Static Analysis for Safe Concurrency

Optional Reading: ***Assuring and Evolving Concurrent Programs: Annotations and Policy***

17-355/17-655: Program Analysis

Jonathan Aldrich

Example: java.util.logging.Logger

[Source: Aaron Greenhouse]

```
public class Logger { ...
  private Filter filter;

  public void setFilter(Filter newFilter) ... {
    if (!anonymous) manager.checkAccess();
    filter = newFilter;
  }

}
```

Consider `setFilter()` in isolation

Example: java.util.logging.Logger

[Source: Aaron Greenhouse]

```
public class Logger { ...
  private Filter filter;

  public void log(LogRecord record) { ...
    synchronized (this) {
      if (filter != null
          && !filter.isLoggable(record)) return;
    } ...
  } ...
}
```

Consider **`log()`** in isolation

Example: java.util.logging.Logger

[Source: Aaron Greenhouse]

```
/** ... All methods on Logger are multi-thread safe. */
public class Logger { ...
  private Filter filter;

  /** ...
   * @param newFilter a filter object (may be null)
   */
  public void setFilter(Filter newFilter) ... {
    if (!anonymous) manager.checkAccess();
    filter = newFilter;
  }

  public void log(LogRecord record) { ...
    synchronized (this) {
      if (filter != null
          && !filter.isLoggable(record)) return;
    } ...
  } ...
}
```

Consider class **Logger** in it's entirety!

Example: java.util.logging.Logger

[Source: Aaron Greenhouse]

```
/** ... All methods on Logger are multi-thread safe. */
public class Logger { ...
  private Filter filter;

  /** ...
   * @param newFilter a filter object (may be null)
   */
  public void setFilter(Filter newFilter)…{
    if (!anonymous) manager.checkAccess();
    filter = newFilter;
  }

  public void log(LogRecord record) { ...
    synchronized (this) {
      if (filter != null
          && !filter.isLoggable(record)) return;
    } ...
  } ...
}
```

1

2

3

Class Logger has a ***race condition***.

Example: java.util.logging.Logger

[Source: Aaron Greenhouse]

```
/** ... All methods on Logger are multi-thread safe. */
public class Logger { ...
  private Filter filter;

  /** ...
   * @param newFilter a filter object (may be null)
   */
  public synchronized void setFilter(Filter newFilter)…{
    if (!anonymous) manager.checkAccess();
    filter = newFilter;
  }

  public void log(LogRecord record) { ...
    synchronized (this) {
      if (filter != null
          && !filter.isLoggable(record)) return;
    } ...
  } ...
}
```

Correction: synchronize `setFilter()`

Example: Summary 1

Problem: Race condition in class **`Logger`**

- ***Race condition*** defined:

  (From Savage et al., *Eraser: A Dynamic Data Race Detector for Multithreaded Programs*)

  - Two threads access the same variable
  - At least one access is a write
  - No explicit mechanism prevents the accesses from being simultaneous

Example: Summary 2

Problem: Race condition in class **`Logger`**

- Non-local error
  - Had to inspect whole class
    - Bad code invalidates good code
  - Could have to inspect all clients of class
- Hard to test
  - Problem occurs non-deterministically
    - Depends on how threads interleave

Example: Summary 3

Problem: Race condition in class **`Logger`**

- Not all race conditions result in errors
- Error results when invariant is violated
  - Logger invariant
    - filter is not null at call following null test
  - Race-related error
    - race between write and dereference of filter
    - if the write wins the race, filter is null at the call

