# Concurrency Assurance in Fluid

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

17-654/17-765
Analysis of Software Artifacts

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Software Engineering Institute

# Example: java.util.logging.Logger

```
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

```
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

```
/** ... 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

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  /** ...
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}
```

1 2 3

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



# Example: java.util.logging.Logger

```
/** ... 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)…{
    if (!anonymous) manager.checkAccess();
    filter = newFilter;
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  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`**

- 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`**



# The Fluid Project

Assure code is consistent with programmer-specified design intent.

- Assure critical ***dependability*** attributes
  - Tend to defy testing and inspection
  - Provide direct static assurance
- Express dependability-related ***models***
  - Incrementally capture design intent
- Emphasize ***adoptability*** and ***scalability***
  - Ease of use by practicing developers
  - Composability and components
  - Incrementality and early rewards
  - Partiality and contingency

# Topics

- Capturing design intent
- Assuring code–model consistency
  - Cutpoints and incrementality
  - Overview of the lock analysis
  - Real world complications
- Fluid Demo
  - Annotations
  - Incrementality
- Case study experiences



# Fluid: Models are Missing

- **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."
  - 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."
  - Fluid: Payoffs early and often
    - Direct programmer utility — ***negative marginal cost***
    - Increments of payoff for increments of effort

# Capturing Design Intent

- *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`



# Categories of Design Intent

- Safe concurrency
  - Race conditions
  - Lock management
  - Single thread concurrency control
  - Lock ordering and deadlocks
- Code safety
  - Ignored exceptions
  - Appropriate typing
- Policy compliance
  - API policy compliance
  - Framework compliance
  - Object references and aliasing
  - Patterns, uses, structure
- Real time
  - Real-time thread/memory policies

Hard to Test — Hard to Inspect

# Races and security

**Source: Bugtraq vulnerabilities list**

- 15-11-2003: monopd Race Condition Denial of Service Vulnerability
- 15-10-2003: Sun Solaris Pipe Function Unspecified Kernel Race Condition Vulnerability
- 10-10-2003: Microsoft Windows RPCSS Multi-thread Race Condition Vulnerability
- 23-08-2003: Glibc Malloc Routine Race Condition Vulnerability
- 26-06-2003: Linux 2.4 Kernel execve() System Call Race Condition Vulnerability
- 29-04-2003: Worker Filemanager Directory Creation Race Condition Vulnerability
- 23-04-2003: SAP Database SDBINST Race Condition Vulnerability
- 20-04-2003: Microsoft Windows Service Control Manager Race Condition Vulnerability
- 15-03-2003: Samba REG File Writing Race Condition Vulnerability
