JThreadSpy

Teaching Multithreading Programming by Analyzing Execution Traces

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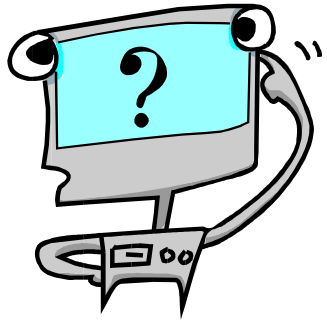
Teaching multi-threading: needs

- Teaching multi-threaded programming is a difficult task
  - ✓ Synchronization problems are often presented only at a very abstract level
  - ✓ Students have to figure out what happens in their programs
    - Single-threaded programs analysis and debugging techniques are not useful
    - Subsequent executions of the same program can produce different execution flows
      - Intrinsic non-determinism of thread scheduling



JThreadSpy: goals

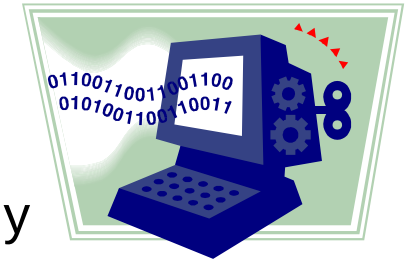
- JThreadSpy is an educational tool
  - Aimed at improving students consciousness of race conditions and multithreading issues
  - Useful to detect anomalies in concurrent programs
- Traces are collected during program execution
  - Registering relevant events
  - A code instrumentation technique is used
  - Execution flows are graphically displayed
    - Synchronization constructs are shown

Collecting execution traces

- Manually insert instructions in the source code
  - Expensive and error prone approach
- Replace the JVM with a custom one
  - Overwhelming task
- Use information provided by the Java Virtual Machine Tool Interface
  - Not available in all JVM implementations
  - Not portable across different operating systems
- Use aspect-oriented programming
  - Easy to use
  - Need of installing the runtime environment
  - Need of some notion of aspects
    - Not present in every curriculum
- Dynamically instrument bytecode

