Principles of Software Construction: Objects, Design, and Concurrency

Concurrency – part 2

Synchronization, communication, and liveness

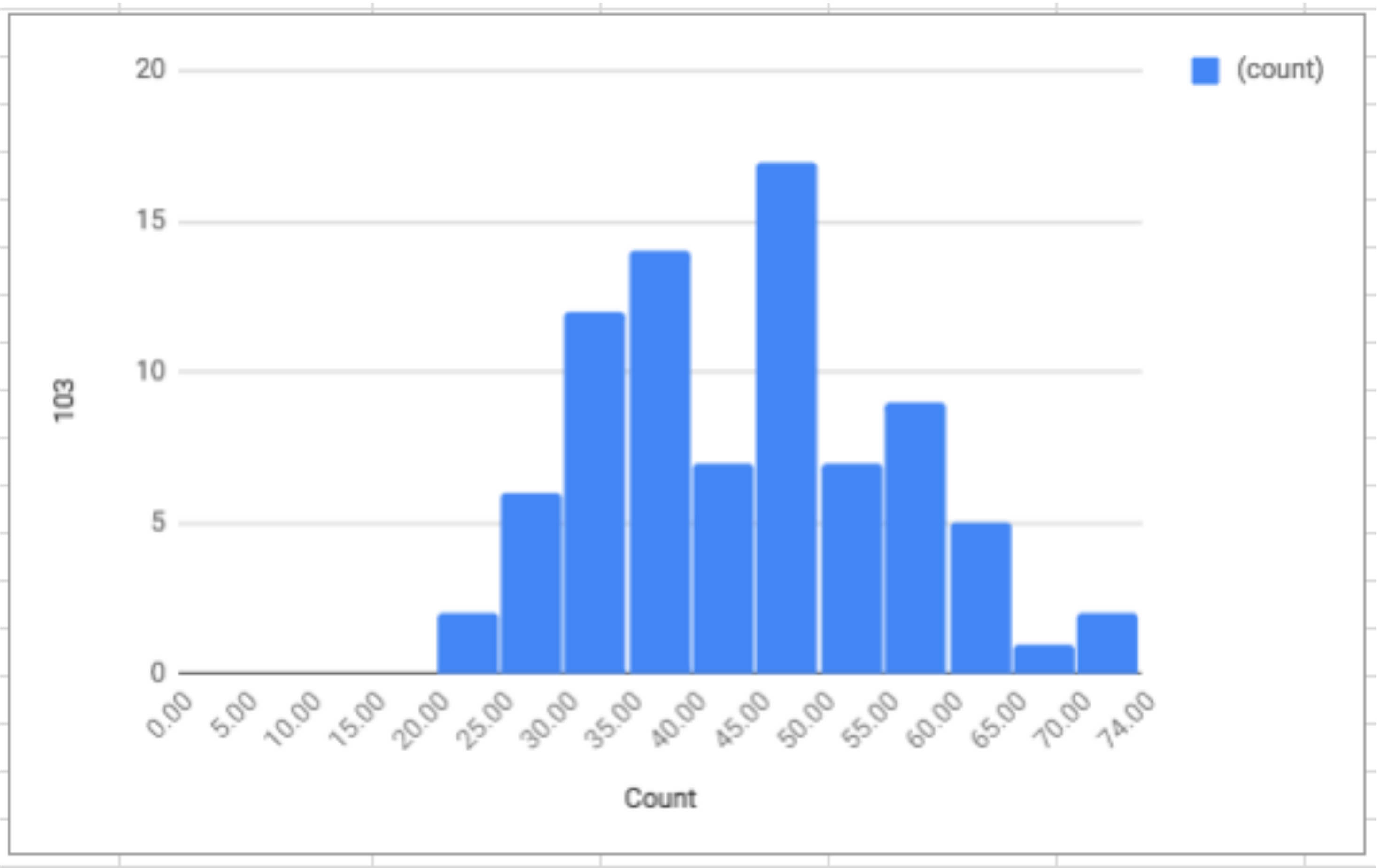
Josh Bloch Charlie Garrod Darya Melicher

