ADVANCED JAVA

Concurrency

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The synchronization mechanisms of Java provide ways to accomplish this goal.

Thread safety

Overview of synchronization mechanisms in Java

Intrinsic locks

Atomicity

Sharing and visibility

Manual locking

High-level concurrency abstractions

General concurrency hazards

WHAT IS THREAD SAFETY?

Thread safety may seem as a somewhat vague concept, with suspiciously circular descriptions such as

> *A piece of code is thread-safe if it only manipulates shared data structures in a manner that guarantees safe execution by multiple threads at the same time.*
> [https://en.wikipedia.org/wiki/Thread_safety]

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- Running `lst.add(x)` and `lst.add(y)` concurrently should result in a list containing `x` and `y` at the end, in some order.
- If e.g. one of the elements is lost, then `ArrayList` is not thread-safe.

A SOMEWHAT MORE PRECISE NOTION OF THREAD-SAFETY

A class is thread-safe *if it behaves correctly when accessed from multiple threads, regardless of the scheduling or interleaving of the execution of those thread by the runtime environment, and with no additional synchronization or other coordination on the part of the calling code.*

[Goetz, p.18]

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To say that a class is thread-safe, you must have a precise idea of what correct behavior is.

Presented in order of preference.

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SYNCHRONIZATION MECHANISMS IN JAVA

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A NEED FOR MUTUAL EXCLUSION

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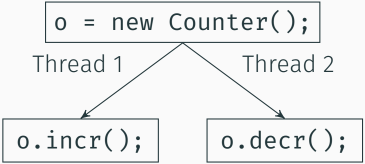

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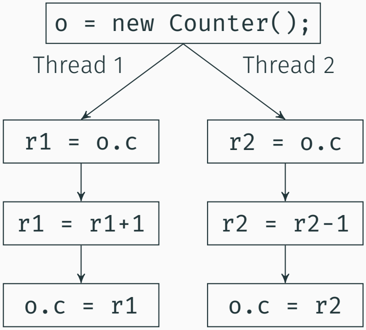

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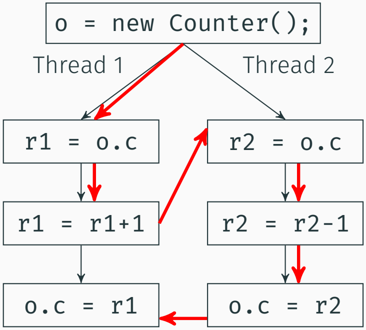

o.c = 1

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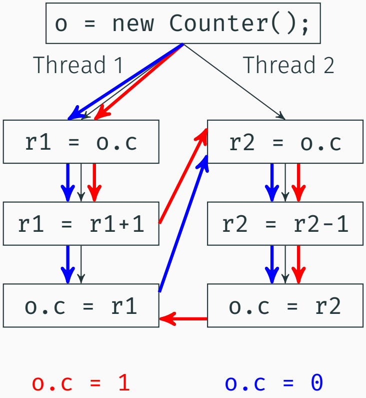

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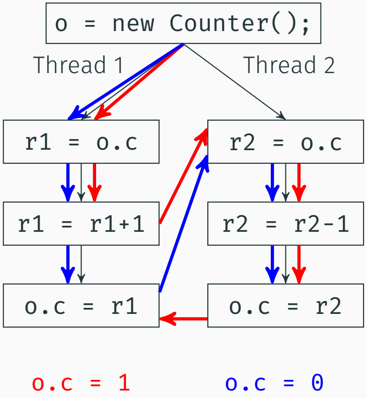

Lost update possible due to interleaving of compound actions.

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- Visibility issues not even taken into account here (details later).

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- Thread must acquire exclusive lock associated with object to enter method body.
- This is known as an intrinsic lock or a monitor lock.
- At most one thread inside any synchronized method at any time.

- Synchronization must be applied to all methods where the `c` field is accessed.