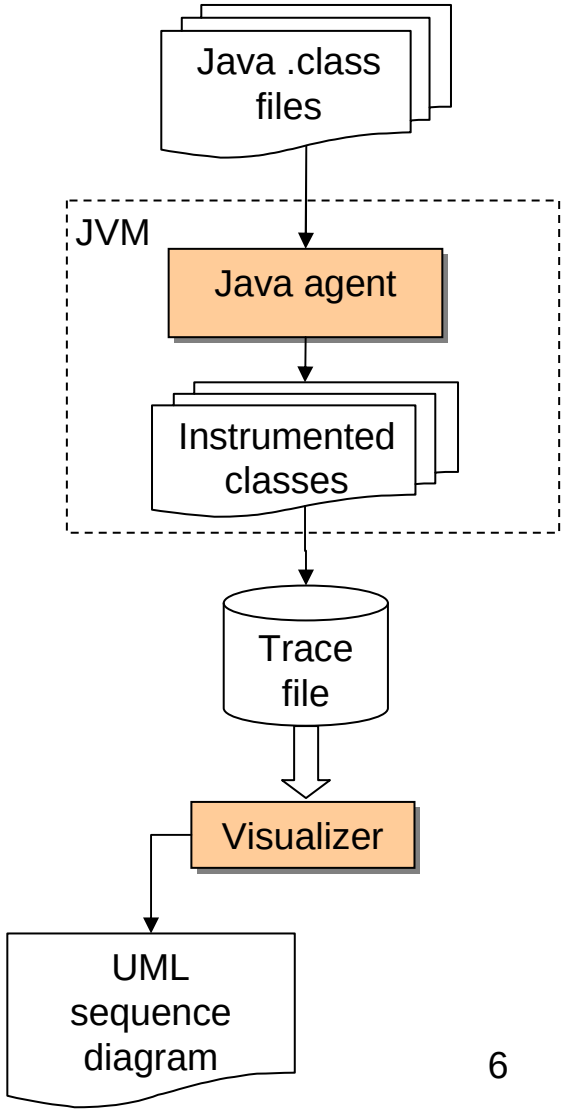
Dynamic bytecode instrumentation

- At class load time, bytecode is inspected by a Java agent registered during the JVM start-up
  - Extra instructions are inserted in order to flag method call and return and relevant synchronization constructs
  - When executed, the inserted code will register the corresponding event in a shared list which will be later saved to a file for subsequent inspection
- Advantages
  - No modification is needed to source code
  - Very low latency between the event and its recording, although some overhead is introduced
- Drawbacks
  - Java agent supported only since JVM version 1.5
  - Core Java classes cannot be instrumented on the fly



JThreadSpy architecture

- Java agent
  - Instruments classes and produces a trace file
- Visualizer
  - Decodes the trace file and produces an enhanced UML sequence diagram
- Eclipse plug-in
  - Integrates the above components inside the IDE



Registered events (I)

- Two categories of events are logged
  - Method invocation
    - Object instance's methods
    - Constructors
    - Static methods
  - Synchronization constructs
    - Synchronized methods
    - Synchronized blocks of code
    - Object.wait()
    - Object.notify() e Object.notifyAll()

Registered events (II)

- Each event record consists of
  - An event type
  - A unique thread identifier
  - A unique object identifier
  - The class name of the object
  - The class name of the caller object
  - The name of the traced method
  - The current stack depth
  - Three timestamps
    - Event start
    - Critical section acquisition (for synchronization events)
    - Event end

Code rewriting rules (I)

- Every method is replaced by a stub
  - Original bytecode is inserted in new private methods
  - "[hidden]" is used to prefix method names
- The actual method is called in a *try/finally* block
  - An event is created before method invocation, with the initial timestamp
  - The finally code updates the event with the return timestamp

```
<anyVisibility> <anyReturnType>
 methodName(...) {
  //create trace event
  TraceEvent te =
    new TraceEvent(this, ...);
  try {
    return [hidden]methodName(...);
  } finally {
    //update & store trace event
    Reporter.exiting(te);
  }
}

private <anyReturnType>
 [hidden]methodName(...) {
  //original code modified
  //in order to monitor
  //access to critical sections
}
```

Code rewriting rules (II)

- The previous approach is not suitable for constructors
  - An overloaded version of the constructor is introduced
- For constructors, the event is created without an object identifier
  - It is set only when the constructor returns
  - If an exception is raised during the super-class construction, the corresponding event is discarded

```
<anyVisibility> ClassName(...) {
  this(...,
    new TraceEvent(null, ...));
}

private ClassName(...,
                  TraceEvent te) {
  super(...);
  try {
    //set trace event object id
    //original code modified
    //in order to monitor
    //access to critical sections
    //before each return instruction,
    //the trace event is updated
    //with the proper timestamp
  } catch(Throwable t) {
    //update & store trace event
  }
}
```

Code rewriting rules (III)

- Synchronized methods need to acquire a lock in order to actually start
  - Same result of executing their code within a synchronized block of code
- Code is rewritten similarly to other methods
  - New private methods are not synchronized
  - They are called within a synchronized block of code
  - The lock acquisition timestamp is set before calling the method

