5. Testing and Debugging

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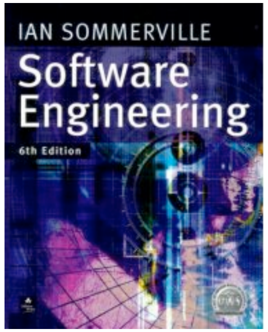
Testing and Debugging

Sources

- I. Sommerville, *Software Engineering*, Addison-Wesley, Sixth Edn., 2000.
- svnbook.red-bean.com
- www.eclipse.org



Roadmap

- Testing — definitions and strategies
- Understanding the run-time stack and heap
- Debuggers
- Timing benchmarks
- Profilers

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> **Testing — definitions and strategies**
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Testing

Unit testing:	test *individual (stand-alone) components*
Module testing:	test a *collection of related components* (a module)
Sub-system testing:	test *sub-system interface mismatches*
System testing:	(i) test *interactions between sub-systems*, and (ii) test that the complete systems fulfils *functional and non-functional requirements*
Acceptance testing (alpha/beta testing):	test system with *real rather than simulated data*.

Testing is always iterative!

Regression testing

Regression testing means testing that *everything that used to work still works* after changes are made to the system!

- tests must be *deterministic and repeatable*
- should test "all" functionality
  - every interface (black-box testing)
  - all boundary situations
  - every feature
  - every line of code (white-box testing)
  - everything that can conceivably go wrong!

It costs extra work to define tests up front, but they more than pay off in debugging & maintenance!

Caveat: Testing and Correctness

"Program testing can be used to show the presence of bugs, but never to show their absence!"

—Edsger Dijkstra, 1970

Testing a Stack

We define a simple regression test that exercises all StackInterface methods and checks the boundary situations:

```
public class LinkStackTest {
   protected StackInterface stack;
   private int size;

   @Before public void setUp() {
     stack = new LinkStack();
   }

   @Test public void empty() {
     assertTrue(stack.isEmpty());
     assertEquals(0, stack.size());
   }
…
```

Build simple test cases

Construct a test case and check the obvious conditions:

```
@Test public void oneElement() {
  stack.push("a");
  assertFalse(stack.isEmpty());
  assertEquals(1, size = stack.size());
  stack.pop();
  assertEquals(size -1, stack.size());
}
```

✎ *What other test cases do you need to fully exercise a Stack implementation?*

Check that failures are caught

How do we check that an assertion fails when it should?

```
@Test(expected=AssertionError.class)
public void emptyTopFails() {
  stack.top();
}

@Test(expected=AssertionError.class)
public void emptyRemoveFails() {
  stack.pop();
}
```

ArrayStack

We can also implement a (variable) Stack using a (fixed-length) array to store its elements:

```
public class ArrayStack implements StackInterface {
   private Object store [] = null;      // default value
   private int capacity = 0;            // current size of store
   private int size = 0;                // number of used slots
...
```

✎ *What would be a suitable class invariant for ArrayStack?*

ArrayStack

We can also implement a (variable) Stack using a (fixed-length) array to store its elements:

```
public class ArrayStack implements StackInterface {
   private Object store [];
   private int capacity;
   private int size;

   public ArrayStack() {
     store = null;        // default value
     capacity = 0;     // available slots
     size = 0;         // used slots
   }
```

✎ *What would be a suitable class invariant for ArrayStack?*

Handling overflow

Whenever the array runs out of space, the Stack "grows" by allocating a larger array, and copying elements to the new array.

```
public void push(Object item)
{
    if (size == capacity) {
      grow();
    }
    store[++size] = item;       // NB: subtle error!
}
```

✎ *How would you implement the grow() method?*

Checking pre-conditions

```
public boolean isEmpty() { return size == 0; }
public int size() { return size; }

public Object top() {
   assert(!this.isEmpty());
   return store[size-1];
}
public void pop() {
   assert(!this.isEmpty());
   size--;
}
```

NB: we only check pre-conditions in this version!

