D-I-Y (Diagnose-It-Yourself): Adaptive Monitoring for Sun Java™ Real-Time System

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Java

Sun microsystems

Agenda

- Need for a Real-Time Monitoring Tool
- Sun Java™ Real-Time System Solaris™ Dynamic Tracing Provider
- Test Cases
- Troubleshooting Tools
- Conclusion

Need for a Real-Time Monitoring Tool

- Complexity of real-time scheduling
  - Run-to-block scheduling policy
  - Priority Inheritance
  - Real-Time Garbage Collection (RTGC)
- Tracking of fleeting events
  - Polling is unadapted
  - “Exact” monitoring
- Computation-oriented rather than method-oriented
  - CPU time / non-running time per period
  - Behavior variations
  - Priority

The Observer Effect

- Definition
  - Changes that the act of observing will make to the phenomenon being observed
- Inevitable in a real system
  - Monitoring code needs:
    - Memory
    - CPU
    - Synchronizations
- Example with dynamic bytecode instrumentation
  - `redefineClass`
    - New class loaded
    - Compilation of modified methods
    - De-optimization of running threads

Observer Effect and Real-Time

- Acceptable in many non-real-time cases
  - Throughput measurement: pessimistic values
  - Memory consumption: over-estimate memory requirement
- Impact on real-time application behavior
  - Additional CPU consumption can cause deadline misses
  - Additional memory consumption can require RTGC reconfiguration
  - Code modification will impact compilation scheme (ITC)
- Consequence
  - Real-time application switching to error management mode

WANTED

- Real-Time Monitoring tool
- Low overhead
- No synchronization
- Supported in production
- No heap allocations
- No application code modification

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Solaris Dynamic Tracing (DTrace)

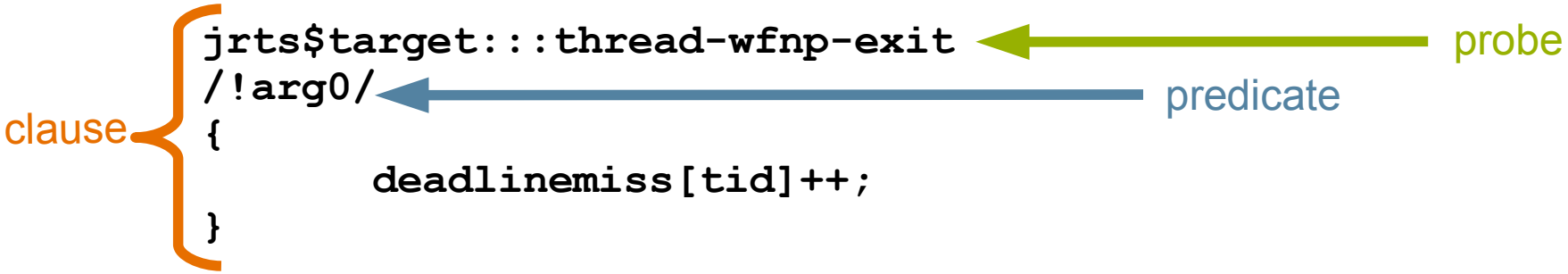
- DTrace components
  - Probes
  - Activation mechanism
  - D language
- Dynamic Tracing
  - No overhead if probes not enabled
  - Safe in production mode
  - Dynamic activation
  - Low overhead
- D language
  - Predicates
  - Aggregates
  - Speculative tracing