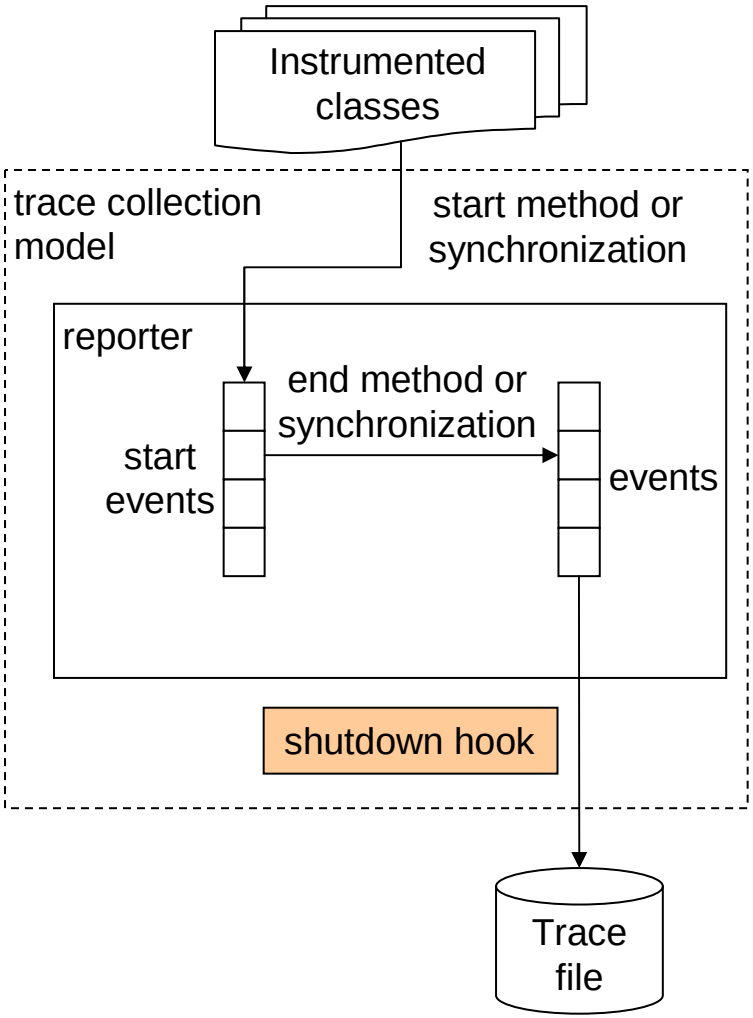
```
<anyVisibility> <anyReturnType>
 methodName(...) {
  TraceEvent te =
    new TraceEvent(this, ...);
  try {
    synchronized(this) {
      //update acquisition time
      //in the trace event
      return [hidden]methodName(...);
    }
  } finally {
    // update & store trace event
    Reporter.exiting(te);
  }
}

private <anyReturnType>
 [hidden]methodName(...) {
// original code modified
// in order to monitor
// access to critical sections
}
```

Code rewriting rules (III)

- Synchronized blocks of code are enclosed within a *try/finally* block
  - An event is created before synchronized block
    - Contains the start event timestamp
  - The lock acquisition timestamp is set before the first instruction of the synchronized block
  - The code in the finally block sets the release timestamp
- wait() instructions are enclosed within a *try/finally* block
  - An event is created before wait() instruction
    - Contains the start event timestamp
  - The finally code sets the end timestamp
- notify() and notifyAll() instructions
  - A single timestamp is recorded