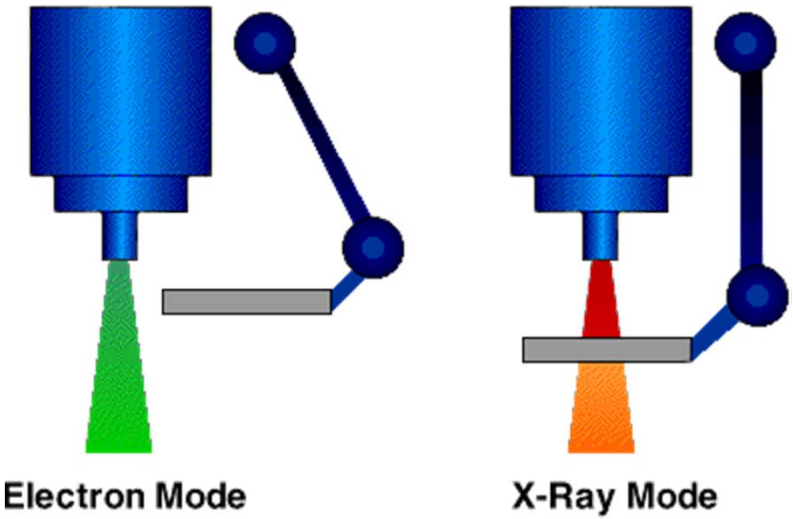
Example: Summary 4

Problem: Race condition in class **`Logger`**

- Need to know ***design intent***
  - *Should instances be used across threads?*
  - *If so, how should access be coordinated?*
    - Assumed **`log`** was correct: **`synchronize`** on **`this`**
    - Could be caller's responsibility to acquire lock
      ⇒ **`log`** is incorrect
      ⇒ Need to check call sites of **`log`** and **`setFilter`**

Software Disasters: Therac-25

- Delivered radiation treatment
- 2 modes
  - Electron: low power electrons
  - X-Ray: high power electrons converted to x-rays with sheild
- Race condition
  - Operator specifies x-ray, then quickly corrects to electron mode
  - Dosage process doesn't see the update, delivers x-ray dose
  - Mode process sees update, removes shield
- Consequences
  - 3 deaths, 3 serious injuries from radiation overdose



from http://www.netcomp.monash.edu.au/cpe9001/assets/readings/HumanErrorTalk6.gif

source: Leveson and Turner, An Investigation of the Therac-25 Accidents, *IEEE Computer*, Vol. 26, No. 7, July 1993.

Thought Experiment

How would you make sure your code avoids race conditions?

- Keep some data local to a single thread
  - Inaccessible to other threads
  - e.g. local variables, Java AWT & Swing, thread state
- Protect shared data with locks
  - Acquire lock before accessing data, release afterwards
  - e.g. Java synchronized, OS kernel locks
- Forbid context switches/interrupts in critical sections of code
  - Ensures atomic update to shared state
  - e.g. many embedded systems, simple single processor OSs
- Analyze all possible thread interleavings
  - Ensure invariants cannot be violated in any execution
  - Does not scale beyond smallest examples
- Future: transactional memory

Thread Locality in the Java AWT

- Event thread
  - Started by the AWT library
  - Invokes user callbacks
    - e.g. to draw a window
- Rules
  - Can create a component from any thread
  - Once component is initialized, can only access from Event thread
  - To access from another thread, register a callback function to be invoked in the Event thread
- Many other GUI libraries have similar rules
  - Microsoft Windows Presentation Foundation: one thread per window
- Why (e.g. vs. locks)?
  - Simple: no need to track relationship between lock and state
  - Predictable: less concurrency in GUI
  - Efficient: acquiring locks is expensive
- Why not?
  - Less concurrency available

Thread Locality: Variations

- Read-only data structures
  - May be freely shared between threads
  - No changes to data allowed

- Ownership transfer
  - Initialize a data structure in thread 1
  - Transfer ownership of data to thread 2
    - Now thread 2 may access the data, but thread 1 may not
    - Transfer may be repeated
    - Note that transfer usually requires synchronization on some other variable

Lock-based Concurrency

- Associate a lock with each shared variable
  - Acquire the lock before all accesses
  - Group all updates necessary to maintain data invariant
  - Hold all locks until update is complete

- Granularity
  - Fine-grained locks allow more concurrency
    - Can be tricky if different parts of a data structure are protected by different—perhaps dynamically created—locks
  - Coarse-grained locks have lower overhead