DTrace Script Example

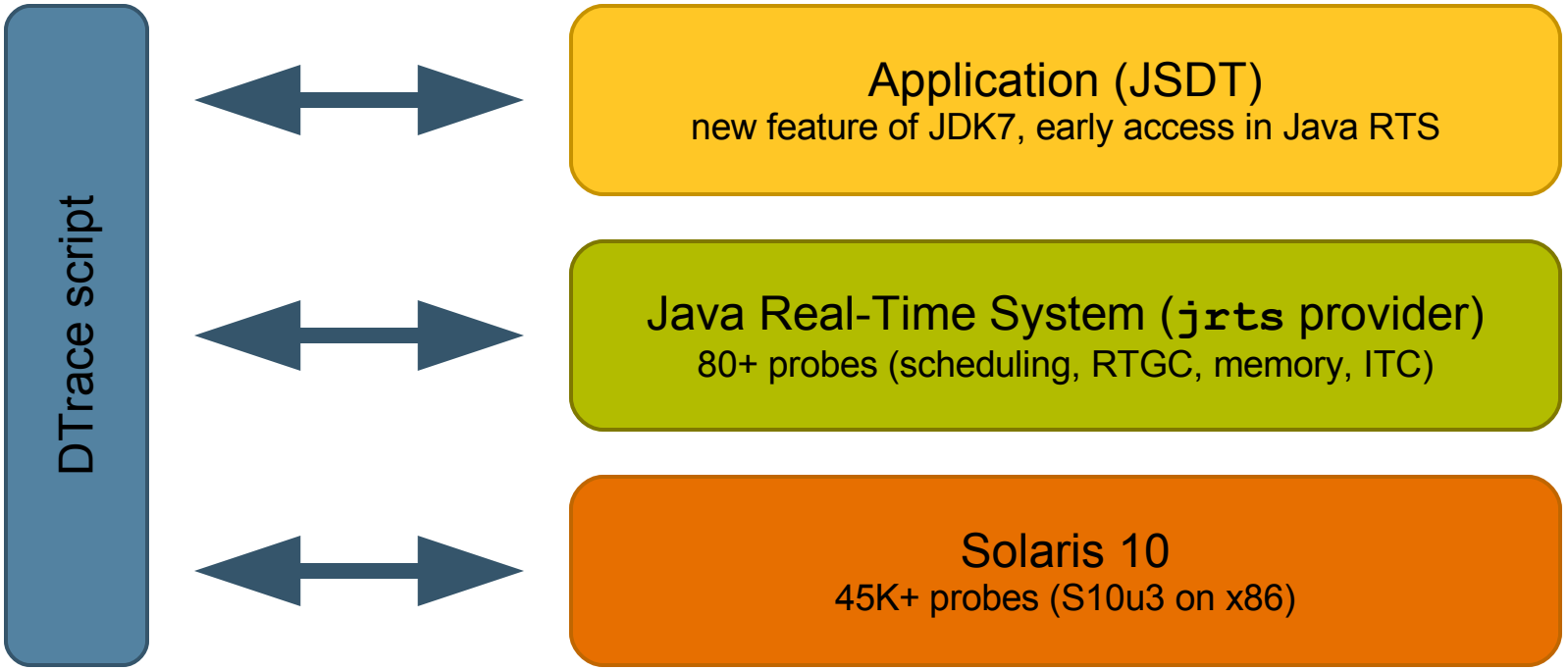
```
#!/usr/bin/dtrace -q

jrts$target:::thread-wfnp-exit
/!arg0/
{
        deadlinemiss[tid]++;
}

jrts$target:::thread-end
/deadlinemiss[tid]>0/
{
        printf("Thread %d missed %d deadlines\n",
        tid,deadlinemiss[tid]);
}
```



DTrace with the Java Real-Time System (Java RTS)/ Solaris Operating System (Solaris OS) Stack



One script, one language, to monitor everything from the application to the OS

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  - Deadline Miss Analysis
  - Profiling
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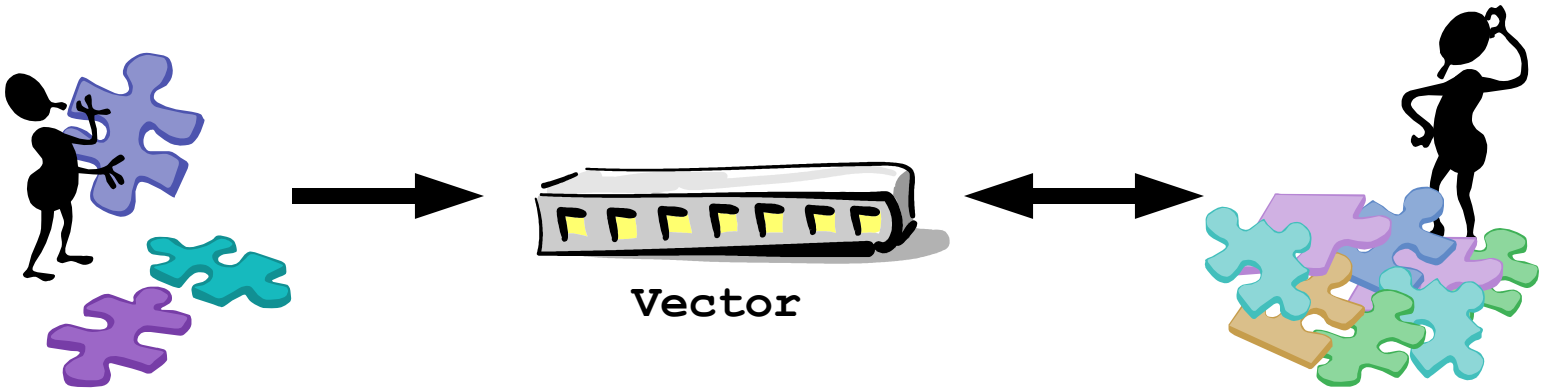
First Test Case: Deadline Miss Analysis