Administrivia

- Reading due today
  - Java Concurrency in Practice, Sections 11.3 and 11.4
- Homework 5a due tomorrow
- 2nd midterm exam returned today, after class
- Oh, and one more thing…


VOTE

Midterm 2 statistics



Mean raw score was 44 / 85

Problem 2 – Boolean expressions

- Many people misinterpreted this problem
- You had to write a library to **represent** Boolean expressions
  - In other words, to allow clients to create & use Boolean expression objects
- Boolean expressions were defined (recursively) as
  - The constant expressions *true* and *false*
  - The unary expression *!x*, where *x* is a Boolean expression
  - The binary expressions *x* & y and *x* | *y*, where *x* and *y* are Boolean expressions
- Instances had to support two functions
  - Compute the `boolean` value to which the expression evaluates
    - e.g., the value of (true | false) & !(true and false) is `true`
  - Convert the expression into an unambiguous string representation
    - e.g., `"((true | false) & !(true and false))"`
- You had to support new operators without modifying library

The most common correct solution (1/3)

```
public interface BooleanExpression {
    boolean eval();
    // You don't need toString in interface; all objects have it
}

public final class ConstantExpression implements BooleanExpression {
    private final boolean val;

    public ConstantExpression2(boolean val) {
        this.val = val;
    }

    @Override public boolean eval() {
        return val;
    }

    @Override public String toString() {
        return String.valueOf(val);
    }
}
```

The most common correct solution (2/3)

```
public final class NotExpression implements BooleanExpression {
    private final BooleanExpression op;

    public NotExpression(BooleanExpression op) {
        this.op = Objects.requireNonNull(op);
    }

    @Override public boolean eval() {
        return !op.eval();
    }

    @Override public String toString() {
        return "!" + op.toString();
    }
}

// And a similar class for AndExpression, OrExpression
```

The most common correct solution (3/3)

```
public final class XorExpression implements BooleanExpression {
    private final BooleanExpression op1, op2;

    public XorExpression(BooleanExpression op1, BooleanExpression op2) {
        this.op1 = Objects.requireNonNull(op1);
        this.op2 = Objects.requireNonNull(op2);
    }

    @Override public boolean eval() {
        return op1.eval() ^ op2.eval();
    }

    @Override public String toString() {
        return String.format("(%s ^ %s)", op1, op2);
    }
}
```

Critique of previous solution

- Not bad!
  - Fully solved the problem, and earned most of the points
- But could be shorter, and achieve better code reuse
- What's the major source of code duplication?
  - Hint: would get worse if we added functionality to `BooleanExpression`
- How do you fix it?
- How could `ConstantExpression` be made (much) shorter?

Improved solution – adds binary operator interface (1/3)

Retains `BooleanExpression` *interface and* `NotExpression` *from previous solution*

```
public enum ConstantExpression implements BooleanExpression {
    TRUE, FALSE;
    public boolean eval() { return this == TRUE; }
}

public interface BinaryOperator {
    boolean apply(boolean operand1, boolean operand2);
}

public enum BasicBinaryOperator2 implements BinaryOperator {
  AND { public boolean apply(boolean op1, boolean op2) { return op1 && op2; }},
  OR  { public boolean apply(boolean op1, boolean op2) { return op1 || op2; }};
}
```

Improved solution – binary expression (2/3)

```
public final class BinaryExpression implements BooleanExpression {
    private final BinaryOperator operator;
    private final BooleanExpression op1, op2;

    public BinaryExpression(BooleanExpression op1,
            BinaryOperator operator, BooleanExpression op2) {
        this.operator = Objects.requireNonNull(operator);
        this.op1 = Objects.requireNonNull(op1);
        this.op2 = Objects.requireNonNull(op2);
    }

    @Override public boolean eval() {
        return operator.apply(op1.eval(), op2.eval());
    }

    @Override public String toString() {
        return String.format("(%s %s %s)", op1, operator, op2);
    }
}
```

