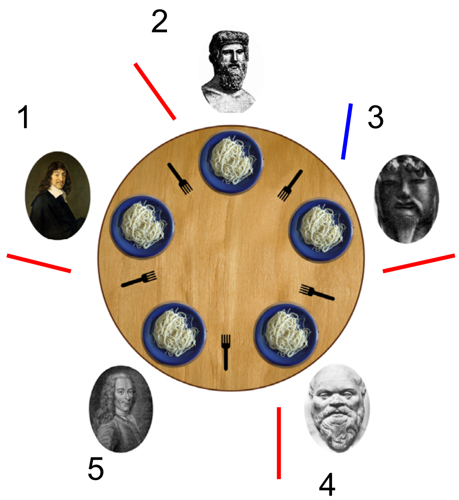
Philosopher 2 eats!

While he is eating philosopher 3 requests their shared fork.

Philosopher 2 is done eating, so his forks become dirty.

CMSC 330 8

Dining Philosophers Example



Philosopher 2 is done eating, so he honors philosopher 3's request and cleans the fork and sends it.

Philosopher 3 eats!

Philosophers Implementation Needs

- Wait until notified about something by another philosopher
  - stay hungry until you have two forks
  - hold onto your fork until your neighbor needs it
- Send a message to a philosopher and have it processed at a later time
  - multiple philosophers can send messages to one
  - when philosopher done eating he should process all

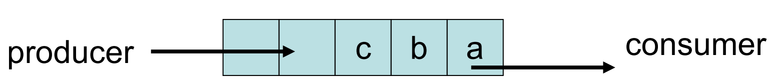
… and here's another problem with these needs…

Producer/Consumer Problem

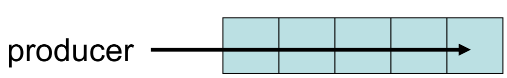
- Suppose we are communicating with a shared variable
  - E.g., some kind of a fixed size buffer holding messages
- One thread *produces* input to the buffer
- One thread *consumes* data from the buffer
- Rules:
  - producer can't add input to the buffer if it's full
  - consumer can't take input from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

Producer / Consumer Idea

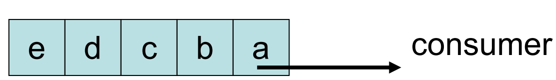
If the buffer is partially full, producer or consumer can run:



If the buffer is empty, only the producer can run:



If the buffer is full, only the consumer can run:



Pseudocode Solution

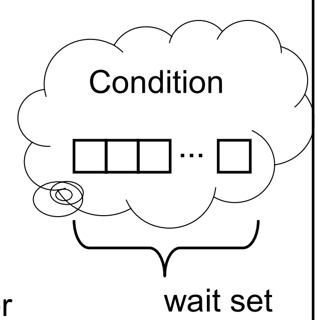
you try!

- How can we solve this problem using one thread for the producer and one for the consumer?
  - no deadlock
  - no data races

Conditions (Java 1.5)

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

- Condition created from a Lock
- await called with lock held
  - Releases the lock (on the fork or buffer)
    - But not any other locks held by this thread
  - Adds this thread to wait set for lock
  - Blocks the thread



when philosopher is waiting for a fork or consumer is waiting for non empty buffer

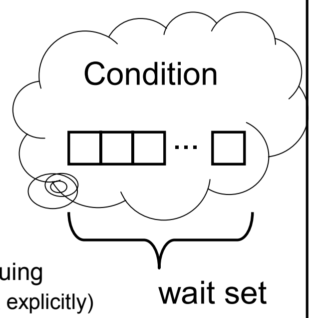
Conditions (Java 1.5)

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

- Condition created from a Lock

  when philosopher is done eating
  or when buffer is non empty:

- signalAll called with lock held
  - Resumes all threads on lock's wait set
  - Those threads must reacquire lock before continuing
    - (This is part of the function; you don't need to do it explicitly)



Producer/Consumer Example

```
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();
  }
```

Use This Design

- This is the right solution to the problem
  - Tempting to try to just use locks directly
  - Very hard to get right
  - Problems with other approaches often very subtle

… here are a few bad solutions…

Broken Producer/Consumer Example

```
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 – no way to make progress

Broken Producer/Consumer Example

```
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 – race condition

Broken Producer/Consumer Example

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

```
void produce(object o) {
    lock.lock();
    if (valueReady)
      ready.await();
    value = o;
    valueReady = true;
    ready.signalAll();
    lock.unlock();
  }
```

```
Object consume() {
    lock.lock();
    if (!valueReady)
      ready.await();
    Object o = value;
    valueReady = false;
    ready.signalAll();
    lock.unlock();
  }
```

what if there are multiple producers or consumers?

Why was it broken?

