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Concurrency and Parallelism
(Concorrência e Paralelismo – CP 11158)

Lecture 7

— Data Races and Memory Reordering, Deadlock, Readers/Writer Locks, Condition Variables —

Slides based in material from:
http://www.cs.washington.edu/homes/djg/teachingMaterials/

Outline

- The other basics an informed programmer needs to know
  - Why you must avoid data races (memory reorderings)
- Another common error: Deadlock
- Other common facilities useful for shared-memory concurrency
  - Readers/writer locks
  - Condition variables, or, more generally, passive waiting

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Motivating memory-model issues

Tricky and *surprisingly wrong* unsynchronized concurrent code

```
class C {
  private int x = 0;
  private int y = 0;

  void f() {
    x = 1;
    y = 1;
  }
  void g() {
    int a = y;
    int b = x;
    assert(b >= a);
  }
}
```

- First understand why it looks like the assertion cannot fail:
  - Easy case: call to g ends before any call to f starts
  - Easy case: at least one call to f completes before call to g starts
  - If calls to f and g *interleave*…

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Interleavings

There is no interleaving of **`f`** and **`g`** where the assertion fails

- Proof #1: Exhaustively consider all possible orderings of access to shared memory (there are 6)
- Proof #2: If **`!(b>=a)`**, then **`a==1`** and **`b==0`**.
  But if **`a==1`**, then **`y=1`** happened before **`a=y`**.
  Because programs execute in order:
  `a=y` happened before **`b=x`** and **`x=1`** happened before **`y=1`**.
  So by transitivity, **`b==1`**. Contradiction.

Thread 1: `f`

```
x = 1;

y = 1;
```

Thread 2: `g`

```
int a = y;

int b = x;

assert(b >= a);
```

Wrong

- However, the code has a *data race*
  - Two actually
  - Recall: data race: unsynchronized read/write or write/write of same location
- If code has data races, you cannot reason about it with interleavings!
  - That is simply the rules of Java (and C, C++, C#, …)
  - (Else would slow down all programs just to "help" programs with data races, and that was deemed a bad engineering trade-off when designing the languages/compilers/hardware)
  - So the assertion can fail
- A basic guideline: No data races
  - unless you really know what you are doing

Why

For performance reasons, the compiler and the hardware often reorder memory operations

Thread 1: `f`

```
x = 1;

y = 1;
```

Thread 2: `g`

```
int a = y;

int b = x;

assert(b >= a);
```

Of course, you cannot just let them reorder anything they want

- Each thread executes in order after all!
- Consider: x=17; y=x;

The grand compromise

- The compiler/hardware will never perform a memory reordering that affects the result of a single-threaded program
- The compiler/hardware will never perform a memory reordering that affects the result of a data-race-free multi-threaded program
- So: If no interleaving of your program has a data race, then you can *forget about all this reordering nonsense*: the result will be equivalent to some interleaving
- Your job: Avoid data races
- Compiler/hardware job: Give illusion of interleaving *if you do your job*

Fixing our example

- Naturally, we can use synchronization to avoid data races
  - Then, indeed, the assertion cannot fail

```
class C {
  private int x = 0;
  private int y = 0;
  void f() {
    synchronized(this) { x = 1; }
    synchronized(this) { y = 1; }
  }
  void g() {
    int a, b;
    synchronized(this) { a = y; }
    synchronized(this) { b = x; }
    assert(b >= a);
  }
}
```

A second fix

- Java has **`volatile`** fields: accesses do not count as data races

- Implementation: slower than regular fields, faster than locks
- Really for experts: avoid them; use standard libraries instead
- And why do you need code like this anyway?

```
class C {
  private volatile int x = 0;
  private volatile int y = 0;
  void f() {
    x = 1;
    y = 1;
  }
  void g() {
    int a = y;
    int b = x;
    assert(b >= a);
  }
}
```

Code that's wrong

- Here is a more realistic example of code that is wrong
  - No *guarantee* Thread 2 will *ever* stop
  - But honestly it will "likely work in practice"

Thread 1: `f()`

Thread 2: `g()`

```
class C {
  boolean stop = false;
  void f() {
    while(!stop) {
      // draw a monster
    }
  }
  void g() {
    stop = didUserQuit();
  }
}
```