Deadlock

- Bank transfer
  - Debit one account and credit another
  - (broken) protocol: lock debit account, then credit account
- Deadlock scenario
  - Thread 1 acquires lock A
  - Thread 2 acquires lock B
  - Thread 2 attempts to acquire lock A and waits
  - Thread 1 attempts to acquire lock B and waits
  - Neither thread 1 nor thread 2 may proceed
- Deadlock definition
  - A set of threads that forms a cycle, such that each thread is waiting to acquire a lock held by the next thread

```
thread1() {
  lock(A);          // protects X
  lock(B);          // protects Y
  debit(X);
  credit(Y);
  unlock(B);
  unlock(A);
}

thread2() {
  lock(B);
  lock(A);
  debit(Y);
  credit(X);
  unlock(A);
  unlock(B);
}
```

Dealing with Deadlock

- Lock ordering
  - Always acquire locks in a fixed order
    - Cycles impossible—both thread 1 and thread 2 will attempt to acquire A before B
  - Release locks in the opposite order

- Detect cycles as they form
  - Runtime system checks for cycles when waiting to acquire
    - Expensive in practice, but simplifies development
  - Force one thread in cycle to give up its lock
    - Typically the last thread, or the lowest priority

Disabling interrupts/context switches

- Disable interrupts for critical sections of code
  - Should be short, so that interrupts aren't delayed too long
  - Must be long enough to update shared data consistently
  - Common in single-processor embedded systems
- Why?
  - Cheap, simple, predictable
- Why not?
  - Does not support true multiprocessor concurrency
  - Suspending interrupts can mean missing real time I/O deadlines
  - Like having a global lock: forbids concurrent access even to different data structures

Analyzing All Possible Interleavings

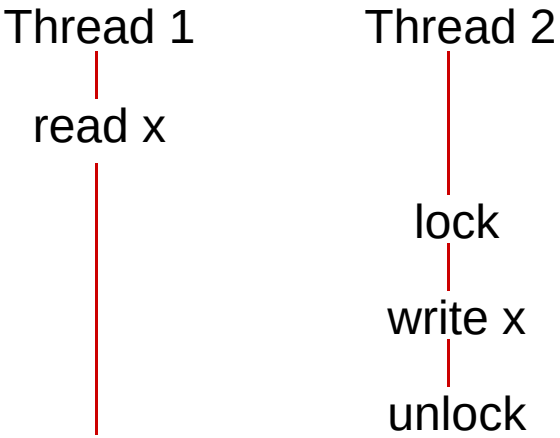
- ***Data race*** defined:

  (From Savage et al., *Eraser: A Dynamic Data Race Detector for Multithreaded Programs*)

  - Two threads access the same variable
  - At least one access is a write
  - No explicit mechanism prevents the accesses from being simultaneous

Analyzing All Possible Interleavings

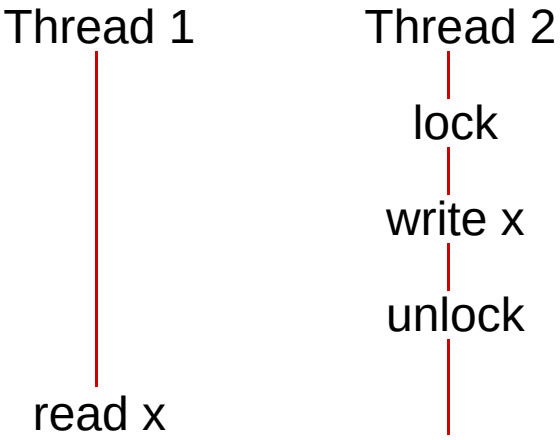
```
thread1() {
    read x;
}
thread2() {
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK

Analyzing All Possible Interleavings

```
thread1() {
    read x;
}
thread2() {
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK
Interleaving 2: OK

Analyzing All Possible Interleavings

```
thread1() {
    read x;
}
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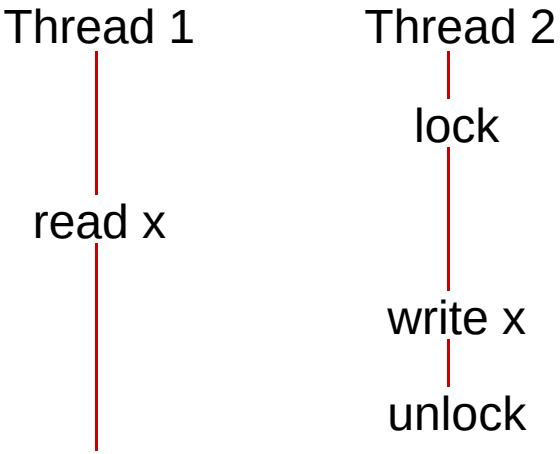
    lock();
    write x;
    unlock();
}
```