RealTimeProducer
`RealtimeThread`
Period: 500ms
Adds 10 values to the **`Vector`** at each period

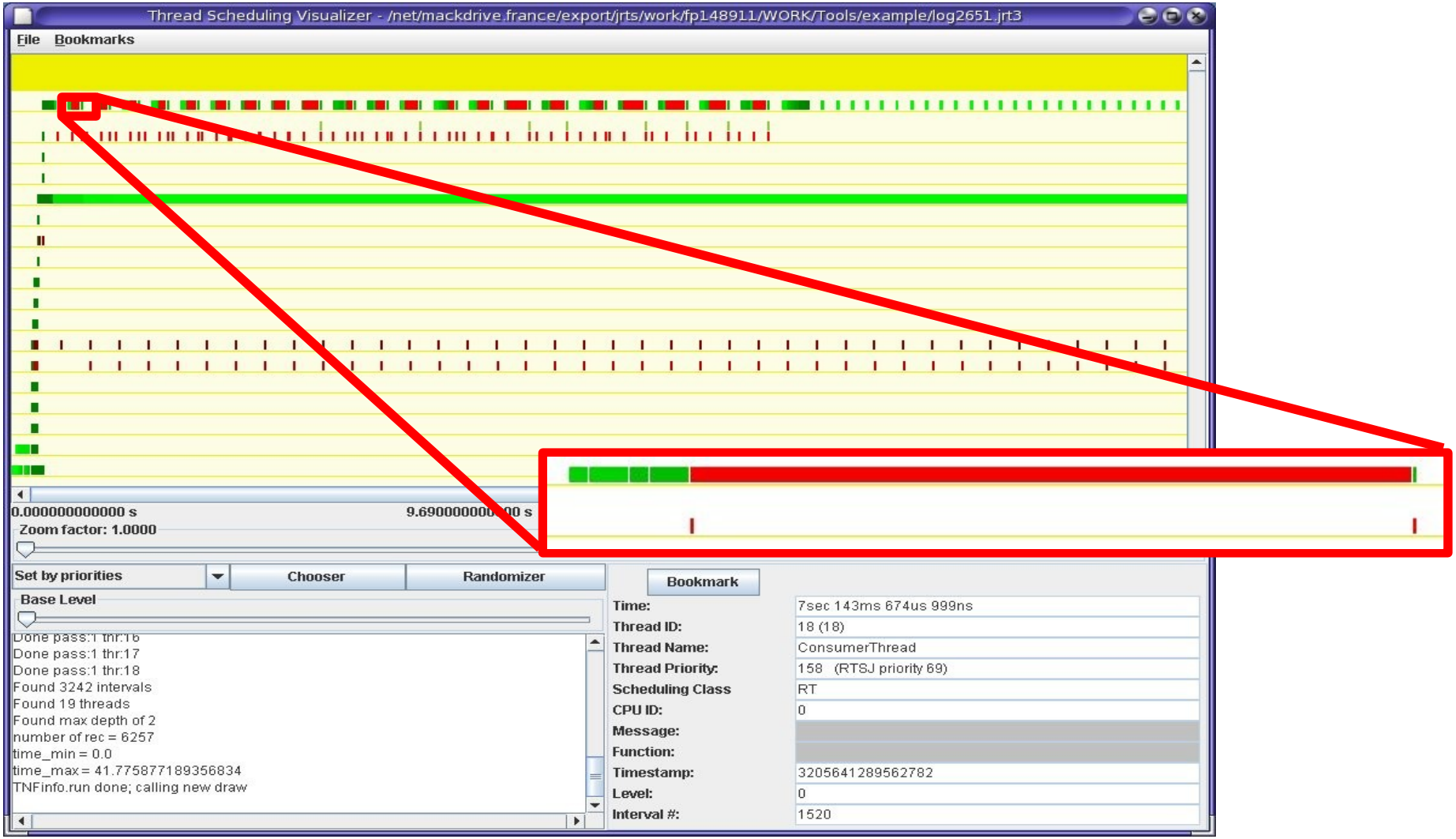
ConsumerThread
`java.lang.Thread`
Loop:
Sort **`Vector`**'s data
Sleep ~500ms