SYNCHRONIZED METHODS, CONTINUED

- Synchronization must be applied to all methods where the `c` field is accessed.

Wrong!

```
class WrongSynchronizedCounter {
  private int c = 0;
  public synchronized void incr() { c++; }
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SYNCHRONIZED METHODS, CONTINUED

- Synchronization must be applied to all methods where the `c` field is accessed.

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Wrong!

- One thread can read `c` while another thread is modifying it.

- General form of `synchronized()` aquires intrinsic lock on arbitrary object.

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synchronized(obj) {
  /* runs while holding lock associated with obj */
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- Synchronized methods syntactic sugar for general form:

```
class Dummy{
  public synchronized void method { /* statements */ }
}
```

is equivalent to

```
class Dummy{
  public void method {
    synchronized(this) { /* statements */ }
  }
}
```

- Use `synchronized` to protect critical regions of code by forcing *serialized* access to data.

INTRINSIC LOCKS

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- `synchronized` is reentrant.
  - Same thread can re-aquire the same lock multiple times.
  - Avoids deadlocks for synchronized methods using recursion, callbacks or inheritance.
- `synchronized` blocks provide more fine-grained concurrency than methods.
  - Also allows for more interleaving. Use with care.

Let’s have a break.

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Intrinsic locks

Atomicity

Sharing and visibility

Manual locking

High-level concurrency abstractions

General concurrency hazards

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- Use caution. While thread-safe, lock-free data structures are notoriously difficult to reason about.
    - See e.g. lock-free queue by Michael & Scott.

```java
import java.util.concurrent.atomic.AtomicInteger;

class AtomicCounter {
  private AtomicInteger c;
  public void incr() {
    c.incrementAndGet();
  }
  public void decr() {
    c.decrementAndGet();
  }
  public int value() {
    return c.get();
  }
  public AtomicCounter() {
    this.c = new AtomicInteger();
  }
}
```

"If you can write a high-performance JVM for a modern microprocessor, then you are qualified to think about whether you can avoid synchronizing."

SEQUENTIAL CONSISTENCY

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invisible! $R(x)\ 0$ $W(y)\ 0$

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- Not how modern architectures work. Visibility not guaranteed!

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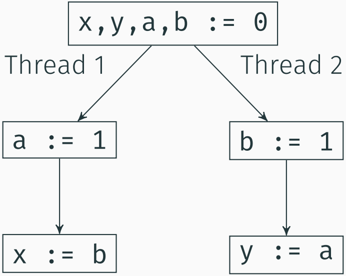

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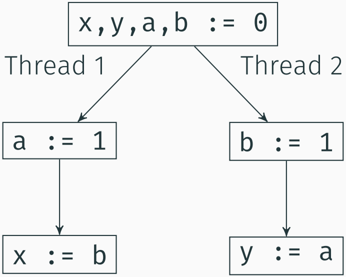

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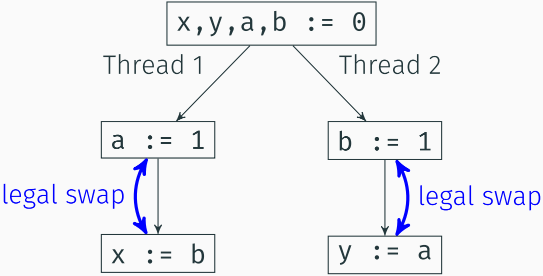

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- No within-thread data dependencies, so reordering is legal.

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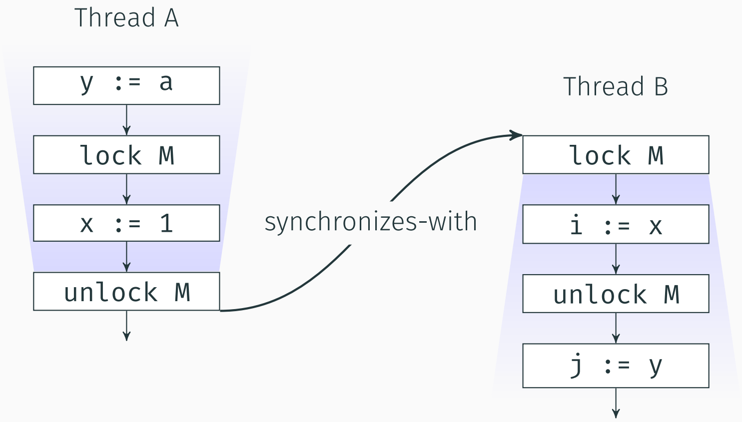
- Luckily, Java guarantees sequential consistency for programs that are correctly synchronized.
- This notion has a clear definition.

Synchronization establishes causality between actions.



All state modifications before the unlock of `M` are visible to all actions coming after the lock of `M`.

HAPPENS-BEFORE

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  - `t.start()` happens-before the thread `t` starts executing.
  - Thread termination for a thread `t` happens-before `t.join()`.
  - A volatile write happens-before a volatile read of the same variable.
  - … (see supplementary material, JSR-133)

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  - A volatile write happens-before a volatile read of the same variable.
  - ... (see supplementary material, JSR-133)
- A program is correctly synchronized if for all sequential executions and for every action `r` reading variable *v*, the most recent write to *v* happens-before `r`.

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Prefer `java.util.concurrent` over manual synchronization.