Improved solution – Part b (3/3)

```
public class XorOperator implements BinaryOperator {
    private XorOperator() { }  // Singleton
    public static final XorOperator XOR = new XorOperator();

    @Override public boolean apply(boolean op1, boolean op2) {
        return op1 ^ op2;
    }

    @Override public String toString() { return "^"; }
}
```

Alternative `BasicBinaryOperator` enum

No instance-specific class bodies, nicer string form

```
public enum BasicBinaryOperator implements BinaryOperator {
    AND((op1, op2) -> op1 & op2, "&"),
    OR( (op1, op2) -> op1 | op2, "|");

    private final BinaryOperator function;
    private final String symbol;

    BasicBinaryOperator(BinaryOperator function, String symbol) {
        this.function = function;
        this.symbol = symbol;
    }

    @Override public boolean apply(boolean op1, boolean op2) {
        return function.apply(op1, op2);
    }

    @Override public String toString() { return symbol; }
}
```

Sample program and its output

```
public class Sample {
    public static void main(String[] args) {
        BooleanExpression e1 = new BinaryExpression(TRUE, OR, FALSE);
        BooleanExpression e2 = new BinaryExpression(FALSE, OR, TRUE);
        BooleanExpression e3 = new BinaryExpression(e1, AND, e2);
        print(e3);
        BooleanExpression e4 = new NotExpression(e2);
        print(e4);
        print(new BinaryExpression(e3, XOR, e4));
    }

    private static void print(BooleanExpression e1) {
        System.out.printf("%s = %b%n", e1, e1.eval());
    }
}
```

```
((TRUE | FALSE) & (FALSE | TRUE)) = true
!(FALSE | TRUE) = false
(((TRUE | FALSE) & (FALSE | TRUE)) ^ !(FALSE | TRUE)) = true
```

The main design pattern: Composite!

- Definition: “Compose objects into **tree structures** to represent part-whole hierarchies. Composite **lets clients treat individual objects and compositions of objects uniformly.**”
- Boolean constants are the “individual objects”
- Operations (unary and binary) are the “Compositions”
- This is a textbook example of the pattern
- Just because it uses an interface doesn't make it strategy pattern
  - `BinaryExpression` / `BinaryOperator` solution uses strategy, too
  - But not many of you did that solution

Lessons from problem 2

- Don’t start work on a problem until you understand it
  - **If you’re not sure, ask!**
- If you think a solution will be long/reprepetitious, ask yourself:
  - **What code is repeated? How could I “factor it out”?**
- If a type has only a few, known, instances, consider an enum
  - Generally prefer instance-specific data to class-bodies
  - But feel free to make exceptions where it works

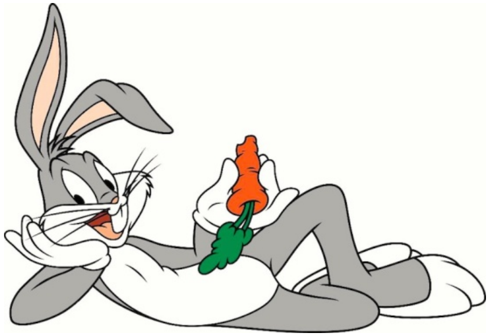
Problem 3 – Bus info system design

- Major design decision: should routes/stops be mutable or immutable?
- Implications of this decision permeate design.
- **All design principles suggest immutable!**
- Arguments for mutability were generally flawed
- Adding responsibility for publishing or subscription-tracking to bus route
  - **Decreases** cohesion
  - **Increases** representational gap
  - Unlikely to improve performance
  - **Let a bus route be a bus route!**
- Maintain a `Map<BusRoute, Set<Subscriber>>` (or some such)