Problem: The RealTimeProducer thread misses some of its deadlines.

First Step: Scheduling Recording

- Objective
  - Find a hint about the cause of the deadline misses
- DTrace monitoring script
  - Scheduling events (threads getting and leaving a CPU)
  - Priority changes
  - Log of events generated for off-line analysis
- Scheduling visualization
  - External tool
  - Post-mortem analysis

Second Step: Scheduling Visualization



Third Step: Lock Contention Investigation

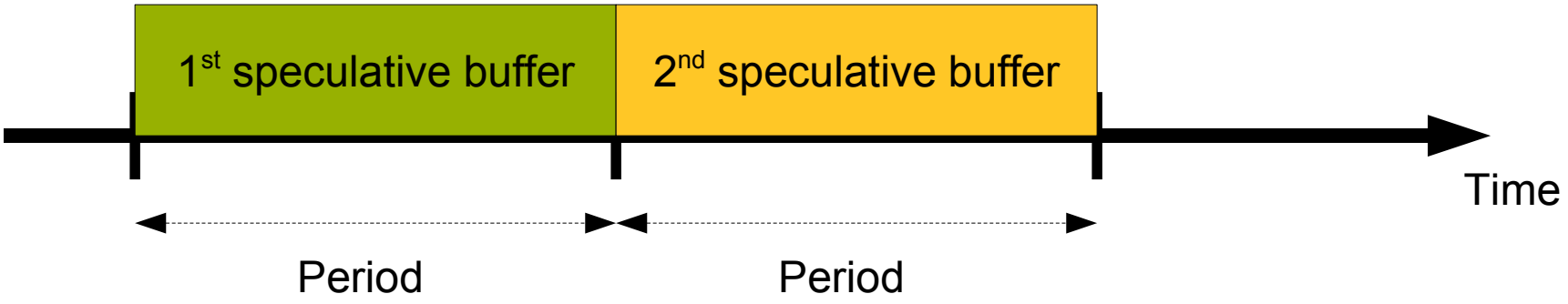
- Objective
  - Confirm the hypothesis of the lock contention issue
  - Identify the problematic lock
- New DTrace script
  - Focused on the RealtimeProducer thread
    - `jrts$target:::thread-start`
    - Predicate: `/thr_id == tid/`
  - Tracking lock contention
    - `jrts$target:::monitor-contended-enter`
    - `jrts$target:::monitor-contended-entered`
  - Tracking priority boosting
    - `sched:::change-pri`
  - Deadline miss notification
    - `jrts$target:::user-event`

Too many events!

```
3642445575887862 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642445575932205 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3642445796606949 : [JRTS] RealTimeProducer enters a contended monitor (after 220719 microseconds)
3642446575892966 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642446575943118 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3642446767605273 : [JRTS] RealTimeProducer enters a contended monitor (after 191712 microseconds)
3642447575882614 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642447575924705 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3642447753314551 : [JRTS] RealTimeProducer enters a contended monitor (after 177431 microseconds)
3642448575929562 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642448575986579 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3642448779819289 : [JRTS] RealTimeProducer enters a contended monitor (after 203889 microseconds)
3642449575885886 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642449575936830 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3642449821475798 : [JRTS] RealTimeProducer enters a contended monitor (after 245589 microseconds)
3642450575887460 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642450575939881 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3642450875563014 : [JRTS] RealTimeProducer enters a contended monitor (after 299675 microseconds)
3642451575890636 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642451575944081 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3642451924810593 : [JRTS] RealTimeProducer enters a contended monitor (after 348919 microseconds)
3642452575889523 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c10d8
3642452575940020 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
```