- 27-02-2003: Hypermail Local Temporary File Race Condition Vulnerability
- 11-02-2003: Sun Microsystems Solaris Mail Reading Local Race Condition Vulnerability
- 27-01-2003: Sun Solaris AT Command Race Condition Vulnerability
- 12-01-2003: BitMover BitKeeper Local Temporary File Race Condition Vulnerability
- 20-12-2002: Tmpwatch Race Condition Vulnerability
- 20-12-2002: STMPClean Race Condition Vulnerability
- 29-07-2002: Multiple Vendor BSD pppd Arbitrary File Permission Modification Race Condition Vulnerability
- 29-07-2002: Util-linux File Locking Race Condition Vulnerability
- 04-07-2002: BEA Systems WebLogic Server and Express Race Condition Denial of Service Vulnerability

+ Many more



# Reporting Code–Model Consistency

- 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

# Incremental Assurance

Payoffs early and often to reward use

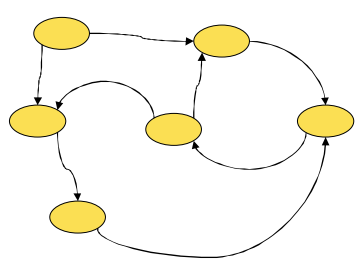
- Reassure after every save
  - Maintain model–code consistency
  - Find errors as soon as they are introduced
- Focus on interesting code
  - Heavily annotate critical code
  - Revisit other code when it becomes critical
- Doesn't require full annotation to be useful



# How Incrementality Works 1

- 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 method annotations

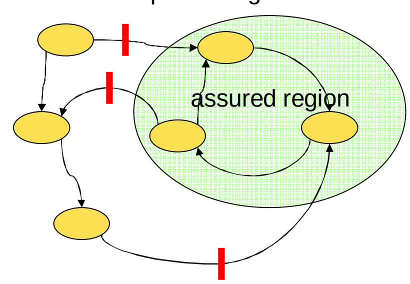
Call Graph of Program



# How Incrementality Works 2

- 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`

- 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.

## Assuring Concurrency

- Annotations are turned into tables
  - `@lock` → Lock–state associations
  - `@requiresLock` → Method preconditions
- Lock analysis is syntax-directed
  - Single pass over the syntax tree
  - (Sample rules follow)

Caveat: Lock analysis is a consumer of other analyses—some of which are data flow analyses.



## Assuring Field Access

Checking field access e.fd

- *P* — The program
- *E* — Current stack frame
- *C* — Currently held locks

Is the lock associated with field *fd* currently held?

$$\frac{P; E; C \vdash e : c \qquad \langle c'.fd, t\rangle \in^{c} c \qquad \mathbf{lockFor}(P, e, c'.fd, c) \subseteq C}{P; E; C \vdash e.fd : t}$$

# Synchronized Blocks

Expression $e_1$ could be any of the locks in set $L$.

Analyze the body of the block ($e_2$) holding the locks $L$.

$$\frac{P; E; C \vdash_{\text{final}} e_1 : c \text{ as } L \qquad P; E; (C \cup L) \vdash e_2 : t}{P; E; C \vdash \text{synchronized}(e_1)\ \{e_2\} : t}$$



# Semantically Rich Models

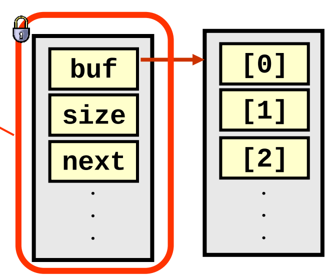
**Expressing lock policy**

– Object protects itself:

@lock BufLock is this protects Instance

– Caller of method must acquire lock:

@requiresLock BufLock

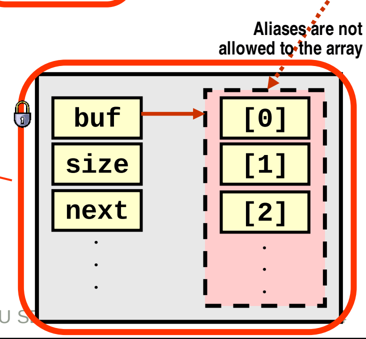



**Aggregating state**

– Only *references to* arrays are protected, not the arrays themselves

– Aggregate unaliased arrays:

@unshared
@aggregate [] into Instance



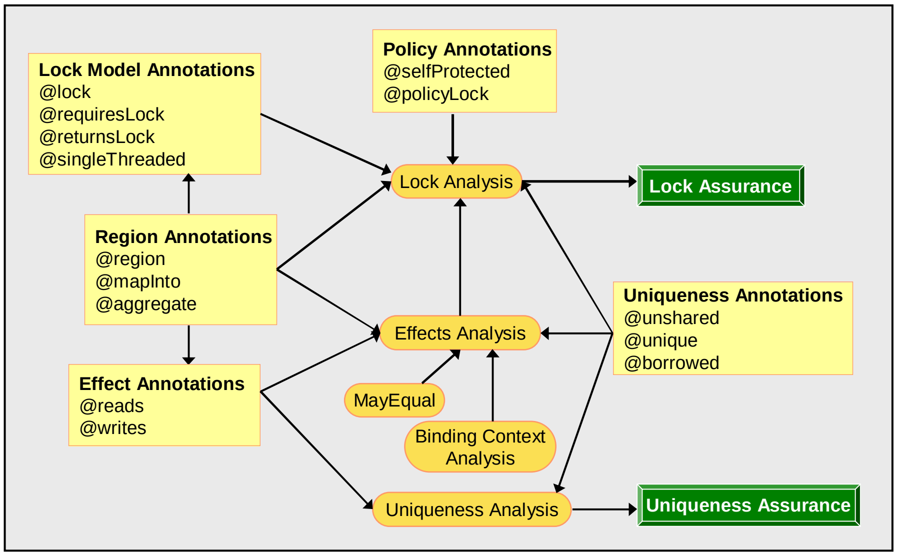

**Constructors**

– Cannot be `synchronized`.

– But most are single-threaded:

@singleThreaded
@borrowed this

## Annotations, Analyses & Assurances






## Lightening the Annotation Burden

**Problem:**
Class has 8 constructors; tens of methods.
They all should have similar annotations.
Annoying to repeat annotations.