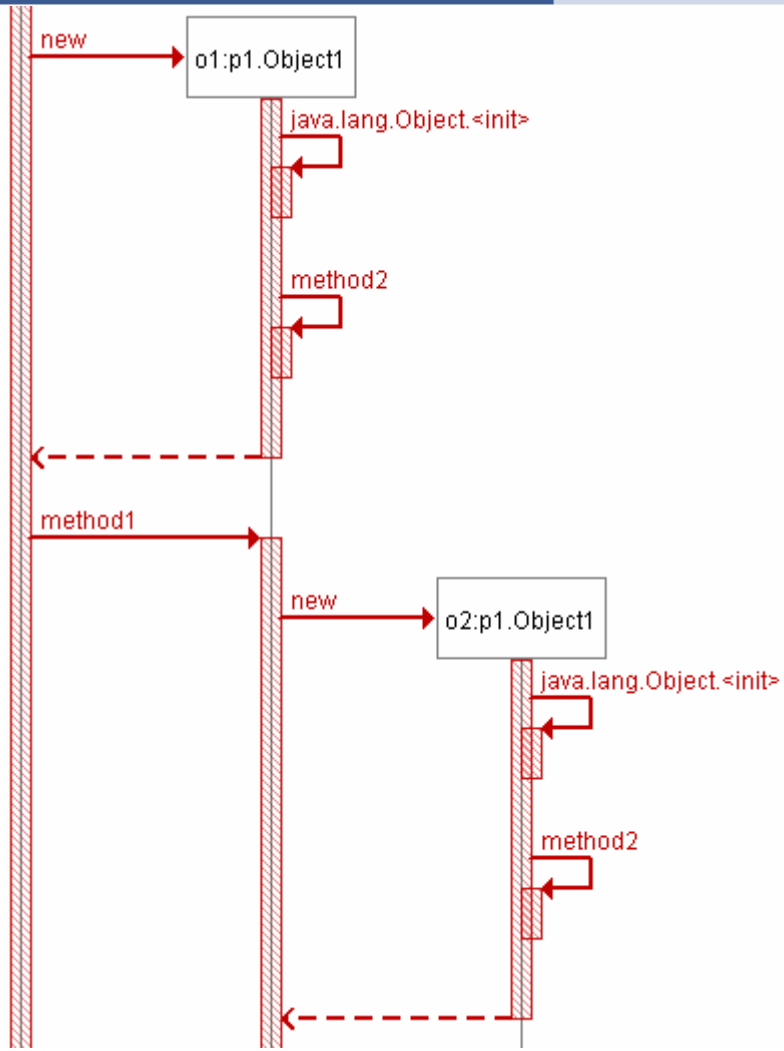
Execution trace file generation

- A shutdown hook is registered
  - Launched when the JVM shutdown starts
  - Sets end timestamps of events not yet terminated
    - Useful in case of System.exit() invocation
  - Serializes events into a file for the subsequent visualization



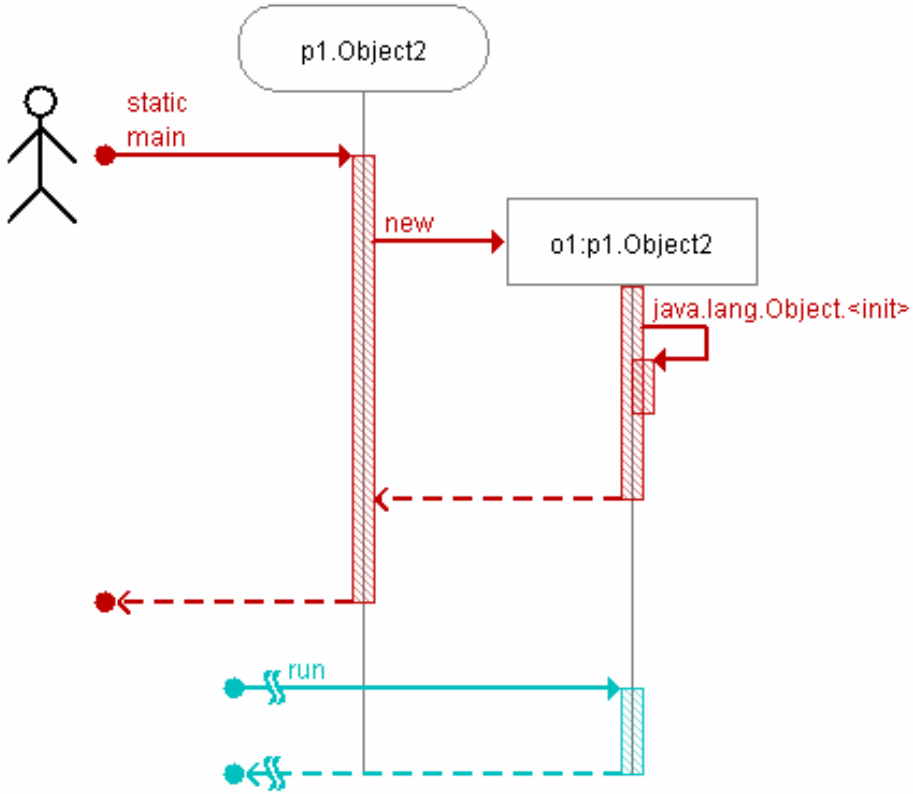
UML sequence diagram

- Standard notation is used where available
  - Object instances
  - Lifelines
  - Activation lines
  - Method invocations
  - Timeline
    - Starts from the top of the diagram
    - Time increases downwards