Fourth Step: Speculative Tracing

- Objective:
  - Reduce the output to the faulty periods



- Beginning of the period: creation of a speculative buffer
- During the period: all events are logged into this buffer
- At the end of the period:
  - If no deadline miss occurred, buffer is discarded.
  - If a deadline miss is detected, buffer is flushed to the output.

Focused Output from Speculative Tracing

- Output from faulty periods

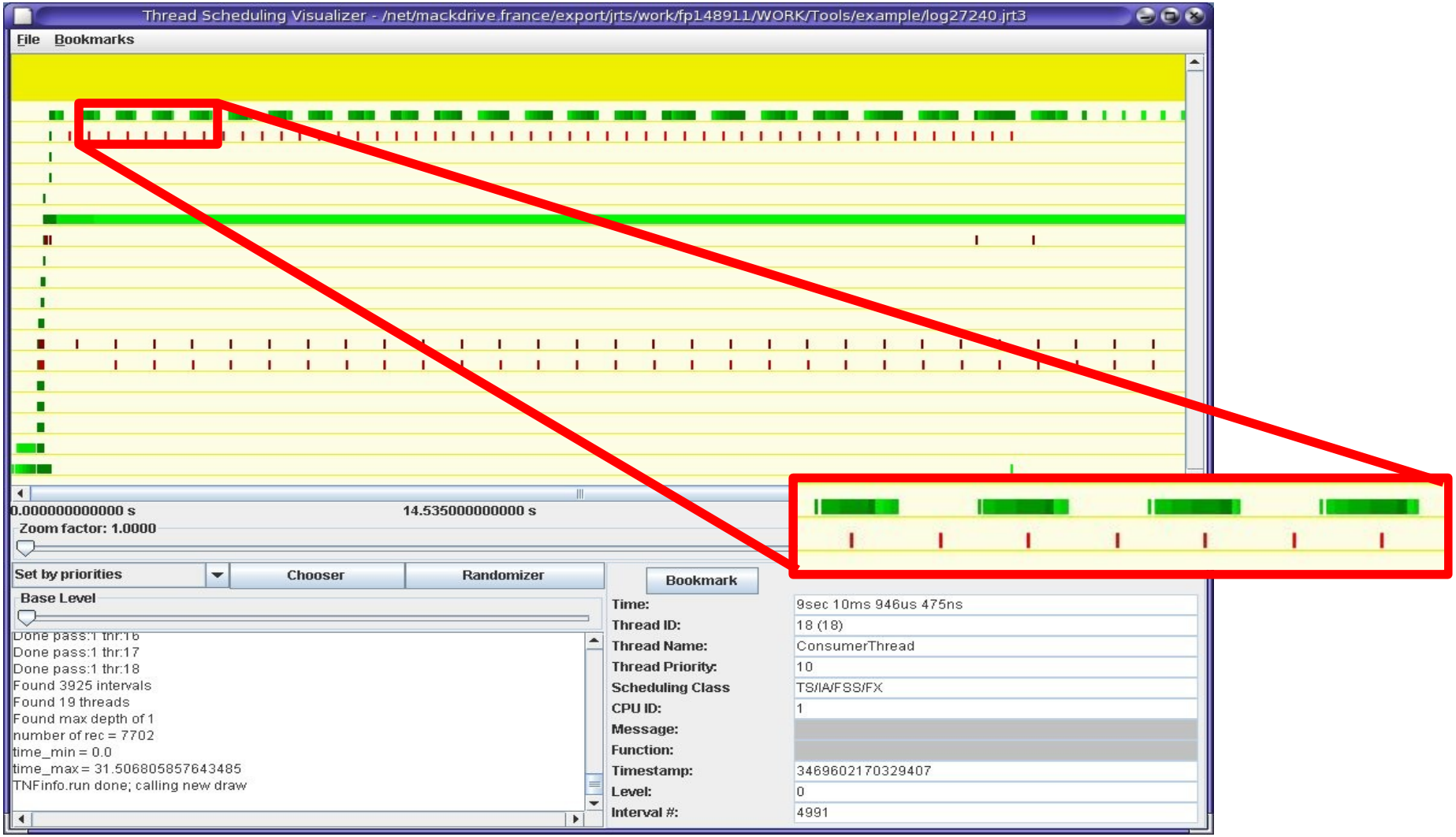
```
Deadline miss at iteration 14
3216035761543004 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c2a78
3216035761604293 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3216036277599464 : [JRTS] RealTimeProducer enters a contended monitor (after 516056 microseconds)
3216036278548215 : [USER] RealTimeProducer is notifying: Deadline miss at iteration 14
Deadline miss at iteration 23
3216040261484198 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c2a78
3216040261532375 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3216040791348997 : [JRTS] RealTimeProducer enters a contended monitor (after 529864 microseconds)

3216040791528654 : [USER] RealTimeProducer is notifying: Deadline miss at iteration 23
```