```
/**
 * @lock L is this protects Instance
 * @promise "@singleThreaded" for new(**)
 * @promise "@borrowed this"
 */
public class DateFormatManager {
  public DateFormatManager(Time… timeZone) {
    super();
    _timeZone = timeZone;
    configure();
  }
  ...
  private synchronized void configure() {…}
}
```

"All constructors are single threaded."
"No method/constructor retains reference to the receiver."

# Missing Code

- "Missing code" is a problem
  - Libraries
  - Unwritten code
  - Code that is "not my problem"

- But assurance may be impossible without assuring missing code
  - E.g., will the called method create aliases?

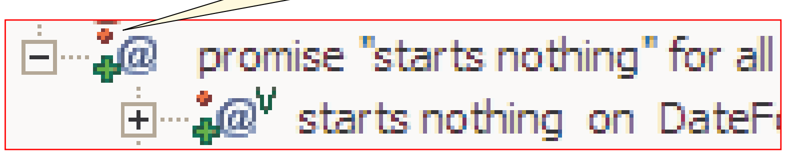


# Missing Code: Assumptions

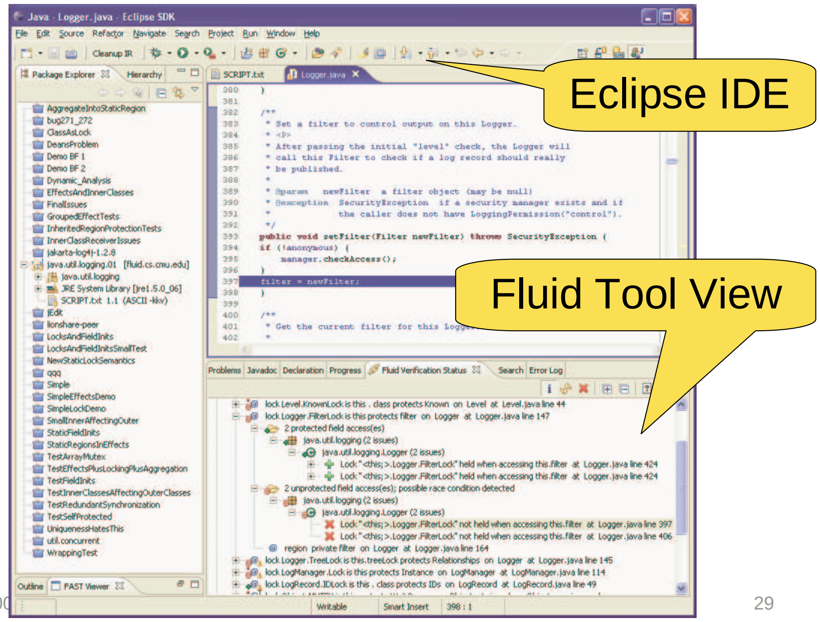
**Work in Progress**

- Allow local assumptions:
  - `@assume "... " for …`
  - ***Trusted locally*** within their scope
  - ***Create obligations*** for the missing code
  - ***Assurance is conditional*** on their truth

"Red Dot" marks conditional assurances.



# The Fluid Eclipse Plug-in



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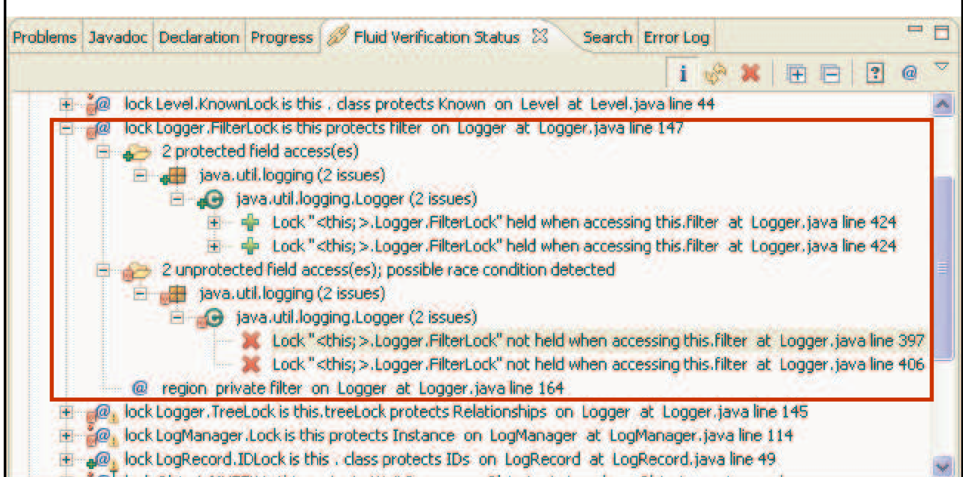

# Fluid Summary: Towards Safer Code

## Realities

- Code is the as-built reality
  - But, we don't understand code
  - Non-local properties are (often) known but not expressed
  - Thus, loss of intellectual control
- Models are necessary
  - Code and design evolve separately
  - We assure consistency
- Adoption barriers exist for present semantic assurance techniques

`http://www.fluid.cs.cmu.edu`

## The Fluid approach

- Incrementality
  - Capture & express critical properties
    - New ways to model and express diverse mechanical properties
  - Create assurance: chains of evidence
    - Couple models/annotations, analysis
    - Are we in the framework? Are we compliant with the API?
  - Build semantic links between code and design
- Integrate into programmer practice
  - Build on existing practice (e.g., open source, Eclipse, etc.)
    - Seek invisible or incremental interventions
    - Instant gratification principle