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Motivating Deadlock Issues

Consider a method to transfer money between

```
class BankAccount {
  …
  synchronized void withdraw(int amt) {…}
  synchronized void deposit(int amt) {…}
  synchronized void transferTo(int amt,
                               BankAccount a) {
    this.withdraw(amt);
    a.deposit(amt);
  }
}
```

Notice that during call to a.transfer(), thread holds *two* locks

– We need to investigate when this may be a problem

The Deadlock

Suppose **x** and **y** are fields holding accounts

Time

Thread 1: `x.transferTo(1,y)`	Thread 2: `y.transferTo(1,x)`
acquire lock for x	
do withdraw from x	
	acquire lock for y
	do withdraw from y
	block on lock for x
block on lock for y	

Deadlock, in general

- A deadlock occurs when there are threads **T1**, …, **Tn** such that:
  - For **i**=1,..,n-1, **Ti** is waiting for a resource held by **T(i+1)**
  - **Tn** is waiting for a resource held by **T1**
- In other words, there is a cycle of waiting
  - Can formalize as a graph of dependencies with cycles bad
- Deadlock avoidance in programming amounts to techniques to ensure a cycle can never arise

Back to our example

- Options for deadlock-proof on transfer:

1. Make a smaller critical section: **`transferTo`** not synchronized
   - Exposes intermediate state after **`withdraw`** before **`deposit`**
   - May be okay, but exposes wrong total amount in bank
2. Coarsen lock granularity: one lock for all accounts allowing transfers between them
   - Works, but sacrifices concurrent deposits/withdrawals
3. Give every bank-account a unique number and always acquire locks in the same order
   - *Entire program* should obey this order to avoid cycles
   - Code acquiring only one lock can ignore the order

Ordering locks

```
class BankAccount {
  …
  private int acctNumber; // must be unique
  void transferTo(int amt, BankAccount a) {
    if(this.acctNumber < a.acctNumber)
       synchronized(this) {
       synchronized(a) {
          this.withdraw(amt);
          a.deposit(amt);
       }}
    else
       synchronized(a) {
       synchronized(this) {
          this.withdraw(amt);
          a.deposit(amt);
       }}
  }
}
```

Another example

From the Java standard library

```
class StringBuffer {
  private int count;
  private char[] value;
  …
  synchronized append(StringBuffer sb) {
    int len = sb.length();
    if(this.count + len > this.value.length)
      this.expand(…);
    sb.getChars(0,len,this.value,this.count);
  }
  synchronized getChars(int x, int, y,
                        char[] a, int z) {
    "copy this.value[x..y] into a starting at z"
  }
}
```

Two problems

- Problem #1: Lock for **`sb`** is not held between calls to **`sb.length`** and **`sb.getChars`**
  - So **`sb`** could get longer
  - Would cause **`append`** to throw an **`ArrayBoundsException`**
- Problem #2: Deadlock potential if two threads try to **`append`** in opposite directions, just like in the bank-account first example
- Not easy to fix both problems without extra copying:
  - Do not want unique ids on every **`StringBuffer`**
  - Do not want one lock for all **`StringBuffer`** objects
- Actual Java library: fixed neither (left code as is; changed javadoc)
  - Up to clients to avoid such situations with own protocols

Perspective

- Code like account-transfer and string-buffer append are difficult to deal with for deadlock
- Easier case: different types of objects
  - Can document a fixed order among types
  - Example: "When moving an item from the hashtable to the work queue, never try to acquire the queue lock while holding the hashtable lock"
- Easier case: objects are in an acyclic structure
  - Can use the data structure to determine a fixed order
  - Example: "If holding a tree node's lock, do not acquire other tree nodes' locks unless they are children in the tree"

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Reading vs. writing

- Recall:
  - Multiple concurrent reads of same memory: *Not* a problem
  - Multiple concurrent writes of same memory: Problem
  - Multiple concurrent read & write of same memory: Problem
- So far:
  - If concurrent write/write or read/write might occur, use synchronization to ensure one-thread-at-a-time
- But this is unnecessarily conservative:
  - Could still allow multiple simultaneous readers!