Interleaving 1: OK
Interleaving 2: OK
Interleaving 3: Race

Analyzing All Possible Interleavings

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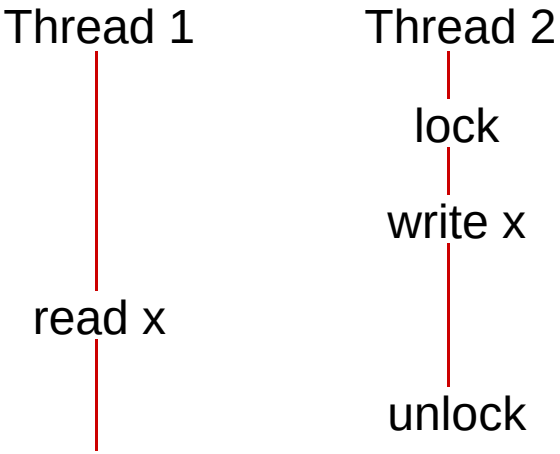


Interleaving 1: OK
Interleaving 2: OK
Interleaving 3: Race
Interleaving 4: Race

Analyzing All Possible Interleavings

- What
  - No race conditions
  - More important: data invariants always hold at appropriate program points
- Why?
  - You are implementing a new synchronization primitive
  - Building on top of other synchronization mechanisms is too expensive
- Why not?
  - Does not scale to large bodies of code
  - Complex and error prone
  - May not be portable, depending on memory model
  - No guarantee the result will be faster!

Transactional Memory

- Group update operations into a *transaction*
  - Goal: invariant holds after operations are complete
- Run-time system ensures update is atomic
  - i.e. updates are consistent with running complete transactions in a linear order
- Implementation
  - Track reads and writes to memory
  - At end, ensure no other process has overwritten cells that were read or written
  - Commit writes if no interference
  - Abort writes (with no effect) if interference observed

Transactional Memory

- Why?
  - Simpler model than others, therefore much easier to get right
  - No problem with deadlock
  - Allows more concurrency
  - Supports reuse of concurrent code
- Why not?
  - Overhead is high without hardware support
    - And hardware support is limited (e.g. transaction size)
  - Still experimental

Fluid: Tool Support for Safe Concurrency

Example: Summary 4

[Source: Aaron Greenhouse]

Problem: Race condition in class **`Logger`**

```
public class Logger { ...
  public void setFilter(Filter newFilter)…{
    if (!anonymous) manager.checkAccess();
    filter = newFilter;
  }
  public void log(LogRecord record) { ...
    synchronized (this) {
      if (filter != null
          && !filter.isLoggable(record)) return;
    } ...
  } ...
}
```

- Need to know ***design intent***
  - *Should instances be used across threads?*
  - *If so, how should access be coordinated?*
    - Assumed **`log`** was correct: **`synchronize`** on **`this`**
    - Could be caller's responsibility to acquire lock
      ⇒ **`log`** is incorrect
      ⇒ Need to check call sites of **`log`** and **`setFilter`**

Models are Missing

[Source: Aaron Greenhouse]

- **Programmer design intent is missing**
  - Not explicit in Java, C, C++, etc
    - *What lock protects this object*?
      - "This lock protects that state"
    - *What is the actual extent of shared state of this object*?
      - "This object is 'part of' that object"
- **Adoptability**
  - Programmers: "Too difficult to express this stuff."
  - Annotations in tools like Fluid: ***Minimal effort*** — concise expression
    - Capture what programmers are ***already thinking about***
    - No full specification
- **Incrementality**
  - Programmers: "I'm too busy; maybe after the deadline."
  - Tool design (e.g. Fluid): Payoffs early and often
    - Direct programmer utility — ***negative marginal cost***
    - Increments of payoff for increments of effort