- Suppose you have 2 consumers, 1 producer
- Producer starts. valueReady set to true.
- Both consumers exit while loop and try to aquire lock.
- One consumer gets the lock and consumes the input.
- The next consumer is still able to get the lock.
  - ERROR!

More on the Condition Interface

```
interface Condition {
  void await();
  boolean await (long time, TimeUnit unit);
  void signal();
  void signalAll();
... }
```

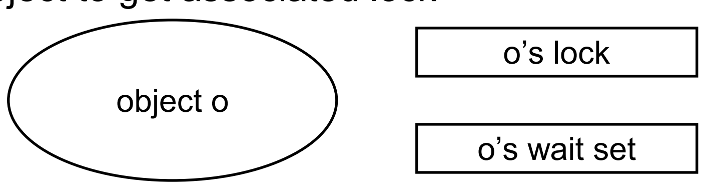
- away(t, u) waits for time t and then gives up
  - Result indicates whether woken by signal or timeout
- signal() wakes up only *one* waiting thread
  - Tricky to use correctly
    - Have all waiters be equal, handle exceptions correctly
  - Highly recommended to just use signalAll()

Await and SignalAll Gotcha's

- await *must* be in a loop
  - Don't assume that when wait returns conditions are met
- Avoid holding other locks when waiting
  - await only gives up locks on the object you wait on

Wait and NotifyAll (Java 1.4)

- Recall that in Java 1.4, use synchronize on object to get associated lock



- Objects also have an associated wait set

Wait and NotifyAll (cont'd)

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

Producer/Consumer in Java 1.4

```
public class ProducerConsumer {
  private boolean valueReady = false;
  private Object value;

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

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

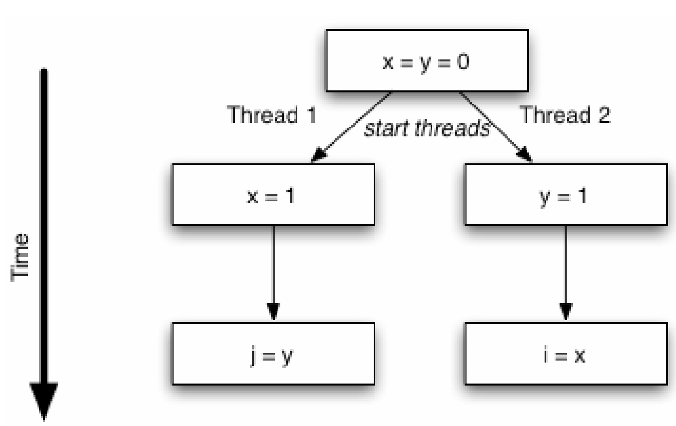
synchronizes on lock for this

waits using lock and wait set for this

Aspects of Synchronization

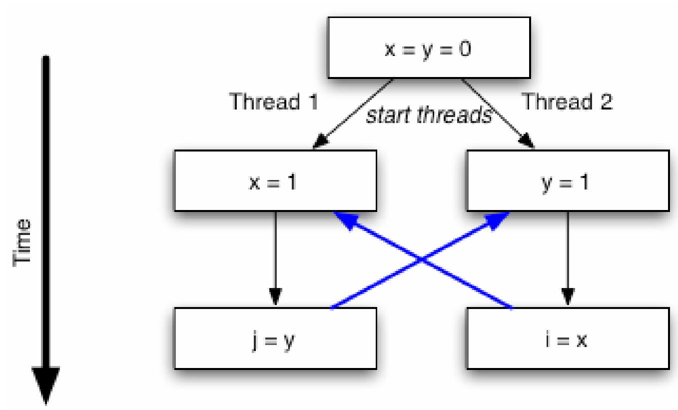
- Atomicity
  - Locking to obtain mutual exclusion
  - What we most often think about
- Visibility
  - Ensuring that changes to object fields made in one thread are seen in other threads
- Ordering
  - Ensuring that you aren't surprised by the order in which statements are executed

Quiz



- Can this result in i=0 and j=0?

Doesn't Seem Possible...

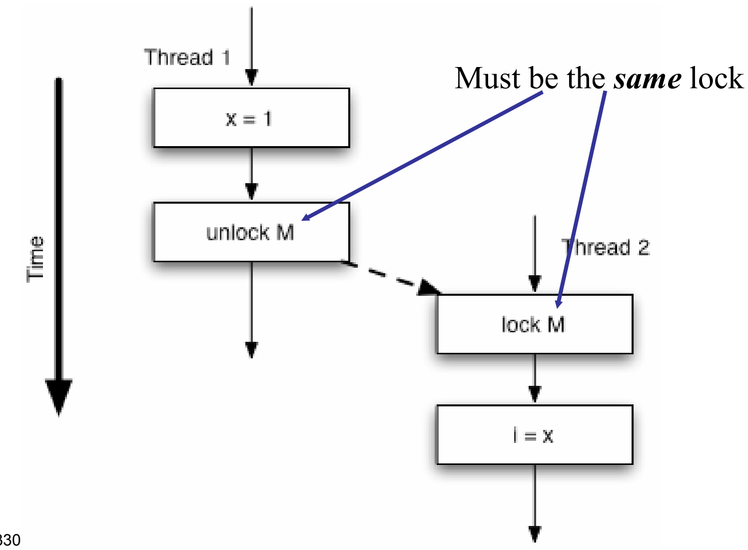


- But this can happen!

How Can This Happen?

- Compiler can reorder statements
  - Or keep values in registers
- Processor can reorder them
- On multi-processor, values not synchronized in global memory… so the data change may not be visible to all threads yet

When Are Actions Visible?



Forcing Visibility of Actions

- All writes from thread that holds lock M are visible to next thread that acquires lock M
  - Must be the same lock
- Use synchronization to enforce **visibility** and **ordering**
  - As well as mutual exclusion

Volatile Fields

- Fields which are visible immediately across all threads
- If you are going to access a shared field without using synchronization
  - It needs to be volatile
- Example uses
  - A one-writer/many-reader value
    - Simple control flags:
      - volatile boolean done = false;
  - Keeping track of a “recent value” of something

Misusing Volatile

- Incrementing a volatile field can cause a data race (just as for any other field)
- A volatile reference to an object isn’t the same as having the fields of that object be volatile
  - No way to make elements of an array volatile
- Can’t keep two volatile fields in sync
- Don’t use for this course

Guidelines for Programming w/Threads

- Synchronize access to shared data
- Don't hold multiple locks at a time
  - Could cause deadlock
- Hold a lock for as little time as possible
  - Reduces blocking waiting for locks
- While holding a lock, don't call a method you don't understand
  - E.g., a method provided by someone else, especially if you can't be sure what it locks
  - Corollary: document which locks a method acquires

Thread Cancellation

- Example scenarios: want to cancel thread
  - Whose processing the user no longer needs (i.e., she has hit the "cancel" button)
  - That computes a partial result and other threads have encountered errors, … etc.
- Java used to have Thread.kill()
  - But it and Thread.stop() are deprecated
  - Use Thread.interrupt() instead

Thread.interrupt()

- Tries to wake up a thread
  - Sets the thread's interrupted flag
  - Flag can be tested by calling
    - interrupted() method
      - Clears the interrupt flag
    - isInterrupted() method
      - Does not clear the interrupt flag
- Won't disturb the thread if it is working
  - Not asynchronous!

Cancellation Example

