Analysis for Safe Concurrency

Optional supplementary reading: ***Assuring and Evolving Concurrent Programs: Annotations and Policy***

15-214: Principles of Software System Construction

Jonathan Aldrich Charlie Garrod

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();
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  public void log(LogRecord record) { ...
    synchronized (this) {
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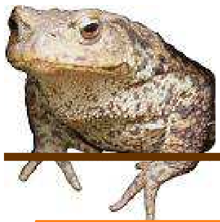
  } ...
}
```

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



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

Example: java.util.logging.Logger

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

  /** ...
   * @param newFilter a filter object (may be null)
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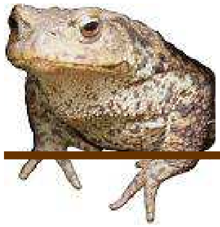
}
```

Correction: synchronize `setFilter()`



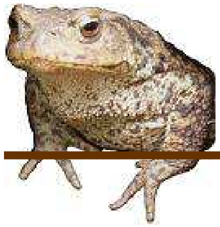
Review: Race Conditions

Problem: Race condition in class **Logger**

- ***Race condition:***
  - A situation in which the result of computation is dependent on the sequence or timing of program events

- ***Data race:*** a common source of race conditions

  (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



Race Condition Challenges

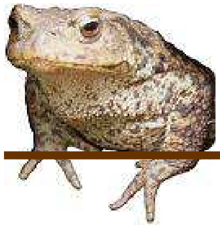
Problem: Race condition in class **`Logger`**

- 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

Races and Invariants

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

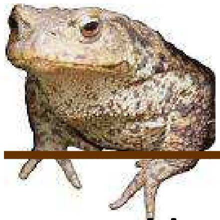
- Not all race conditions result in errors
- Error results when invariant is violated
  - Logger invariant
    - filter is not null at call following null test
  - Race-related error
    - race between write and dereference of filter
    - if the write wins the race, filter is null at the call



Races and Design Intent

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

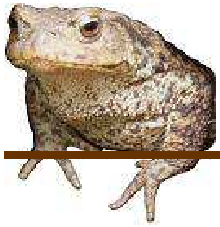
- Need to know ***design intent***
  - *Should instances be used across threads*?
  - *If so, how should access be coordinated*?
    - Assumed **`log`** was correct: **`synchronize`** on **`this`**
    - Could be caller's responsibility to acquire lock
      - ⇒ **`log`** is incorrect
      - ⇒ Need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



Review: Avoiding Races

How would you make sure your code avoids race conditions?

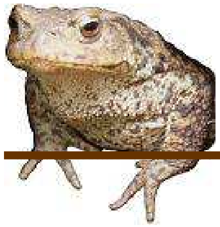
- Keep some data local to a single thread
  - Inaccessible to other threads
  - e.g. local variables, Java AWT & Swing, thread state
- Protect shared data with locks
  - Acquire lock before accessing data, release afterwards
  - e.g. Java synchronized, OS kernel locks
- Forbid context switches/interrupts 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



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

JSure: Tool Support for Safe Concurrency



Races and Design Intent

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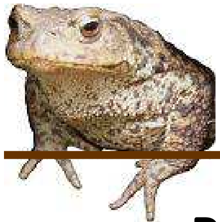


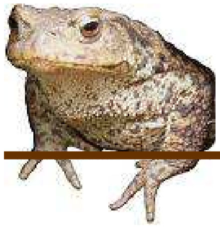
Models are Missing

[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

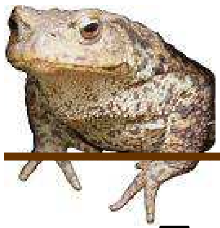
- **Incrementality**
  - Programmers: "I'm too busy; maybe after the deadline."
  - Tool design (e.g. Fluid): Payoffs early and often
    - Direct programmer utility — ***negative marginal cost***
    - Increments of payoff for increments of effort



Capturing Design Intent

[Source: Aaron Greenhouse]

- *What data is shared by multiple threads*?
- *What locks are used to protect it*?
  - Annotate class: **`@RegionLock("FL is this protects filter")`**



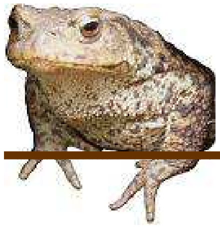
Reporting Code–Model Consistency

[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

Fluid Demonstration: Locks



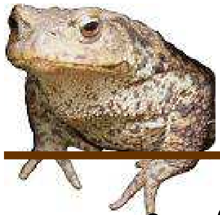
Incremental Assurance

[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

Fluid Demonstration: Aliasing, Inheritance, and Constructors



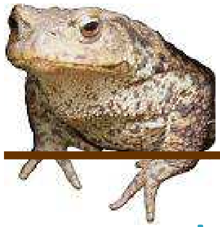
Analysis Issues: Aliasing

- Other pointers can invalidate reasoning
  - @Unique – can other threads access through an alias?

