Analysis for Safe Concurrency

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

17-654/17-754: Analysis of Software Artifacts

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)
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  public void setFilter(Filter newFilter)…{
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    synchronized (this) {
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    } ...
  } ...
}
```

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)
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  public synchronized void setFilter(Filter newFilter)…{
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    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

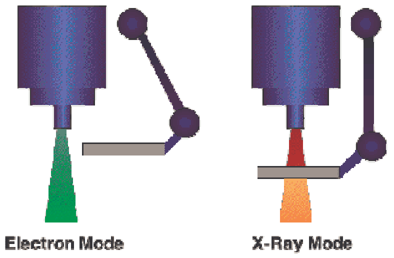
Example: Summary 4

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

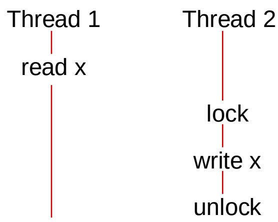
- Disable interrupts for critical sections of code
  - Should be short, so that interrupts aren't delayed too long
  - Must be long enough to update shared data consistently
  - Common in single-processor embedded systems
- Why?
  - Cheap, simple, predictable
- Why not?
  - Does not support true multiprocessor 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

- ***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

Analyzing All Possible Interleavings

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



Interleaving 1: OK

Analyzing All Possible Interleavings

```
thread1() {
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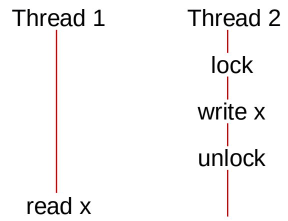

Interleaving 1: OK
Interleaving 2: OK

Analyzing All Possible Interleavings

```
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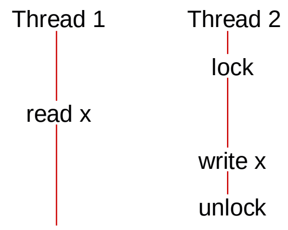

Interleaving 1: OK
Interleaving 2: OK
Interleaving 3: Race

Analyzing All Possible Interleavings

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   write x;
   unlock();
}
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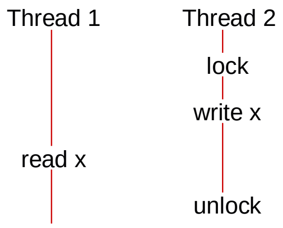


Interleaving 1: OK
Interleaving 2: OK
Interleaving 3: Race
Interleaving 4: Race

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 may be high
  - Still experimental
- My view: ***inevitable*** as concurrency becomes more common

Fluid: Tool Support for Safe Concurrency

Example: Summary 4

[Source: Aaron Greenhouse]

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`**

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: `@lock FL is this protects filter`

Whose responsibility is it to acquire the lock?

Annotate method: `@requiresLock FL`

Is this delegate object owned by its referring object?

Annotate field: `@aggregate … into Instance`

Reporting Code–Model Consistency

[Source: Aaron Greenhouse]

- Tool analyzes consistency
  - No annotations ⇒ 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
  - @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

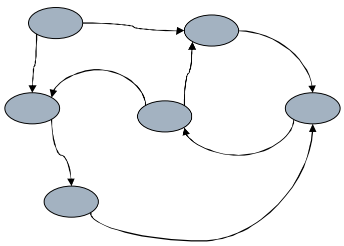
Fluid Demonstration: Cutpoints, Aliasing

How Incrementality Works 1

[Source: Aaron Greenhouse]

- How can one provide incremental benefit with mutual dependencies?

Call Graph of Program

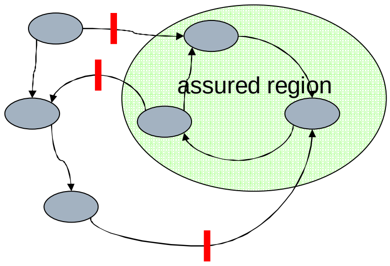


How Incrementality Works 2

[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 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`**

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

Questions?