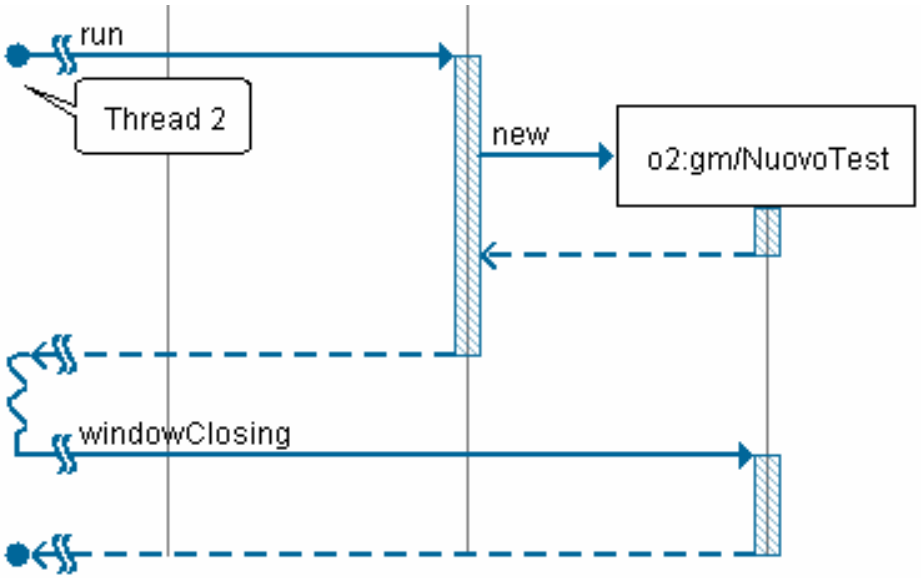
Augmented UML notation (I)

- Static method invocation
  - Related to the class of the method
  - Represented with a rounded rectangle
  - Other rules as for standard objects
- One trace for each thread
  - Each thread is drawn wit a different colour



Augmented UML notation (II)