Key concepts from last Thursday

Example: Money-grab

```
public static void main(String[] args) throws InterruptedException
   {
    BankAccount bugs = new BankAccount(100);
    BankAccount daffy = new BankAccount(100);

    Thread bugsThread = new Thread(()-> {
        for (int i = 0; i < 1_000_000; i++)
            transferFrom(daffy, bugs, 100);
    });

    Thread daffyThread = new Thread(()-> {
        for (int i = 0; i < 1_000_000; i++)
            transferFrom(bugs, daffy, 100);
    });

    bugsThread.start(); daffyThread.start();
    bugsThread.join(); daffyThread.join();
    System.out.println(bugs.balance() + daffy.balance());
}
```



Example: Money-grab

Broken – What's wrong?

```
public class BankAccount {
    private long balance;

    public BankAccount(long balance) {
        this.balance = balance;
    }
    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        source.balance -= amount;
        dest.balance   += amount;
    }
    public long balance() {
        return balance;
    }
}
```

Outline (such as it is) for today's lecture

I. Serial number generation example
II. Cooperative thread termination example
III. Liveness and deadlock

I. Example: serial number generation

What would you expect this to print?

```
public class SerialNumber {
    private static long nextSerialNumber = 0;

    public static long generateSerialNumber() {
        return nextSerialNumber++;
    }

    public static void main(String[] args) throws InterruptedException {
        Thread threads[] = new Thread[5];
        for (int i = 0; i < threads.length; i++) {
            threads[i] = new Thread(() -> {
                for (int j = 0; j < 1_000_000; j++)
                    generateSerialNumber();
            });
            threads[i].start();
        }
        for(Thread thread : threads) thread.join();
        System.out.println(generateSerialNumber());
    }
}
```

What went wrong?

- The ++ (increment) operator is not atomic!
  - It reads a field, increments the value, and writes it back
- If multiple calls to `generateSerialNumber` see the same value, they generate duplicates

The fix is easy

```
public class SerialNumber {
    private static int nextSerialNumber = 0;

    public static synchronized int generateSerialNumber() {
        return nextSerialNumber++;
    }

    public static void main(String[] args) throws InterruptedException{
        Thread threads[] = new Thread[5];
        for (int i = 0; i < threads.length; i++) {
            threads[i] = new Thread(() -> {
                for (int j = 0; j < 1_000_000; j++)
                    generateSerialNumber();
            });
            threads[i].start();
        }
        for(Thread thread : threads) thread.join();
        System.out.println(generateSerialNumber());
    }
}
```

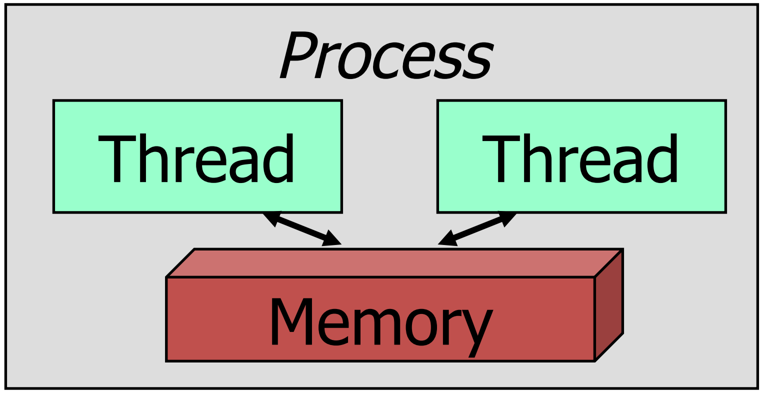
But you can do better!