Capturing Design Intent

[Source: Aaron Greenhouse]

- *What data is shared by multiple threads?*
- *What locks are used to protect it?*
- Annotate class to answer these questions

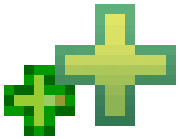
```
// @lock FL is this protects filter
public class Logger { ...
  public void setFilter(Filter newFilter)…{
    if (!anonymous) manager.checkAccess();
    filter = newFilter;
  }
  public void log(LogRecord record) { ...
    synchronized (this) {
      if (filter != null
          && !filter.isLoggable(record)) return;
    } ...
  } ...
}
```

Reporting Code–Model Consistency

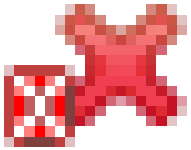
[Source: Aaron Greenhouse]

- Tool analyzes consistency
  - No annotations $\Rightarrow$ no assurance
  - Identify likely model sites

- Three classes of results



Code–model consistency



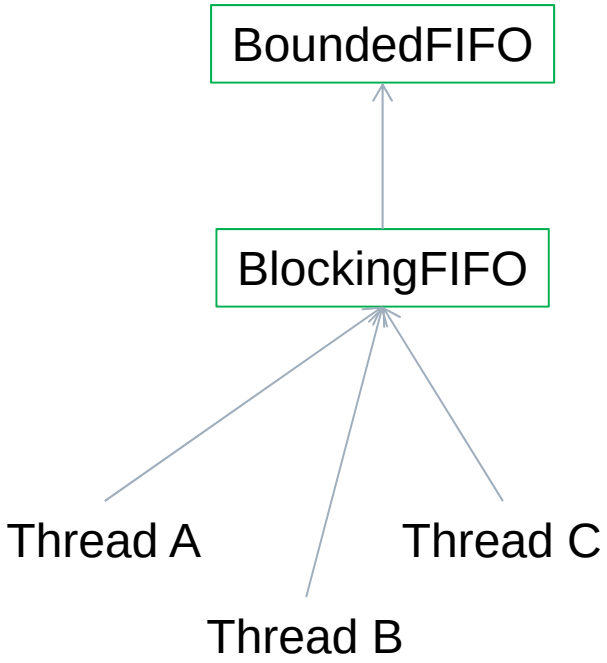
Code–model inconsistency

Informative — Request for annotation

Example: BoundedFIFO

Context:

- Actual class taken from Apache Log4J
  - Implements a first-in, first-out buffer
- Client: BlockingFIFO
  - Uses BoundedFIFO
  - Includes synchronization code, allowing it to be used in a concurrent setting



Initial Interaction

Lock identified – what state is being protected?

```
public class BoundedFIFO {
   LoggingEvent[] buf;

   int numElts = 0;
   public int length() { return numElts; }
   ...
}

public class BlockingFIFO {
   public int length() {
      synchronized (fifo) {
         return fifo.length();
      }
   }
   ...
}
```

Initial Interaction

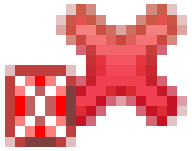
Lock identified – what state is being protected?

```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {
   LoggingEvent[] buf;

   int numElts = 0;
   public int length() { return numElts; }
   ...
}

public class BlockingFIFO {
   public int length() {
      synchronized (fifo) {
         return fifo.length();
      }
   }
   ...
}
```

Warning – Possibly Unprotected State



Lock "<this>.BufLock" not held when accessing this.numElts

```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {
   LoggingEvent[] buf;

   int numElts = 0;


   public int length() { return numElts; }
   ...
}

public class BlockingFIFO {
   public int length() {
      synchronized (fifo) {
         return fifo.length();
      }
   }
   ...
}
```

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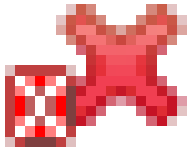