- The class of the lock is known.
- Is it possible to get the method name?
  - Call stack inspection: **`jstack()`**

Final Step: Call Stack Inspection

```
Deadline miss at iteration 16
3554713806699954 : [JRTS] RealTimeProducer tries to enter contended monitor java/util/Vector@81c2a78
              libjvm.so`void ObjectMonitor::enter_interruptible(int,Thread*)+0x284
              libjvm.so`void ObjectSynchronizer::instance_slow_enter(Handle,BasicLock*,int,Thread*)+0x16a
              libjvm.so`void ObjectSynchronizer::slow_enter_interruptible(Handle,BasicLock*,int,Thread*)+0x37
              libjvm.so`void InterpreterRuntime::monitorenter(JavaThread*,BasicObjectLock*)+0x63
              java/util/Vector.add
              synchronizedvector/Main$RealTimeProducer.run
              StubRoutines (1)
              libjvm.so`void JavaCalls::call_helper(JavaValue*,methodHandle*,JavaCallArguments*,Thread*)+0x1a1
              libjvm.so`void os::os_exception_wrapper(void(*)(JavaValue*,methodHandle*,JavaCallArguments*,Thre
              libjvm.so`void JavaCalls::call(JavaValue*,methodHandle,JavaCallArguments*,Thread*)+0x28
              libjvm.so`void JavaCalls::call_virtual(JavaValue*,KlassHandle,symbolHandle,symbolHandle,JavaCall
              libjvm.so`void JavaCalls::call_virtual(JavaValue*,Handle,KlassHandle,symbolHandle,symbolHandle,T
              libjvm.so`void thread_entry(JavaThread*,Thread*)+0x12b
              libjvm.so`void RealtimeThread::thread_main_inner()+0x154
              libjvm.so`void JavaThread::run()+0x163
              libjvm.so`void*_start(void*)+0x4c
              libc.so.1`_thr_setup+0x4e
              libc.so.1`_lwp_start
3554713807556194 : [SOLARIS] RealTimeProducer is changing ConsumerThread's priority to 158
3554714315214592 : [JRTS] RealTimeProducer enters a contended monitor (after 508514 microseconds)
3554714316098828 : [USER] RealTimeProducer is notifying: Deadline miss at iteration 16
```

Scheduling of the New Code



First Test Case Solved

- Cause of deadline misses found
  - Synchronized method of class Vector
  - Replacement of the `Vector` instance by a `WaitFreeWriteQueue` instance solves the issue
- What has been achieved with DTrace
  - Overview of the application scheduling
  - Tracking of Java environment events: lock contention on Java object
  - Focused tracing on faulty behavior using speculative tracing
  - Inspection of call stacks including Java code

Second Test Case: Profiling

- Real-Time measurements are often “computation-based” and not “method-based”
- Execution time has two components:
  - CPU time
  - Non-running time (waiting, blocked, preempted)
- DTrace script to profile periodic execution
  - Measure execution for each periodic execution (whatever methods are called)
  - Measure elapsed time and CPU time
    - `timestamp`, `vtimestamp`
  - Display results with distribution graphs
    - `@exectime[tid] = quantize(end[tid]-begin[tid]);`