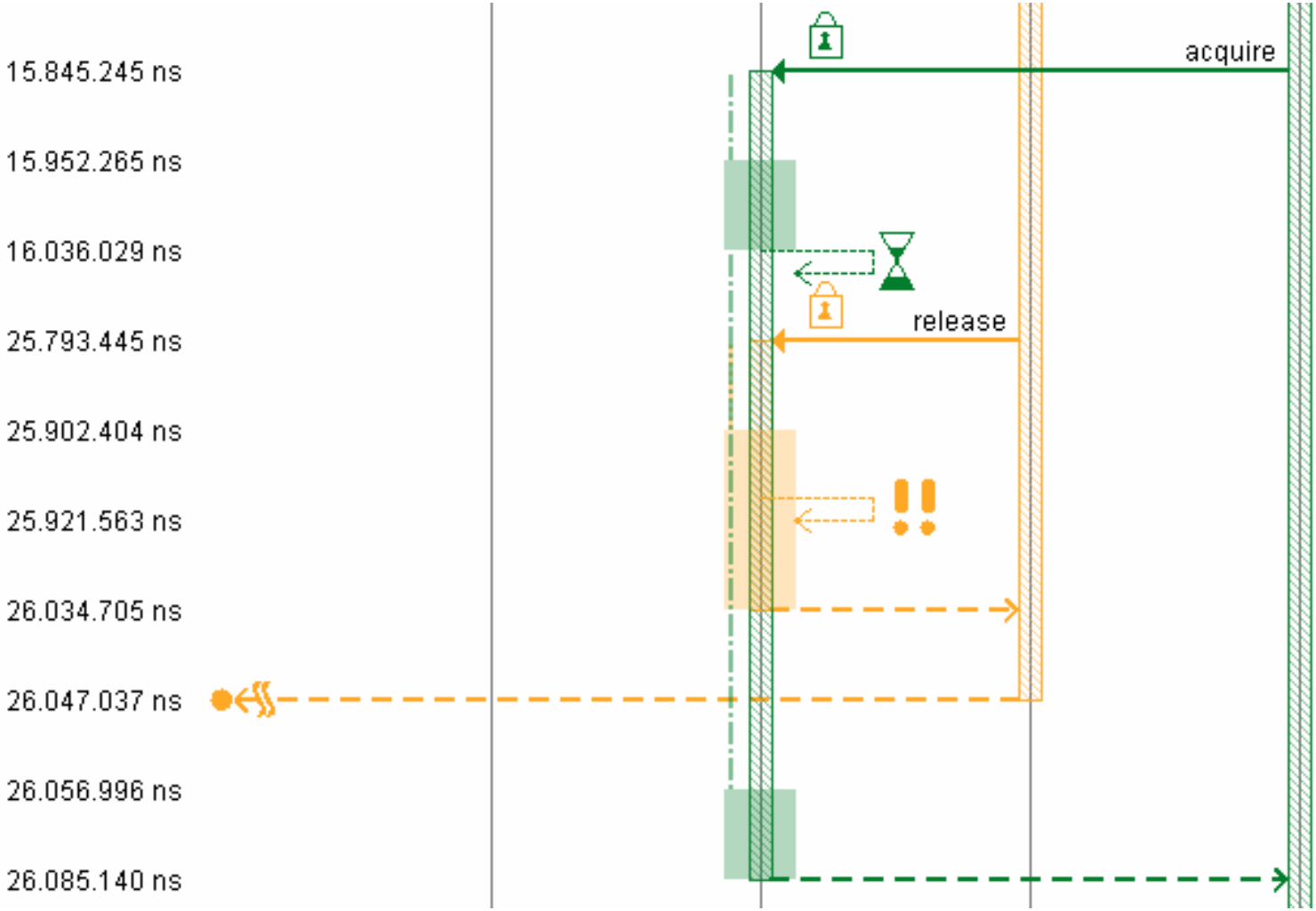
- Sometimes, methods are called from non-instrumented code
  - Represented with a broken horizontal arrow
  - A wave-shaped vertical line depicts execution taking place in non-instrumented code



Augmented UML notation (III)

- Synchronization
  - A padlock identifies
    - Synchronized method calls
    - Synchronized blocks of code
  - Synchronized blocks of code are marked with dotted start and end arrows
  - An hourglass identifies wait instructions
  - An exclamation mark is used for notify instructions
    - notifyAll is represented by a double exclamation mark
  - A dotted and dashed line on the left of the lifeline identifies a thread waiting for lock acquisition
  - A semi-transparent rectangle overlapping the lifeline shows that the thread owns the object lock

Augmented UML notation (IV)