Lock "<this>.BufLock" not held when accessing this.numElts

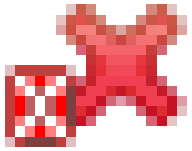
```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {
   LoggingEvent[] buf;

   int numElts = 0;

   @RequiresLock("BufLock")
   public int length() { return numElts; }
   ...
}

public class BlockingFIFO {
   public int length() {
      synchronized (fifo) {
         return fifo.length();
      }
   }
   ...
}
```

Warning – Possibly Unprotected State



Lock "<this>.BufLock" not held when accessing this.numElts

- Repeat for all other methods of BoundedFIFO

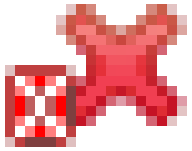
```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {
   LoggingEvent[] buf;

   int numElts = 0;

   @RequiresLock("BufLock")
   public int length() { return numElts; }
   ...
}

public class BlockingFIFO {
   public int length() {
      synchronized (fifo) {
         return fifo.length();
      }
   }
   ...
}
```

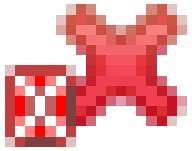
Warning – Lock Precondition



@RequiresLock("BufLock") precondition is not satisfied

```
public class BlockingFIFO {
   public void put(LoggingEvent e) {
      synchronized (this) {
         while (fifo.isFull()) {
            try {
               fifo.wait();
            } catch (InterruptedException ie) {
               // ignore
            }
         }
         fifo.put(e);
         if (fifo.wasEmpty()) {
            fifo.notify();
         }
         fifo.put(e);
         fifo.put(e);
      }
   }
}
```

Warning – Lock Precondition



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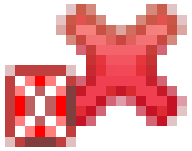
               // ignore
            }
         }
         fifo.put(e);
         if (fifo.wasEmpty()) {
            fifo.notify();
         }
         fifo.put(e);
         fifo.put(e);
      }
   }
}
```

Warning – Possibly Unprotected State

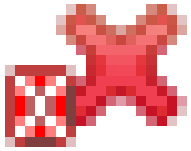


Lock "<this>.BufLock" not held when accessing this.size and this.buf

```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {


   public BoundedFIFO(int size) {
      if (size < 1)
         throw new IllegalArgumentException();
      this.size = size;
      buf = new LoggingEvent[size];
   }
   ...
}
```

Warning – Possibly Unprotected State

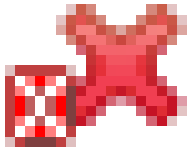


Lock "<this>.BufLock" not held when accessing this.size and this.buf

```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {

   @Unique("return")
   public BoundedFIFO(int size) {
      if (size < 1)
         throw new IllegalArgumentException();
      this.size = size;
      buf = new LoggingEvent[size];
   }
   ...
}
```

Warning – Reference to Shared State



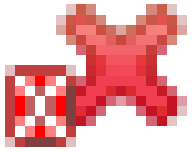
Field reference this.buf[this.next] may be to a shared unprotected object

```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {


   LoggingEvent[] buf;

   @RequiresLock("BufLock")
   public LoggingEvent get() {
      if (numElts == 0)
         return null;
      LoggingEvent r = buf[next];
      if (++first == size)
         first = 0;
      numElts--;
      return r;
   }
   ...
}
```

Warning – Reference to Shared State



Field reference this.buf[this.next] may be to a shared unprotected object

```
@RegionLock("BufLock is this protects Instance")
public class BoundedFIFO {

   @Unique
   LoggingEvent[] buf;

   @RequiresLock("BufLock")
   public LoggingEvent get() {
      if (numElts == 0)
         return null;
      LoggingEvent r = buf[next];
      if (++first == size)
         first = 0;
      numElts--;
      return r;
   }
   ...
}
```

Incremental Assurance

[Source: Aaron Greenhouse]

Payoffs early and often to reward use

- Reassure after every save
  - Maintain model–code consistency
  - Find errors as soon as they are introduced
- Focus on interesting code
  - Heavily annotate critical code
  - Revisit other code when it becomes critical
- Doesn’t require full annotation to be useful

Analysis Issues: Aliasing

- Other pointers can invalidate reasoning
  - @singlethreaded – can other threads access through an alias?
  - @aggregate … into Instance – can the field be accessed though an alias that is not protected by the lock?
- Similar issues in other analyses, e.g. Typestate