Profiling : Test Case Description

- Same computation code executed in three different contexts:
  - High Priority **`RealtimeThread`**
    - High Real-Time priority
    - using **`waitForNextPeriod()`**
  - Low Priority **`RealtimeThread`**
    - Low Real-Time priority (same priority as RTGC)
    - using **`waitForNextPeriod()`**
  - **`java.lang.Thread`**
    - Time-Sharing priority
    - Emulating **`waitForNextPeriod()`** with **`sleep()`**
    - Using user-events to emulate **`waitForNextPeriod()`** DTrace probes

Execution Times per Period

Per thread, expressed in microseconds

HighPriorityRealtimeThread

```
value  ------------- Distribution ------------- count
22000 |                                         0
23000 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ 200
24000 |                                         0
```

LowPriorityRealtimeThread

```
value  ------------- Distribution ------------- count
22000 |                                         0
23000 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@   195
24000 |                                         1
25000 |                                         0
26000 |                                         0
27000 |                                         1
28000 |                                         1
29000 |                                         0
30000 |                                         2
31000 |                                         0
```

RegularJavaThread

```
value  ------------- Distribution ------------- count
22000 |                                         0
23000 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@    178
24000 |                                         1
25000 |                                         0
26000 |                                         1
27000 |                                         2
28000 |@                                        6
29000 |                                         0
30000 |                                         0
31000 |                                         1
32000 |                                         0
33000 |                                         0
34000 |                                         0
35000 |                                         0
36000 |                                         0
37000 |                                         0
38000 |                                         0
39000 |                                         0
40000 |                                         0
41000 |                                         0
42000 |                                         0
43000 |                                         0
44000 |                                         0
45000 |                                         0
46000 |@                                        6
47000 |@                                        5
48000 |                                         0
```

- Each thread shows a different behavior

CPU Times per Period

Per thread, expressed in microseconds

```
HighPriorityRealtimeThread
           value  ------------- Distribution ------------- count
           22000 |                                         0
           23000 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ 200
           24000 |                                         0

  LowPriorityRealtimeThread
           value  ------------- Distribution ------------- count
           22000 |                                         0
           23000 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ 200
           24000 |                                         0

  RegularJavaThread
           value  ------------- Distribution ------------- count
           22000 |                                         0
           23000 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@   190
           24000 |@@                                       9
           25000 |                                         1
           26000 |                                         0
```

- But CPU times are the same

Blocked+Preempted Times per Period

Per thread, expressed in microseconds

HighPriorityRealtimeThread

```
value  ------------- Distribution ------------- count
  < 0 |                                         0
    0 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@ 200
 1000 |                                         0
```

LowPriorityRealtimeThread

```
value  ------------- Distribution ------------- count
  < 0 |                                         0
    0 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@   196
 1000 |                                         0
 2000 |                                         0
 3000 |                                         1
 4000 |                                         1
 5000 |                                         0
 6000 |                                         2
 7000 |                                         0
```

RegularJavaThread

```
value  ------------- Distribution ------------- count
  < 0 |                                         0
    0 |@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@  179
 1000 |                                         0
 2000 |                                         1
 3000 |@@                                       8
 4000 |                                         0
 5000 |                                         0
 6000 |                                         1
 7000 |                                         0
 8000 |                                         0
 9000 |                                         0
10000 |                                         0
11000 |                                         0
12000 |                                         0
13000 |                                         0
14000 |                                         0
15000 |                                         0
16000 |                                         0
17000 |                                         0
18000 |                                         0
19000 |                                         0
20000 |                                         0
21000 |                                         0
22000 |                                         0
23000 |@@                                       11
24000 |                                         0
```

- Differences come from the scheduling

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Java RTS Troubleshooting Tools

- Java 2 Platform Standard Edition 5.0 Serviceability Agent tools have been modified:
  - Need for memory-related statistics (`jmap`) and stack traces (`jstack`)
  - They suspend the live process and real-time behavior is unavailable. To be used on core files (generated using `gcore`).
  - `jmap`: memory information on heap, immortal, scoped areas.
  - `jstack`: stack trace and nature of all type of threads provided. (Thread, RealtimeThread, NoHeapRealtimeThread)