```java
class NoVisibility extends Thread {
    boolean stop = false;

    public static void main(String[] args) {
        NoVisibility t = new NoVisibility();
        t.start();
        Thread.sleep(1000);
        t.stop = true;
        System.out.println("Waiting for thread to stop");
        t.join();
    }
    public void run() {
        while (!stop) {}
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VOLATILE VARIABLES

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Wrong!

Correct

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    - Thread-safe classes from `java.util.concurrent`.
2. **Low level locking.** Provides blocking synchronization.
    - `synchronized` methods and blocks.
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3. **Low level primitives.** Provides non-blocking synchronization.
    - Volatile variables.
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Prefer `java.util.concurrent` over manual synchronization.

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- Locks have the same memory visibility guarantees as `synchronized` and `volatile`.
- Why manual locking when `synchronized` seems to work fine?
    - There is no way to interrupt a `synchronized` waiting for a lock.
    - Cannot specify a wait timeout for `synchronized` blocks.
    - Acquire/release must occur in the same block. Also defined statically.

The `java.util.concurrent.locks` package provide explicit locking mechanisms.

```
public interface Lock {
    void lock();
    void lockInterruptibly()
      throws InterruptedException;
    boolean tryLock();
    boolean tryLock(long time, TimeUnit unit)
      throws InterruptedException;
    void unlock();
    Condition newCondition();
}
```

- Always wrap critical region in `try-finally`.

```
class Dummy {
  public void f() {
    Lock lock = new ReentrantLock();
    /* ... */
    lock.lock();
    try {
     /* update object state */
    }
    finally { lock.unlock(); }
  }
}
```

- Failing to do so is a ticking bomb – deadlocks will happen on exceptions.
- Not necessary when code is guaranteed not to throw exceptions.

```java
class LockedCounter {
    private ReentrantLock lock = new ReentrantLock();
    private int c = 0;
    public void incr() {
        lock.lock();
        c++;
        lock.unlock();
    }
    public void decr() {
        lock.lock();
        c--;
        lock.unlock();
    }
    public int value() {
        lock.lock();
        return this.c;
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    }
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EXAMPLE

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Wrong!

EXAMPLE

Correct

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        int temp;
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        temp = this.c;
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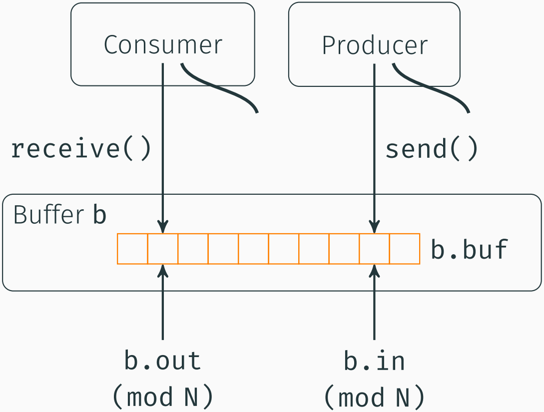
```