✎ *Should we also shrink() if the Stack gets too small?*

Adapting the test case

We can easily adapt our test case by overriding the `setUp()` method in a subclass.

```
public class ArrayStackTest extends LinkStackTest {
   @Before public void setUp() {
     stack = new ArrayStack();
   }
}
```

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Testing ArrayStack

When we test our `ArrayStack`, we get a surprise:

```
java.lang.ArrayIndexOutOfBoundsException: 2
   at p2.stack.ArrayStack.push(ArrayStack.java:27)
   at p2.stack.LinkStackTest.twoElement(LinkStackTest.java:46)
   at ...
```

*The stack trace tells us exactly **where** the exception occurred ...*

The Run-time Stack

The **run-time stack** is a fundamental data structure used to record the *context* of a procedure that will be returned to at a later point in time. This **context** (AKA "**stack frame**") *stores the arguments to the procedure and its local variables*.

Practically all programming languages use a run-time stack:

```
public static void main(String args[]) {
  System.out.println( "fact(3) = " + fact(3));
}
public static int fact(int n) {
  if (n<=0) { return 1; }
  else { return n*fact(n-1) ; }
}
```

The run-time stack in action ...

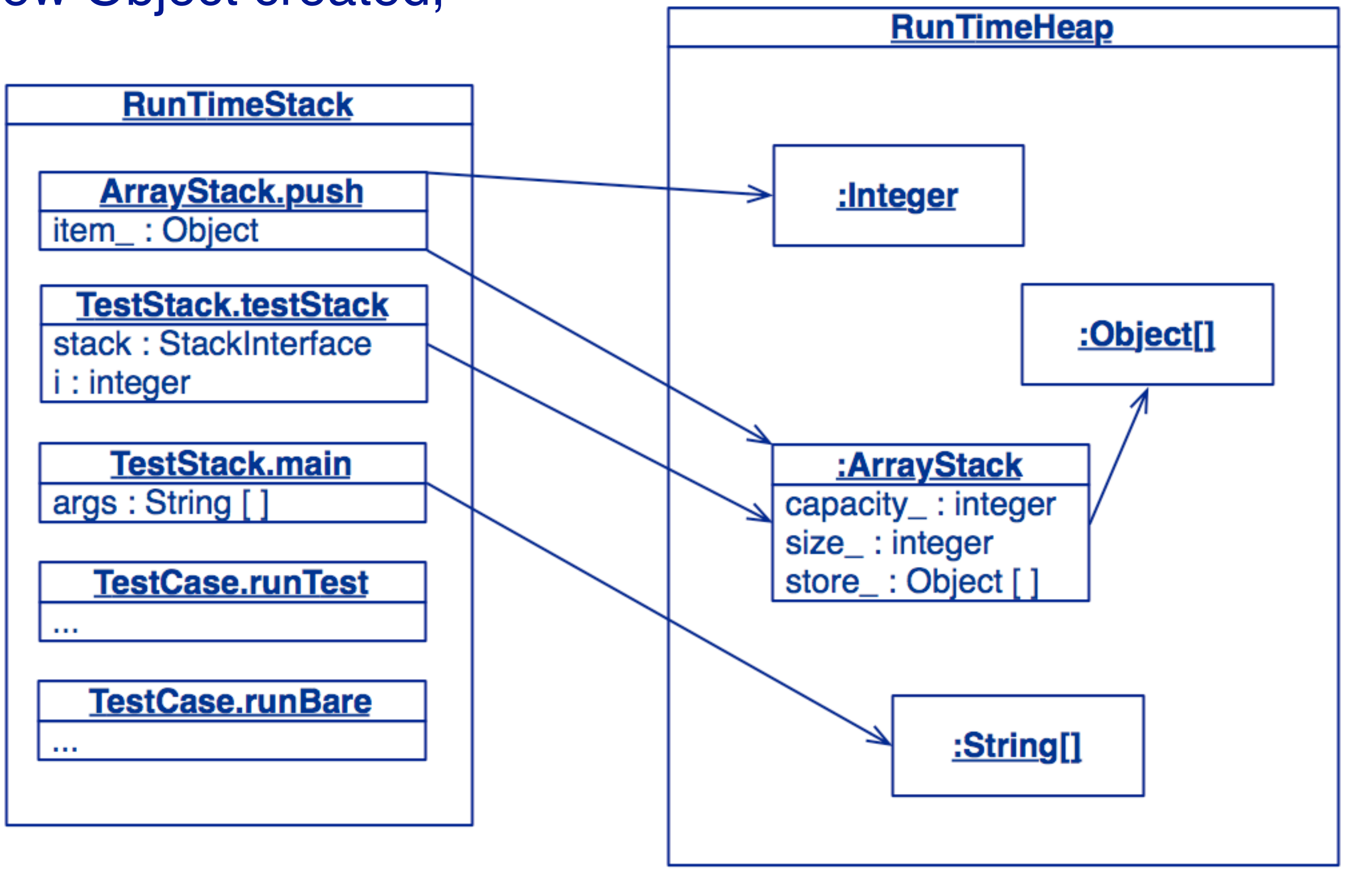
main …				
fact(3)=?	n=3; ...			
fact(3)=?	n=3;fact(2)=?	n=2;fact(2) ...		
fact(3)=?	n=3;fact(2)=?	n=2;fact(1)=?	n=1;fact(1) ...	
fact(3)=?	n=3;fact(2)=?	n=2;fact(1)=?	n=1;fact(0)=?	n=0;fact(0) ...
fact(3)=?	n=3;fact(2)=?	n=2;fact(1)=?	n=1;fact(0)=?	return 1
fact(3)=?	n=3;fact(2)=?	n=2;fact(1)=?	return 1	
fact(3)=?	n=3;fact(2)=?	return 2		
fact(3)=?	return 6			
fact(3)=6				