Example

- Consider a hashtable with one coarse-grained lock
  - So only one thread can perform operations at a time
- But suppose:
  - There are many simultaneous **`lookup`** operations
  - **`insert`** operations are very rare
- Note: Important that **`lookup`** does not actually mutate shared memory, like a move-to-front list operation would

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Readers/writer locks

- A new synchronization ADT: The readers/writer lock
- A lock's states fall into three categories:
  - "not held"
  - "held for writing" by one thread
  - "held for reading" by *one or more* threads

$0 \le writers \le 1$
$0 \le readers$
$writers * readers == 0$

- `new:` make a new lock, initially "not held"
- `acquire_write:` block if currently "held for reading" or "held for writing", else make "held for writing"
- `release_write:` make "not held"
- `acquire_read:` block if currently "held for writing", else make/keep "held for reading" and increment *readers count*
- `release_read:` decrement readers count, if 0, make "not held"

Pseudocode example (not Java)

```
class Hashtable<K,V> {
  …
  // coarse-grained, one lock for table
  RWLock lk = new RWLock();
  V lookup(K key) {
    int bucket = hasher(key);
    lk.acquire_read();
    … read array[bucket] …
    lk.release_read();
  }
  void insert(K key, V val) {
    int bucket = hasher(key);
    lk.acquire_write();
    … write array[bucket] …
    lk.release_write();
  }
}
```

Readers/writer lock details

- A readers/writer lock implementation usually gives *priority* to writers:
  - Once a writer blocks, no readers *arriving later* will get the lock before the writer
  - Otherwise an **`insert`** could *starve*
- Re-entrant?
  - Mostly an orthogonal issue
  - But some libraries support *upgrading* from reader to writer
- Why not use readers/writer locks with more fine-grained locking, like on each bucket?
  - Not wrong, but likely not worth it due to low contention

In Java

- Java's **`synchronized`** statement does not support readers/writer
- Instead, library
  - **`java.util.concurrent.locks.ReentrantReadWriteLock`**
- Different interface
  - methods **`readLock`** and **`writeLock`** return objects that themselves have **`lock`** and **`unlock`** methods
- Does *not* have writer priority or reader-to-writer upgrading
  - Always read the documentation

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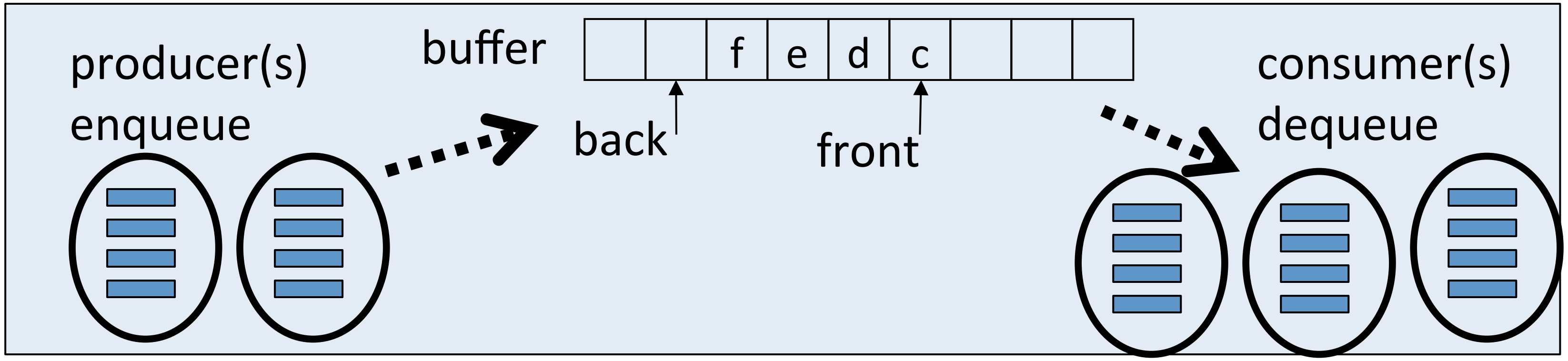
Motivating Condition Variables

- To motivate condition variables, consider the canonical example of a bounded buffer for sharing work among threads