- 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
```

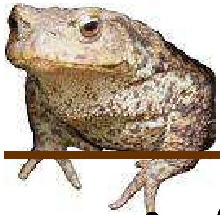
- Solution from Fugue (Microsoft Research)
  - @NotAliased annotation indicates that b has no aliases
  - Therefore closing a does not affect b
  - Requires alias analysis to verify
  - Can sometimes be inferred by analysis
    - e.g. see Fink et al., ISSTA ’06



Capturing Design Intent

[Source: Aaron Greenhouse]

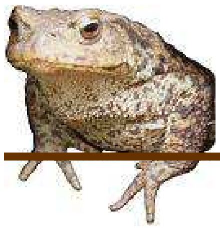
- *What data is shared by multiple threads*?
- *What locks are used to protect it*?
  - Annotate class: `@RegionLock(“FL is this protects filter")`
- *Is this delegate object owned by its referring object*?
  - Annotate field: `@Unique`
- *Can an object escape to the heap during construction*?
  - Annotate constructor: `@Unique("return")`



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: @Unique("return") 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

Fluid Demonstration: Cutpoints, Aliasing

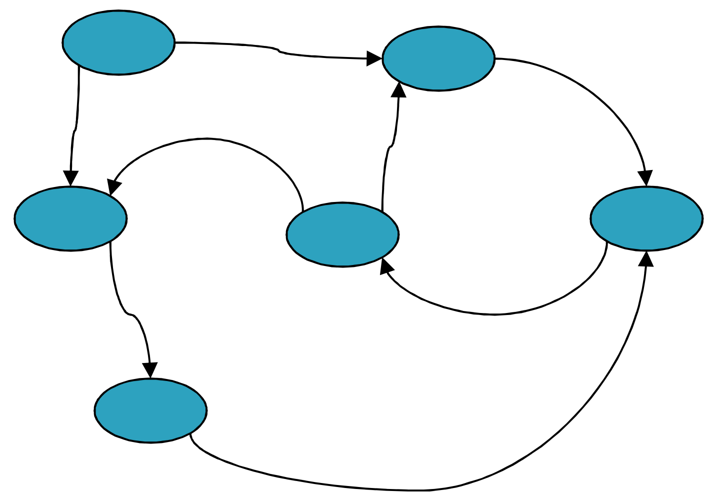


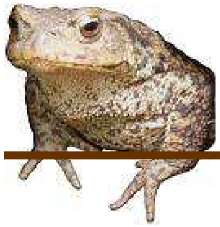
How Incrementality Works 1

[Source: Aaron Greenhouse]

- How can one provide incremental benefit with mutual dependencies?

Call Graph of Program



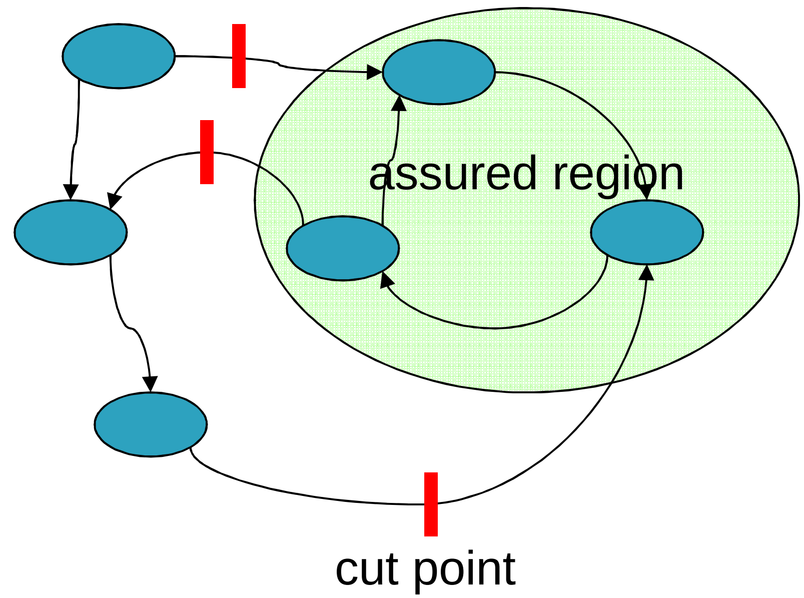


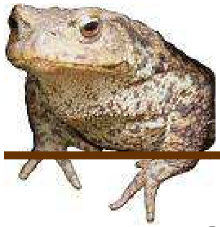
How Incrementality Works 2

[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

Call Graph of Program

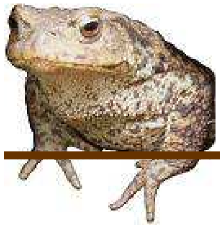




Cutpoint Example: `@requiresLock`

[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(BufLock)`**
  - 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.



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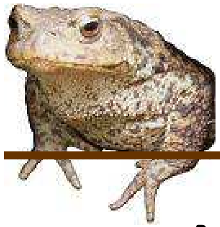
- *What locks are used to protect it*?
  - Annotate class: **`@RegionLock(“FL is this protects filter")`**
- *Is this delegate object owned by its referring object*?
  - Annotate field: **`@Unique`**
- *Whose responsibility is it to acquire the lock*?
  - Annotate method: **`@RequiresLock(BufLock)`**



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 automated analysis