A stack frame is *pushed* with each procedure call ...

... and *popped* with each return.

The Stack and the Heap

The **Heap** grows with each new Object created,



and shrinks when Objects are **garbage-collected**.

NB: allocating objects is *<u>cheap</u>* *on modern VMs*

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Debuggers

A **debugger** is a tool that allows you to examine the state of a running program:

- step through the program instruction by instruction
- view the source code of the executing program
- inspect (and modify) values of variables in various formats
- set and unset breakpoints anywhere in your program
- execute up to a specified breakpoint
- examine the state of an aborted program (in a “core file”)

Using Debuggers

Interactive debuggers are available for most mature programming languages and integrated in IDEs.

Classical debuggers are *line-oriented* (e.g., jdb); most modern ones are *graphical*.

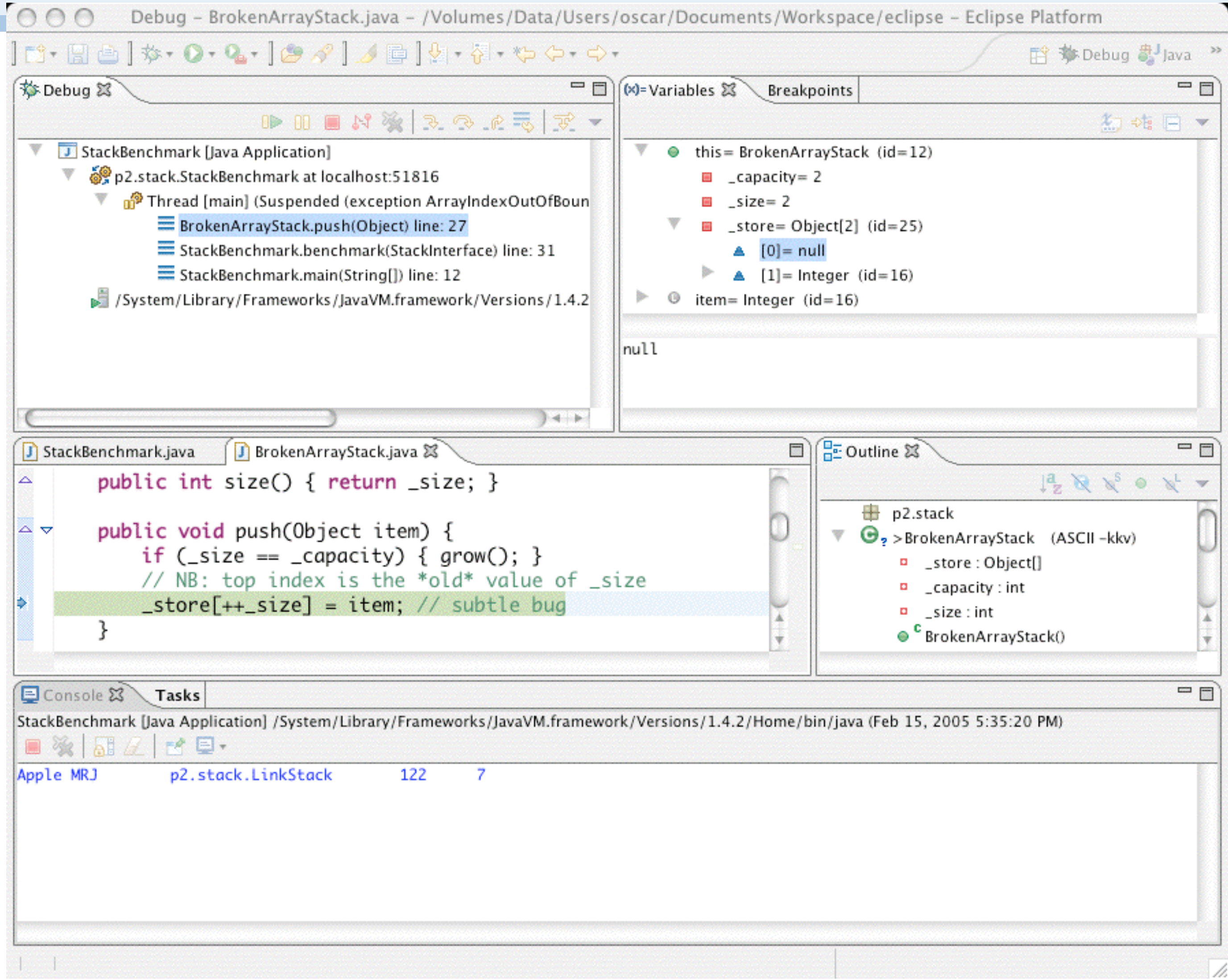
✎ When should you use a debugger?