```
public class CancellableReader extends Thread {
  private FileInputStream dataFile;
  public void run() {
    try {
      while (!Thread.interrupted()) {
        try {
          int c = dataFile.read();
          if (c == -1) break;
          else process(c);
        } catch (IOException ex) { break; }
      }
    } finally { // cleanup here }
  }
}
```

This could acquire locks, be on a wait set, etc.

What if the thread is blocked on a lock or wait set, or sleeping when interrupted?

InterruptedException

- Exception thrown if interrupted on certain ops
  - wait, await, sleep, join, and lockInterruptibly
  - Also thrown if call one of these with interrupt flag set
- *Not thrown* when blocked on 1.4 lock or I/O

```
class Object {
  void wait() throws IE;
  ... }
interface Lock {
  void lock();
  void lockInterruptibly() throws IE;
  ... }
interface Condition {
  void await() throws IE;
  void signalAll();
  ... }
```


Responses to Interruption

- Early Return
  - Clean up and exit without producing errors
  - May require rollback or recovery
  - Callers can poll cancellation status to find out why an action was not carried out
- Continuation (i.e., ignore interruption)
  - When it is too dangerous to stop
  - When partial actions cannot be backed out
  - When it doesn’t matter

Responses to Interruption (cont'd)

- Re-throw InterruptedException
  - When callers must be alerted on method return
- Throw a general failure exception
  - When interruption is a reason method may fail
- In general
  - Must reset invariants before cancelling
  - E.g., close file descriptors, notify other waiters, etc.

Handling InterruptedException

```
synchronized (this) {
  while (!ready) {
    try { wait(); }
    catch (InterruptedException e) {
      // make shared state acceptable
      notifyAll();
      // cancel processing
      return;
    }
    // do whatever
  }
}
```

Why No Thread.kill()?

- What if the thread is holding a lock when it is killed? The system could
  - Free the lock, but the data structure it is protecting might be now inconsistent
  - Keep the lock, but this could lead to deadlock
- A thread needs to perform its own cleanup
  - Use InterruptedException and isInterrupted() to discover when it should cancel