`java.util.concurrent` *is your friend*

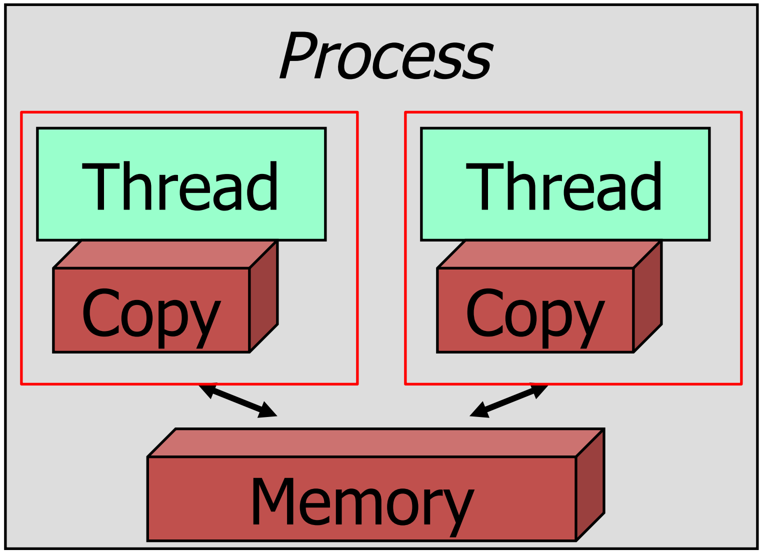
```
public class SerialNumber {
    private static AtomicLong nextSerialNumber = new AtomicLong();

    public static long generateSerialNumber() {
        return nextSerialNumber.getAndIncrement();
    }

    public static void main(String[] args) throws InterruptedException {
        Thread threads[] = new Thread[5];
        for (int i = 0; i < threads.length; i++) {
            threads[i] = new Thread(() -> {
                for (int j = 0; j < 1_000_000; j++)
                    generateSerialNumber();
            });
            threads[i].start();
        }
        for(Thread thread : threads) thread.join();
        System.out.println(generateSerialNumber());
    }
}
```

Aside: Hardware abstractions

- Supposedly:
  - Thread state shared in memory



- A (slightly) more accurate view:
  - Separate state stored in registers and caches, even if shared



Atomicity

- An action is *atomic* if it is indivisible
  - Effectively, it happens all at once
    - No effects of the action are visible until it is complete
    - No other actions have an effect during the action
- In most languages (including java) increment is *not* atomic

`val++;` is actually

1. **Load** data from field `val`
2. Increment data by **1**
3. **Store** data to field `val`

Some actions are atomic

Precondition:

```
int i == 7;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

Some actions are atomic

Precondition:

```
int i == 7;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

ans: 00000…00000111

ans: 00000…00101010

Some actions are atomic

Precondition:

```
int i == 7;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

- What are the possible values for `ans`?

`ans:` `00000…00000111`

`ans:` `00000…00101010`

- In Java:
  - Reading an `int` field is atomic
  - Writing an `int` field is atomic
  - Thankfully, `ans:` `00000…00101111` is not possible

Bad news: some simple actions are not atomic

- Consider a single 64-bit `long` value

high bits	low bits

  - Concurrently:
    - Thread A writing high bits and low bits
    - Thread B reading high bits and low bits

Precondition:

```
long i == 10_000_000_000;
```

Thread A:

```
i = 42;
```

Thread B:

```
ans = i;
```

ans:	**01001…00000000**	**(10,000,000,000)**
ans:	**00000…00101010**	**(42)**
ans:	**01001…00101010**	**(10,000,000,042)**

But none of this matters if you synchronize access to any shared mutable state!

II. Another example: cooperative thread termination

```
public class StopThread {
    private static boolean stopRequested;