✔ *When you are unsure why (or where) your program is not working.*

NB: debuggers are object code specific — pick the right one for your platform!

Debugging in Eclipse

When unexpected exceptions arise, you can use the debugger to **inspect** the program **state** …



Debugging Strategy

Develop tests as you program

- Apply *Design by Contract* to decorate classes with **invariants** and **pre-** and **post-conditions**
- Develop *unit tests* to exercise all paths through your program
  - use **assertions** (not print statements) to probe the program state
  - print the state **only** when an assertion fails
- After every modification, do regression testing!

If errors arise during testing or usage

- Use the test results to track down and fix the bug
- If you can't tell where the bug is, *then use a debugger* to identify the faulty code
  - fix the bug
  - identify and *add any missing tests!*

All software bugs are a matter of *false assumptions*. If you make your assumptions *explicit*, you will find and stamp out your bugs!

Fixing our mistake

We erroneously used the *incremented size* as an index into the store, instead of the new size of the stack - 1:

```
public void push(Object item) ... {
   if (size == capacity) { grow(); }
   store[size++] = item;
   assert(this.top() == item);
   assert(invariant());
}
```

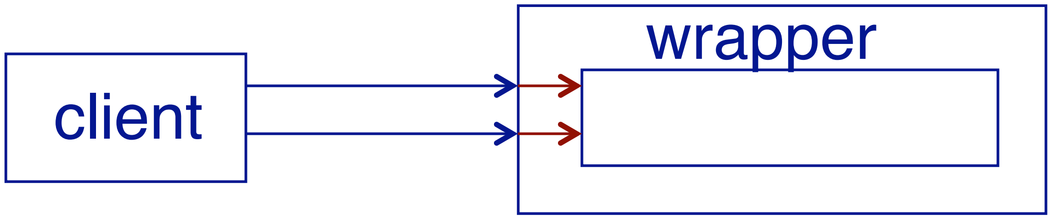
NB: perhaps it would be clearer to write:

```
store[this.topIndex()] = item;
```

Wrapping Objects

Wrapping is a fundamental programming technique for systems integration.

- ✎ What do you do with an object whose interface doesn't fit your expectations?
- ✔ *You **wrap** it.*



- ✎ *What are possible **disadvantages** of wrapping?*

java.util.Stack

Java also provides a Stack implementation, but it is not compatible with our interface:

```
public class Stack extends Vector {
   public Stack();
   public Object push(Object item);
   public synchronized Object pop();
   public synchronized Object peek();
   public boolean empty();
   public synchronized int search(Object o);
}
```

If we change our programs to work with the Java Stack, we won't be able to work with our own Stack implementations ...