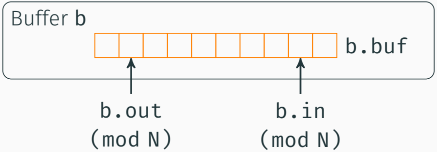

Consumer
Producer
receive()
send()
Buffer b
b.buf
b.out
(mod N)
b.in
(mod N)

BOUNDED BUFFER PSEUDOCODE

(Assume visibility of all writes)

```
def send(b, msg):
  while b.in - b.out == N: do nothing
  b.buf[b.in mod N] := msg
  b.in := b.in + 1

def receive(b):
  while b.in = b.out: do nothing
  msg := b.buf[b.out mod N]
  b.out := b.out + 1
  return msg
```



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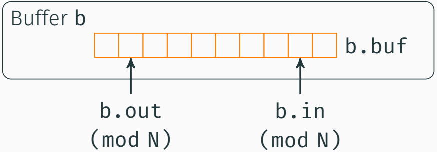
Race condition if more than one producer



BUSY WAITING

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- Keep polling a condition across threads.
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- Keep polling a condition across threads.
- Wastes machine cycle with useless work due to polling if the condition is not satisfied.
- Implementing bounded buffer by busy waiting:
    - Lock free implementation possible $\rightarrow$ low synchronization overhead.
    - We will have to use locks to support multiple producers/consumers.
    - Will waste CPU cycles if producer and consumer does not work at same pace, or if throughput low.

See `BusyWaitBoundedBuffer.java` in handout material.

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1. If you suspend a thread, respond to interrupts.
2. Thread safety is relative to specification/usage. Document the supported threading scenarios.

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```
class Object {
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  - *t* was interrupted.
  - Spurious wake (rare, but possible).

wait/notify: correct usage

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- It is an error to call `wait()` or `notify()` outside a `synchronized` block.
- Due to possibility of spurious wakes, always *spin* on a wait condition:

```
synchronized(obj) {
  while (!condition) { obj.wait(); }
}
```

See `WaitNotifyBoundedBuffer.java` in handout material.

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- Condition objects created via `Lock` interface.
- Can be seen as a fine-grained wait/notify mechanism:
    - `wait()` $\simeq$ `await()`
    - `notify()` $\simeq$ `signal()`
    - `notifyAll()` $\simeq$ `signalAll()`
- Optimized syntactic sugared version of wait/notify.

BOUNDEDBUFFER WITH CONDITION OBJECTS

See `ConditionBoundedBuffer.java` in handout material.

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- They are correct and fast – **use them before rolling your own concurrency abstraction!**

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    - Compound actions still require synchronization!

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- Great for safe, throttled communication between threads.

SYNCHRONIZERS

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Barriers. Similar to latches, but may be reset. All threads must meet at a particular point in time. Often used in simulations. See `CyclicBarrier`, `Exchanger`.

LIVENESS

- Safety: *"Nothing bad ever happens"*.
- Liveness: *"Something good eventually happens"*.

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- Liveness: *"Something good eventually happens"*.
- Hazards to liveness:

Deadlock Threads wait for each other indefinitely, making no progress.

Starvation A thread needs a resource but is persistently denied access to it.

Livelock A thread does not make progress because it persistently fails and retries an operation. May happen with e.g. *optimistic concurrency*.

Synchronization is hard - try not to be too clever. Use existing abstractions when possible.