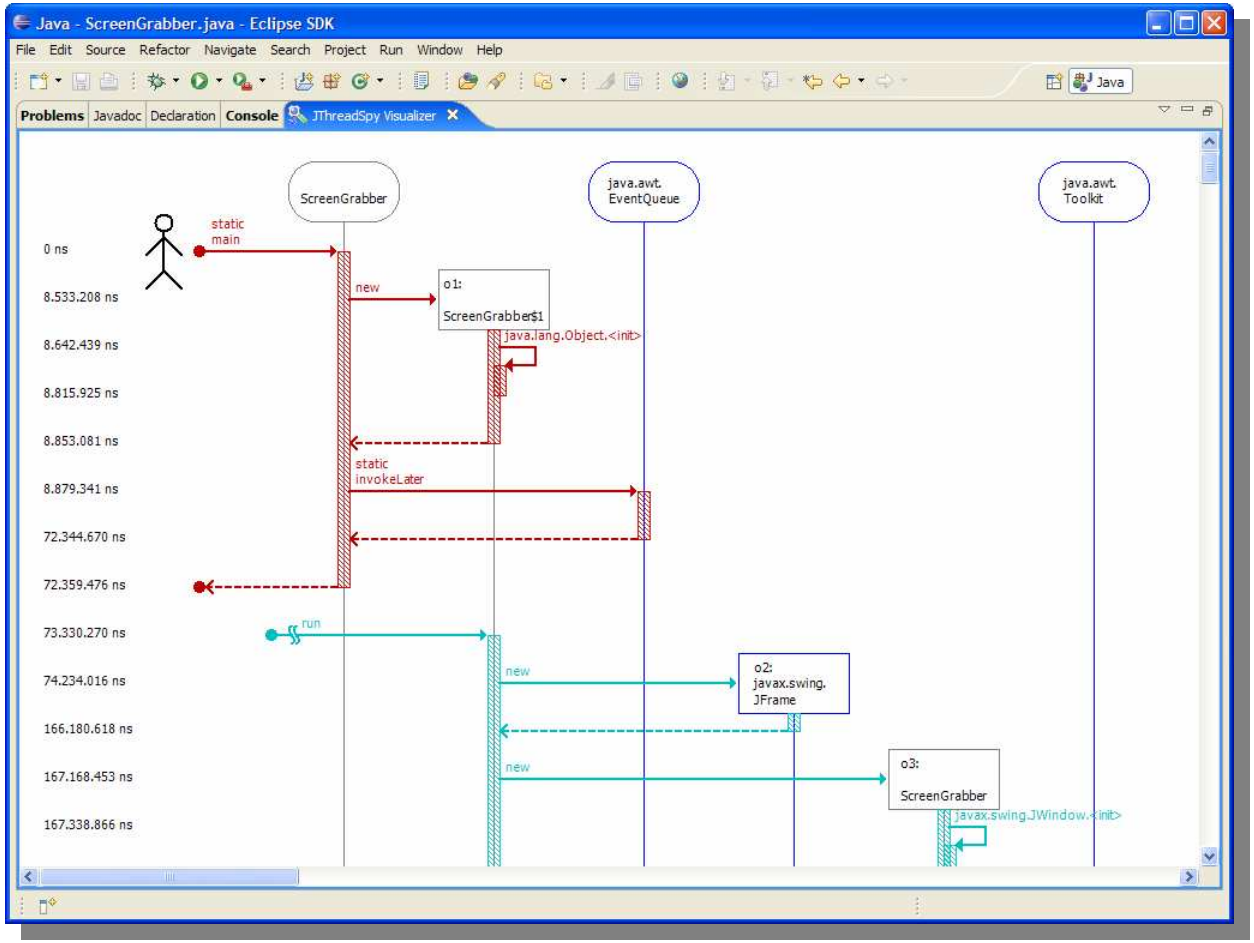
Results

- First student feedbacks are generally positive
  - The tool helps in creating a visual representation of the execution of programs
  - It stimulates personal experimentation and it highlights several details of the inner working of the JVM, which are often disregarded in OO courses
  - People tend to engage more and to contribute to the improvement of the tool with useful suggestions
- Still a lot of work to be done
  - Currently tested only with a small “controlled” group (15 people)
  - Next year it will be used with the whole class (about 150 students)

Current issues and future work

- Enhance the code rewrite engine
  - Provide support for the semantics of the Java Synchronization Framework classes and interfaces
  - Trace access to object fields
- Introduce reasoning about collected data
  - Highlight possible conflicts
  - Identify blocked threads
  - Provide suggestions about possible anti-patterns
- Improve the usability of the visualizer
  - Print information about the pointed object
  - Introduce a navigation modality, in order to follow the execution of a given thread, automatically scrolling back and forth
  - Support dynamic object layout rearrangement

JThreadSpy in action



Thank you!

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