A Wrapped Stack

A wrapper class implements a required interface, by ***delegating*** *requests* to an instance of the wrapped class:

```
public class SimpleWrappedStack implements StackInterface {
    Stack stack;
    public SimpleWrappedStack() { stack = new Stack(); }
    public boolean isEmpty() { return stack.empty(); }
    public int size() { return stack.size(); }
    public void push(Object item) { stack.push(item); }
    public Object top() { return stack.peek(); }
    public void pop() { stack.pop(); }
}
```

✎ *Do you see any flaws with our wrapper class?*

A contract mismatch

But running the test case yields:

```
java.lang.Exception: Unexpected exception,
expected<java.lang.AssertionError> but
was<java.util.EmptyStackException>
    ...
Caused by: java.util.EmptyStackException
    at java.util.Stack.peek(Stack.java:79)
    at p2.stack.SimpleWrappedStack.top(SimpleWrappedStack.java:32)
    at p2.stack.LinkStackTest.emptyTopFails(LinkStackTest.java:28)
    ...
```

✎ *What went wrong?*

Fixing the problem ...

Our tester ***expects*** an empty Stack to throw an exception when it is popped, but java.util.Stack doesn't do this — *so our wrapper should check its preconditions!*

```
public class WrappedStack implements StackInterface {
   public Object top() {
      assert !this.isEmpty();
      return super.top();
   }
   public void pop() {
      assert !this.isEmpty();
      super.pop();
      assert invariant();
   }
   …
}
```

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Timing benchmarks

Which of the Stack implementations performs better?

```
timer.reset();
for (int i=0; i<iterations; i++) {
   stack.push(item);
}
elapsed = timer.timeElapsed();
System.out.println(elapsed + " milliseconds for "
      + iterations + " pushes");
...
```

✎ Complexity aside, how can you tell which implementation strategy will perform best?

✔ *Run a benchmark.*

Timer

```
import java.util.Date;
public class Timer {                    // Abstract from the
   protected Date startTime;           // details of timing
   public Timer() {
     this.reset();
   }
   public void reset() {
     startTime = new Date();
   }
   public long timeElapsed() {
     return new Date().getTime() - startTime.getTime();
   }
}
```

Sample benchmarks (milliseconds)

Stack Implementation	***100K pushes***	***100K pops***
p2.stack.LinkStack	126	6
p2.stack.ArrayStack	138	3
p2.stack.**WrappedStack**	104	154

✎ *Can you explain these results? Are they what you expected?*

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Profilers

A profiler tells you where a terminated program has *spent its time*.

1. your program must first be *instrumented* by
   I. setting a compiler (or interpreter) option, or
   II. adding instrumentation code to your source program
2. the program is run, generating a profile data file
3. the profiler is executed with the profile data as input