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested)
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(10);
        stopRequested = true;
    }
}
```

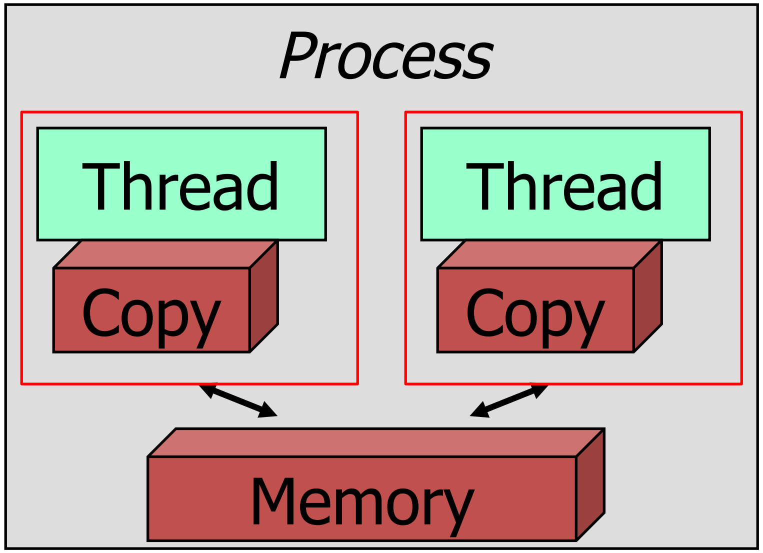
What went wrong?

- **In the absence of synchronization, there is no guarantee as to when, if ever, one thread will see changes made by another!**
- JVMs can and do perform this optimization:

```
while (!done)
    /* do something */ ;
```

becomes:

```
if (!done)
    while (true)
        /* do something */ ;
```



How do you fix it?

```
public class StopThread {
    private static boolean stopRequested;
    private static synchronized void requestStop() {
        stopRequested = true;
    }

    private static synchronized boolean stopRequested() {
        return stopRequested;
    }

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested())
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(10);
        requestStop();
    }
}
```

A better(?) solution

volatile *is synchronization without mutual exclusion*

```
public class StopThread {
    private static volatile boolean stopRequested;

    public static void main(String[] args) throws Exception {
        Thread backgroundThread = new Thread(() -> {
            while (!stopRequested)
                /* Do something */ ;
        });
        backgroundThread.start();

        TimeUnit.SECONDS.sleep(10);
        stopRequested = true;
    }
}
```

Outline for today's lecture

I. Serial number generation example
II. Cooperative thread termination example
III. Liveness and deadlock

A liveness problem: poor performance

```
public class BankAccount {
    private long balance;

    public BankAccount(long balance) {
        this.balance = balance;
    }
    static synchronized void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        source.balance -= amount;
        dest.balance   += amount;
    }
    public synchronized long balance() {
        return balance;
    }
}
```

Equivalent to code on previous slide

```
public class BankAccount {
    private long balance;

    public BankAccount(long balance) {
        this.balance = balance;
    }
    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        synchronized(BankAccount.class) {
            source.balance -= amount;
            dest.balance   += amount;
        }
    }
    public synchronized long balance() {
        return balance;
    }
}
```

A proposed fix: *lock splitting*

```
public class BankAccount {
    private long balance;