- Bounded buffer: A queue with a fixed size
  - (Unbounded still needs a condition variable, but 1 instead of 2)
- For sharing work – think an assembly line:
  - Producer thread(s) do some work and enqueue result objects
  - Consumer thread(s) dequeue objects and do next stage
  - Must synchronize access to the queue

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Code, attempt 1

```
class Buffer<E> {
  E[] array = (E[])new Object[SIZE];
  … // front, back fields, isEmpty, isFull methods
  synchronized void enqueue(E elt) {
    if(isFull())
      ???
    else
      … add to array and adjust back …
  }
  synchronized E dequeue()
    if(isEmpty())
      ???
    else
      … take from array and adjust front …
  }
}
```

Waiting

- **`enqueue`** to a full buffer should *not* raise an exception
  - Wait until there is room
- **`dequeue`** from an empty buffer should *not* raise an exception
  - Wait until there is data

```
void enqueue(E elt) {
  while(true) {
    synchronized(this) {
      if(isFull()) continue;
      … add to array and adjust back …
      return;
}}}
// dequeue similar
```

- Bad approach is to *spin* (wasted work and keep grabbing lock)

What we want

- Better would be for a thread to *wait* until it can proceed
  - Be *notified* when it should try again
  - In the meantime, let other threads run
- Like locks, not something you can implement on your own
  - Language or library gives it to you, typically implemented with operating-system support
- An ADT that supports this: condition variable
  - Informs waiter(s) when the *condition* that causes it/them to wait has *varied*
- Terminology not completely standard; will mostly stick with Java

Java approach: not quite right

```
class Buffer<E> {
  …
  synchronized void enqueue(E elt) {
    if(isFull())
      this.wait(); // releases lock and waits
    add to array and adjust back
    if(buffer was empty)
      this.notify(); // wake somebody up
  }
  synchronized E dequeue() {
    if(isEmpty())
      this.wait(); // releases lock and waits
    take from array and adjust front
    if(buffer was full)
      this.notify(); // wake somebody up
  }
}
```

Key ideas

- Java weirdness: every object "is" a condition variable (and a lock)
  - other languages/libraries often make them separate
- `wait`:
  - "register" running thread as interested in being woken up
  - then atomically: release the lock and block
  - when execution resumes, *thread again holds the lock*
- `notify`:
  - pick one waiting thread and wake it up
  - no guarantee woken up thread runs next, just that it is no longer blocked on the *condition* – now waiting for the *lock*
  - if no thread is waiting, then do nothing

Bug #1

- Between the time a thread is notified and it re-acquires the lock, the condition can become false again!

```
synchronized void enqueue(E elt){
  if(isFull())
    this.wait();
  add to array and adjust back
  …
}
```

Thread 1 (enqueue)	Thread 2 (dequeue)	Thread 3 (enqueue)
`if(isFull())` `this.wait();`		
	take from array `if(`*was full*`)` `this.notify();`	
		make full again
add to array		

Time ↓

Bug fix #1

- Guideline: *Always* re-check the condition after re-gaining the lock
  - In fact, for obscure reasons, Java is technically allowed to notify a thread *spuriously* (i.e., for no reason)

```
synchronized void enqueue(E elt) {
  while(isFull())
    this.wait();
  …
}
synchronized E dequeue() {
  while(isEmpty())
    this.wait();
  …
}
```

Bug #2

- If multiple threads are waiting, we wake up only one
  - Sure only one can do work *now*, but can't forget the others!

Time ↓

Thread 1 (enqueue)

```
while(isFull())
   this.wait();

…
```

Thread 2 (enqueue)

```
while(isFull())
   this.wait();

…
```

Thread 3 (dequeues)

```
// dequeue #1
if(buffer was full)
   this.notify();

// dequeue #2
if(buffer was full)
   this.notify();
```

Bug fix #2

- **`notifyAll`** wakes up all current waiters on the condition variable

```
synchronized void enqueue(E elt) {
   …
   if(buffer was empty)
      this.notifyAll(); // wake everybody up
}
synchronized E dequeue() {
   …
   if(buffer was full)
      this.notifyAll(); // wake everybody up
}
```