The profiler can then display the call graph in various formats

Caveat: the technical details vary from compiler to compiler

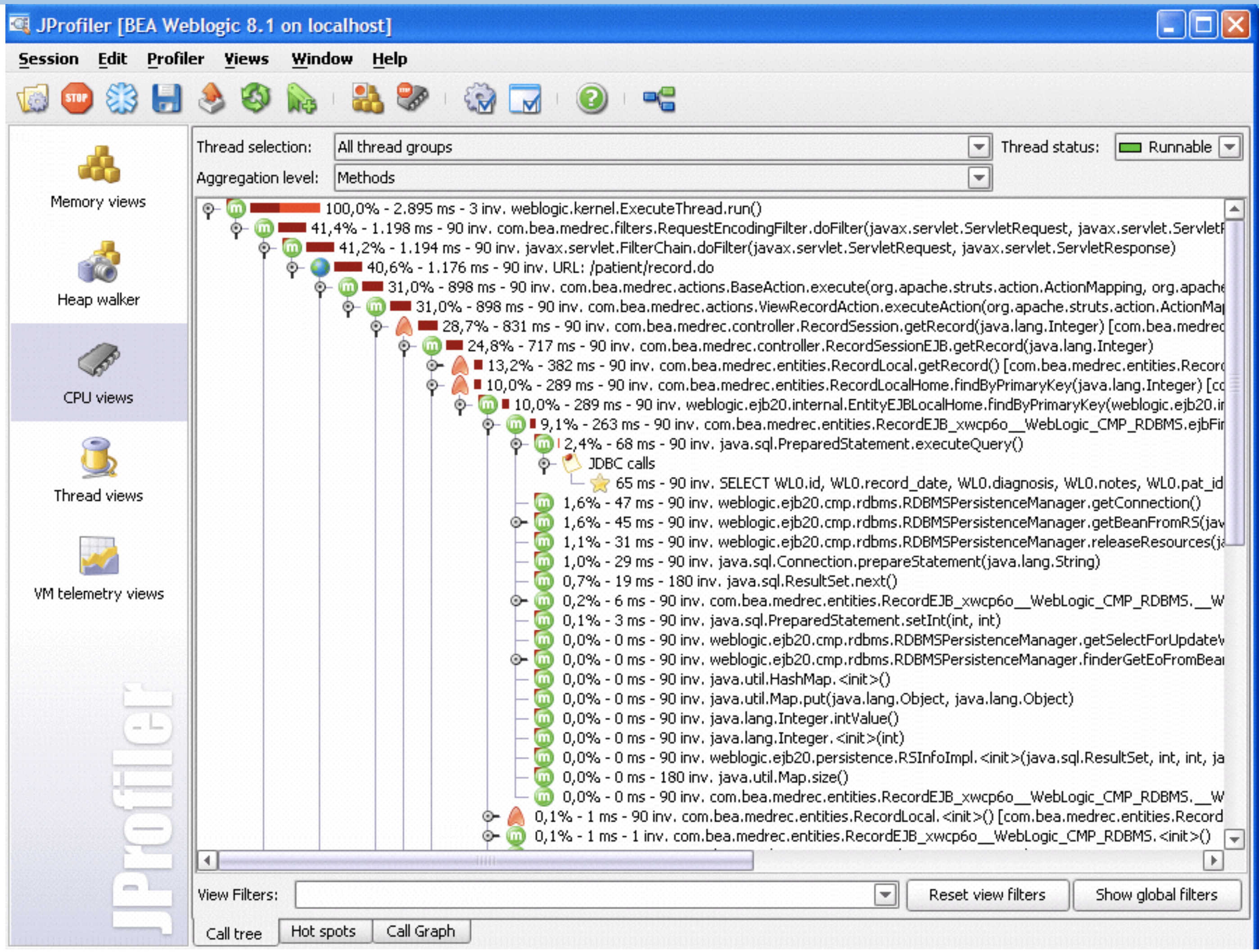
Using java -Xprof

```
Flat profile of 0.61 secs (29 total ticks): main

  Interpreted + native   Method
 20.7%      0  +     6    java.io.FileOutputStream.writeBytes
  3.4%      0  +     1    sun.misc.URLClassPath$FileLoader.<init>
  3.4%      0  +     1    p2.stack.LinkStack.push
  3.4%      0  +     1    p2.stack.WrappedStack.push
  3.4%      0  +     1    java.io.FileInputStream.open
  3.4%      1  +     0    sun.misc.URLClassPath$JarLoader.getResource
  3.4%      0  +     1    java.util.zip.Inflater.init
  3.4%      0  +     1    p2.stack.ArrayStack.grow
 44.8%      1  +    12    Total interpreted

…
```

Example of Profiler Features



Using Profilers

✎ When should you use a profiler?

✔ *Always run a profiler before attempting to tune performance.*

✎ How early should you start worrying about performance?

✔ *Only after you have a clean, running program with poor performance.*

NB: The call graph also tells you which parts of the program have (not) been tested!

http://www.javaperformancetuning.com/resources.shtml#ProfilingToolsFree

What you should know!

- ✎ *What is a **regression test**? Why is it important?*
- ✎ *What **strategies** should you apply to design a test?*
- ✎ *What are the **run-time** stack and **heap**?*
- ✎ *How can you adapt client/supplier **interfaces** that don't **match**?*
- ✎ *When are **benchmarks** useful?*

Can you answer these questions?

- ✎ *Why can't you use tests to demonstrate absence of defects?*
- ✎ *How would you implement ArrayStack.grow()?*
- ✎ *Why doesn't Java allocate objects on the run-time stack?*
- ✎ *What are the advantages and disadvantages of wrapping?*
- ✎ *What is a suitable class invariant for WrappedStack?*
- ✎ *How can we learn where each Stack implementation is spending its time?*
- ✎ *How much can the same benchmarks differ if you run them several times?*

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