```
FileInputStream a = …
FileInputStream b = …
a.close()                 // what if a and b alias?
b.read(…)                 // may read a closed file
```

- Solution from Fugue (Microsoft Research)
  - @NotAliased annotation indicates that b has no aliases
  - Therefore closing a does not affect b
  - Requires alias analysis to verify
  - Can sometimes be inferred by analysis
    - e.g. see Fink et al., ISSTA ’06

Capturing Design Intent

[Source: Aaron Greenhouse]

- *What data is shared by multiple threads?*
- *What locks are used to protect it?*
  - Annotate class: `@lock FL is this protects filter`
- *Is this delegate object owned by its referring object?*
  - Annotate field: `@aggregate … into Instance`
- *Can this object be accessed by multiple threads?*
  - Annotate method: `@singleThreaded`
- *Can this argument escape to the heap?*
  - Annotate method: `@borrowed this`

Analysis Issues: Constructors, Inheritance

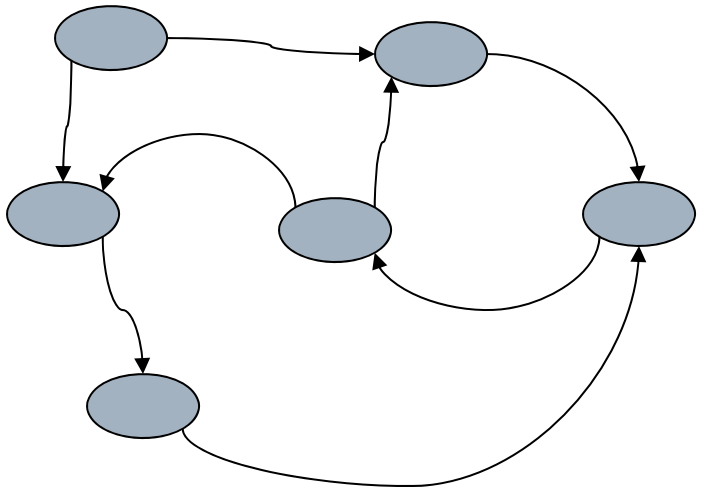
- Constructors
  - Often special cases for assurance
  - Fluid: can't protect with "this" lock
    - But OK since usually not multithreaded yet
  - Others
    - Invariants may not hold until end of constructor
- Subtyping
  - Subclass must inherit specification of superclass
  - Example: @singlethreaded for Formatter
  - Sometimes subclass extends specification
    - e.g. to be multi-threaded safe
    - requires care in inheriting or overriding superclass methods
- Inheritance
  - Representation of superclass may have different invariants than subclass
  - super calls must obey superclass specs
    - e.g. call to Formatter constructor

How Incrementality Works 1

[Source: Aaron Greenhouse]

- How can one provide incremental benefit with mutual dependencies?

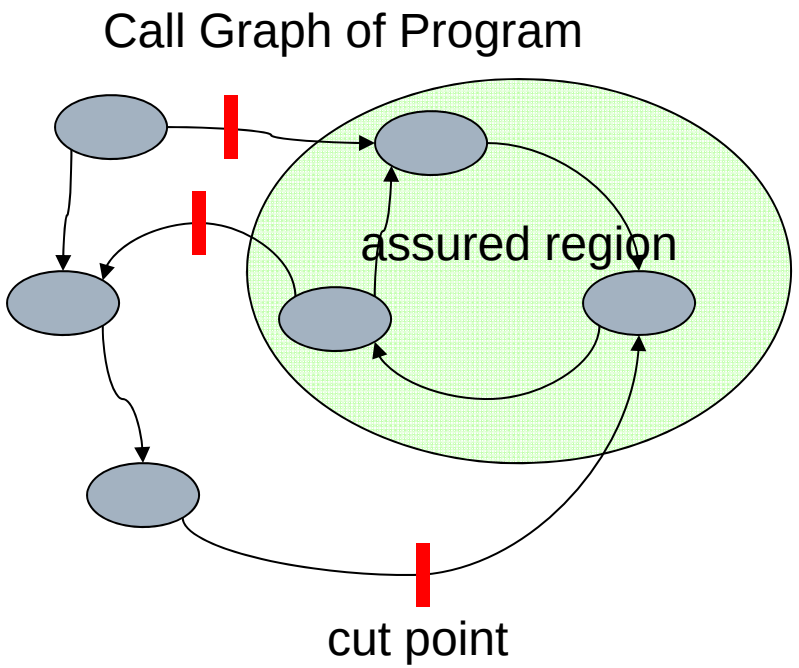
Call Graph of Program



How Incrementality Works 2

[Source: Aaron Greenhouse]

- How can one provide incremental benefit with mutual dependencies?
- Cut points
  - Method annotations partition call graph
  - Can assure property of a subgraph
  - Assurance is *contingent* on accuracy of trusted cut point method annotations



Cutpoint Example: `@requiresLock` [Source: Aaron Greenhouse]

- Analysis normally assumes a method acquires and releases all the locks it needs.
  - Prevents caller's correctness from depending on internals of called method.

- Method can require the caller to already hold a certain lock: **`@requiresLock FilterLock`**
  - Analysis of method gets to assume the lock is held.
    - Doesn't need to know about caller(s).
  - Analysis of caller checks for lock acquisition.
    - Still ignores internals of called method.

Capturing Design Intent

[Source: Aaron Greenhouse]

- *What data is shared by multiple threads?*
- *What locks are used to protect it?*
  - Annotate class: `@lock FL is this protects filter`
- *Is this delegate object owned by its referring object?*