    public BankAccount(long balance) {
        this.balance = balance;
    }
    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        synchronized(source) {
            synchronized(dest) {
                source.balance -= amount;
                dest.balance   += amount;
            }
        }
    }
    …
}
```

A liveness problem: deadlock

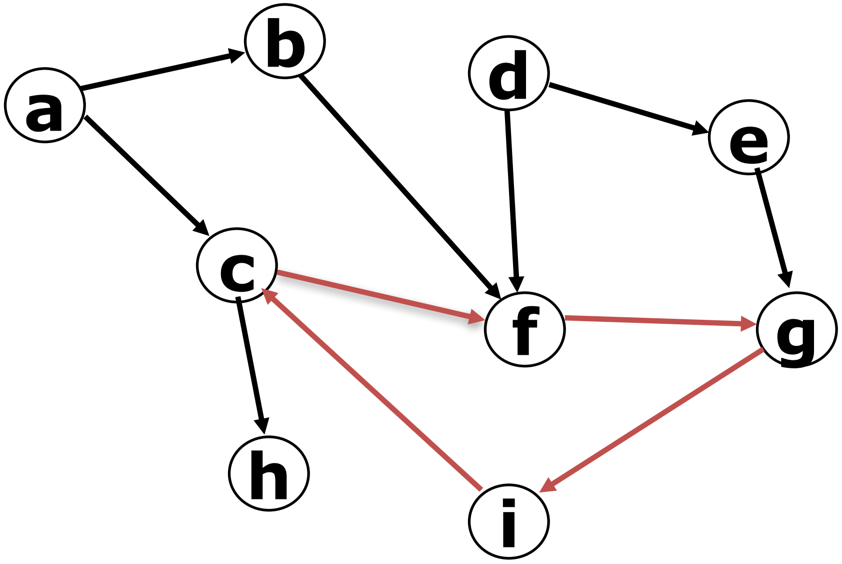
- A possible interleaving of operations:
  - `bugsThread` locks the `daffy` account
  - `daffyThread` locks the `bugs` account
  - `bugsThread` attempts to lock the `bugs` account…
  - `daffyThread` attemps to lock the `daffy` account…

A liveness problem: deadlock

```
public class BankAccount {
    private long balance;

    public BankAccount(long balance) {
        this.balance = balance;
    }
    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
        synchronized(source) {
            synchronized(dest) {
                source.balance -= amount;
                dest.balance   += amount;
            }
        }
    }
    …
}
```

Avoiding deadlock

- The *waits-for graph* represents dependencies between threads
  - Each node in the graph represents a thread
  - An edge T1->T2 represents that thread T1 is waiting for a lock T2 owns
- Deadlock has occurred iff the waits-for graph contains a cycle
- One way to avoid deadlock: locking protocols that avoid cycles



Avoiding deadlock by ordering lock acquisition

```
public class BankAccount {
    private long balance;
    private final long id = SerialNumber.generateSerialNumber();

    public BankAccount(long balance) {
        this.balance = balance;
    }

    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
    BankAccount first = source.id < dest.id ? source : dest;
    BankAccount second = first == source ? dest : source;
    synchronized (first) {
        synchronized (second) {
            source.balance -= amount;
            dest.balance += amount;
        }
    }
}
```

Another subtle problem: The lock object is exposed

```
public class BankAccount {
    private long balance;
    private final long id = SerialNumber.generateSerialNumber();

    public BankAccount(long balance) {
        this.balance = balance;
    }

    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
    BankAccount first = source.id < dest.id ? source : dest;
    BankAccount second = first == source ? dest : source;
    synchronized (first) {
        synchronized (second) {
            source.balance -= amount;
            dest.balance += amount;
        }
    }
}
```

An easy fix: Use a private lock

```
public class BankAccount {
    private long balance;
    private final long id = SerialNumber.generateSerialNumber();
    private final Object lock = new Object();

    public BankAccount(long balance) {
        this.balance = balance;
    }

    static void transferFrom(BankAccount source,
                             BankAccount dest, long amount) {
    BankAccount first = source.id < dest.id ? source : dest;
    BankAccount second = first == source ? dest : source;
    synchronized (first.lock) {
        synchronized (second.lock) {
            source.balance -= amount;
            dest.balance += amount;
        }
    }
}
```

Concurrency and information hiding

- Encapsulate an object's state: Easier to implement invariants
  - Encapsulate synchronization: Easier to implement synchronization policy

Summary

- Like it or not, you're a concurrent programmer
- **Ideally, avoid shared mutable state**
- If you can't avoid it, synchronize properly
  - Failure to do so causes safety and liveness failures
  - **If you don't synchronize properly, your program won't work**
- Even atomic operations require synchronization
  - e.g., `stopRequested = true;`
  - And some things that look atomic aren't (e.g., `val++`)
- If you use locks, watch out for deadlock!
  - Resource-ordering required for multiple locks