- Guideline: If in any doubt, use **`notifyAll`**
  - Wasteful waking is better than never waking up
- So why does **`notify`** exist?
  - Well, it is faster when correct…

Alternate approach

- An alternative is to call **`notify`** (not **`notifyAll`**) on every **`enqueue`** / **`dequeue`**, not just when the buffer was empty / full
  - Easy: just remove the **`if`** statement
- Alas, makes our code subtly wrong since it is technically possible that an **`enqueue`** and a **`dequeue`** are both waiting
- Details for the curious:
  - Buffer is full and then > **`SIZE`** **`enqueue`** calls wait
  - So each **`dequeue`** wakes up one **`enqueue`**, but maybe so many **`dequeue`** calls happen so fast that the buffer is empty and a **`dequeue`** call waits
  - Then a **`dequeue`** may wake a **`dequeue`**, but now everybody will wait forever
- Works fine if buffer is unbounded since then only dequeuers wait

Alternate approach fixed

- The alternate approach works if the enqueuers and dequeuers wait on *different* condition variables
  - But for mutual exclusion both condition variables must be associated with the same lock
- Java's "everything is a lock / condition variable" does not support this: each condition variable is associated with itself
- Instead, Java has classes in **`java.util.concurrent.locks`** for when you want multiple conditions with one lock
  - **`class ReentrantLock`** has a method **`newCondition`** that returns a new **`Condition`** object associate with the lock
  - See the documentation if curious

Last condition-variable comments

- **`notify/notifyAll`** often called **`signal/ broadcast`**, also called **`pulse/pulseAll`**
- Condition variables are subtle and harder to use than locks
- But when you need them, you need them
  - Spinning and other work-arounds do not work well
- Fortunately, like most things in a data-structures course, the common use-cases are provided in libraries written by experts
  - Example: **`java.util.concurrent.ArrayBlockingQueue<E>`**
  - All uses of condition variables hidden in the library; client just calls **put** and **take**

Concurrency summary

- Access to shared resources introduces new kinds of bugs
  - Data races
  - Critical sections too small
  - Critical sections use wrong locks
  - Deadlocks
- Requires synchronization
  - Locks for mutual exclusion (common, various flavors)
  - Condition variables for signaling others (less common)
- Guidelines for correct use help avoid common pitfalls
- Is shared-memory worth the pain?
  - Other models (e.g., message passing) are not a panacea!

The Java Memory Model

- The memory model semantics create a partial ordering on
  - memory operations: read field, write field, lock, unlock
  - other thread operations: start and join

  where some actions are said to happen before other operations.

- When one action happens before another, the first is guaranteed to be ordered before and visible to the second.

The Java Memory Model

1. Acquiring a lock and entering a synchronized block forces the thread to refresh data from memory.
2. Upon exiting the synchronized block, data written is flushed to memory.

- This ensures that values written by a thread in a synchronized block are visible to other threads in synchronized blocks.

The Java Memory Model

1. Every action in a thread happens before every other action that comes after it in the thread.
2. An unlock on a monitor happens before a subsequent lock on the same monitor.
3. A volatile write on a variable happens before a subsequent volatile read on the same variable.
4. A call to Thread.start() happens before any other statement in that thread.
5. All actions in thread happen before any other thread returns from a join() on that thread.

- The term "action" is defined in section 17.4.2 of the Java language specification as statements that can be detected or influenced by other threads. Normal read/write, volatile read/write, lock/unlock are some actions.

The Java Memory Model

- Rules 1 ,4 and 5 guarantee that within a single thread, all actions will execute in the order in which they appear in the authored program.
- Rules 2 and 4 guarantee that between multiple threads working on shared data, the relative ordering of synchronized blocks and the order of read/writes on volatile variables is preserved.
- Rules 2 and 4 makes volatile very similar to a synchronized block.
  - Prior to JSR 133, volatile still meant that a write to volatile variable is written directly to memory and a read is read from memory.
  - But a compiler could reorder volatile read/writes with non volatile read/writes causing incorrect results. Not possible after JSR 133.
- One additional notable point related to final members that are initialized in the constructor of a class. As long as the constructor completes execution properly, the final members are visible to other threads without synchronization. If you however share the reference to the object from within the constructor, then all bets are off.

The End