  - Annotate field: `@aggregate … into Instance`
- *Whose responsibility is it to acquire the lock?*
  - Annotate method: `@requiresLock FL`

Principal case study results, 1

- Major software vendor
  - Multiple systems evaluated – all in production
    - Highly multi-threaded code
    - E.g., 300KLOC framework system
    - 3 days modeling time
  - Results
    - 45 lock models
      - Models: requiresLock, aggregate, unshared, mapinto, etc.
      - 1500 “**+**”, 200 “**X**”, 1500 “**i**”
    - Several major architectural issues detected
      - Deadlocks and races
    - Many faults detected and corrected in code base
    - The tool identified additional areas for code review
  - Vendor staff developed many models themselves
    - UI “natural” for developers
    - Highly interactive use

Principal case study results, 1

- Comments from developers and their managers:

  "So this tool will let me put in the design intent and then tells me if it is consistent with the code?"

  "It would have been very difficult if not impossible to find these issues without the Fluid analysis"

  "The tool can be used to increase concurrency which should lead to performance and scalability benefits. "

  "Sweeping changes (impacting thousands of locks in this case) would be risky and are not likely to be attempted without the assurance that the Fluid tool provides."

  "I'm actually considering implementing a policy that you can't add a synchronize to the code without documenting [in Fluid notation] what region it applies to."

Principal case study results, 2

- Major software vendor
  - Multiple systems evaluated
    - E.g., 200KLOC Java, production design tool
      - Geographically distributed development team
      - Based on earlier C and C++ versions
      - Multi-threaded, abundant use of non-lock concurrency
      - 1 day modeling/analysis time
  - Results
    - Major thread use (color) bug identified
      - Developers later reported “several full-time weeks” to locate – caused “frequent exceptions and crashes”
      - Positive assurance of thread use for most methods
        - 50% of methods: thread-use modeled
    - Locking and synchronization faults identified
      - Race condition with nested locks
    - Performance improvements: remove unnecessary locks

Principal case study results, 3

- Major aerospace organization
  - Four production systems evaluated, *already passed QA*
    - 250KLOC
    - Including key critical systems already deployed
  - Found races in all systems
    - Code changes were checked in for three of the systems

Concurrency: Summary

- Many ways to make concurrency safe
  - Single-threaded data
  - Locks
  - Disabled interrupts
  - Analysis of interleavings (simple settings)
  - Transactions (future)

- Design intent useful
  - Document assumptions for team
  - Aids in manual analysis
  - Enables (eventual) automated analysis