Memory Area Dump

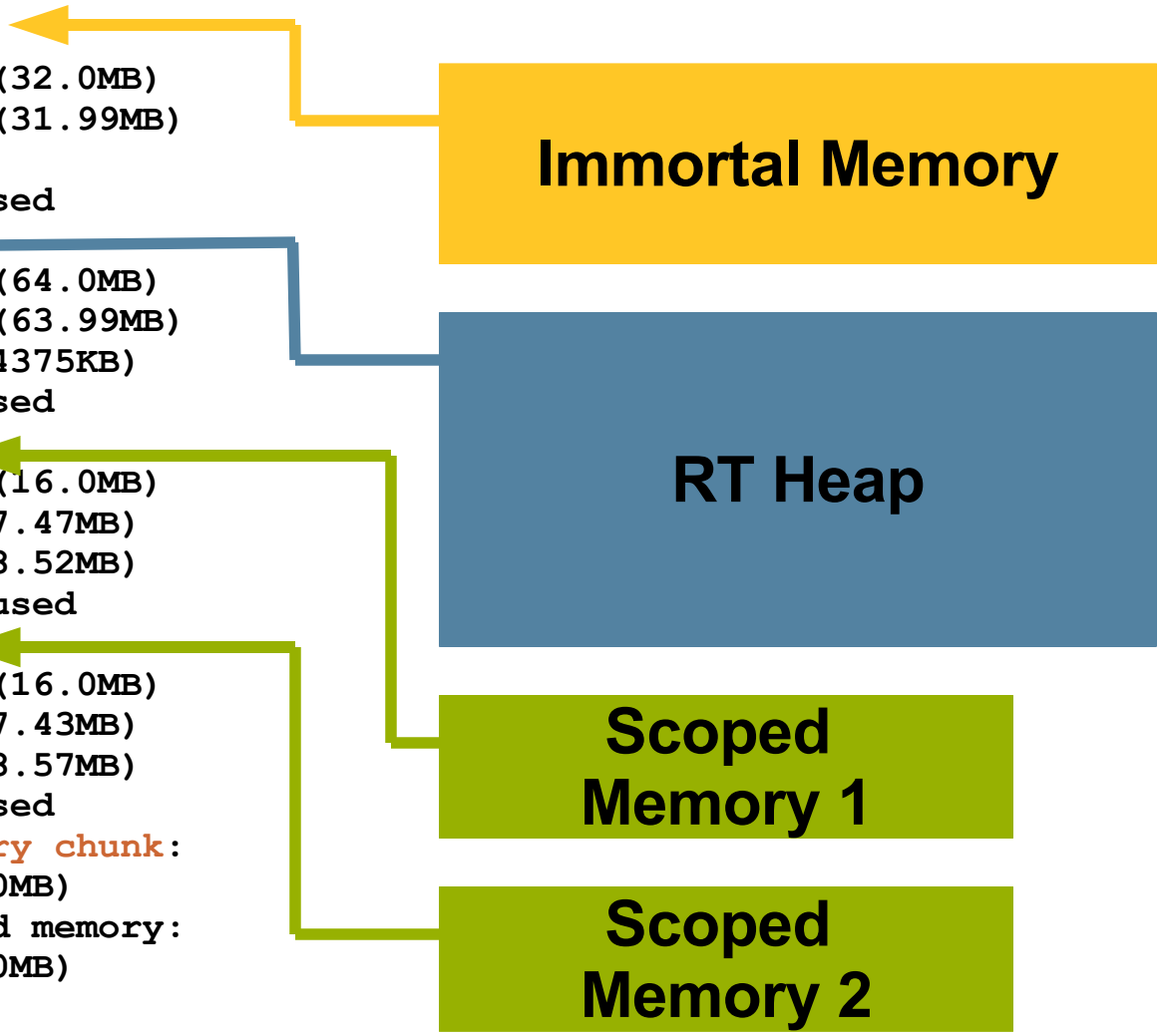
- Jmap dumps memory objects in HPROF binary format
  - "`jmap -heap:format=b`" generates `heap.bin` file that follows HPROF binary format.
  - All memory areas are dumped : Heap, Immortal memory and Scoped memory.
  - `heap.bin` can be browsed using `jhat` or `hat` (hat.dev.java.net), or even VisualVM.

jstack Sample Output

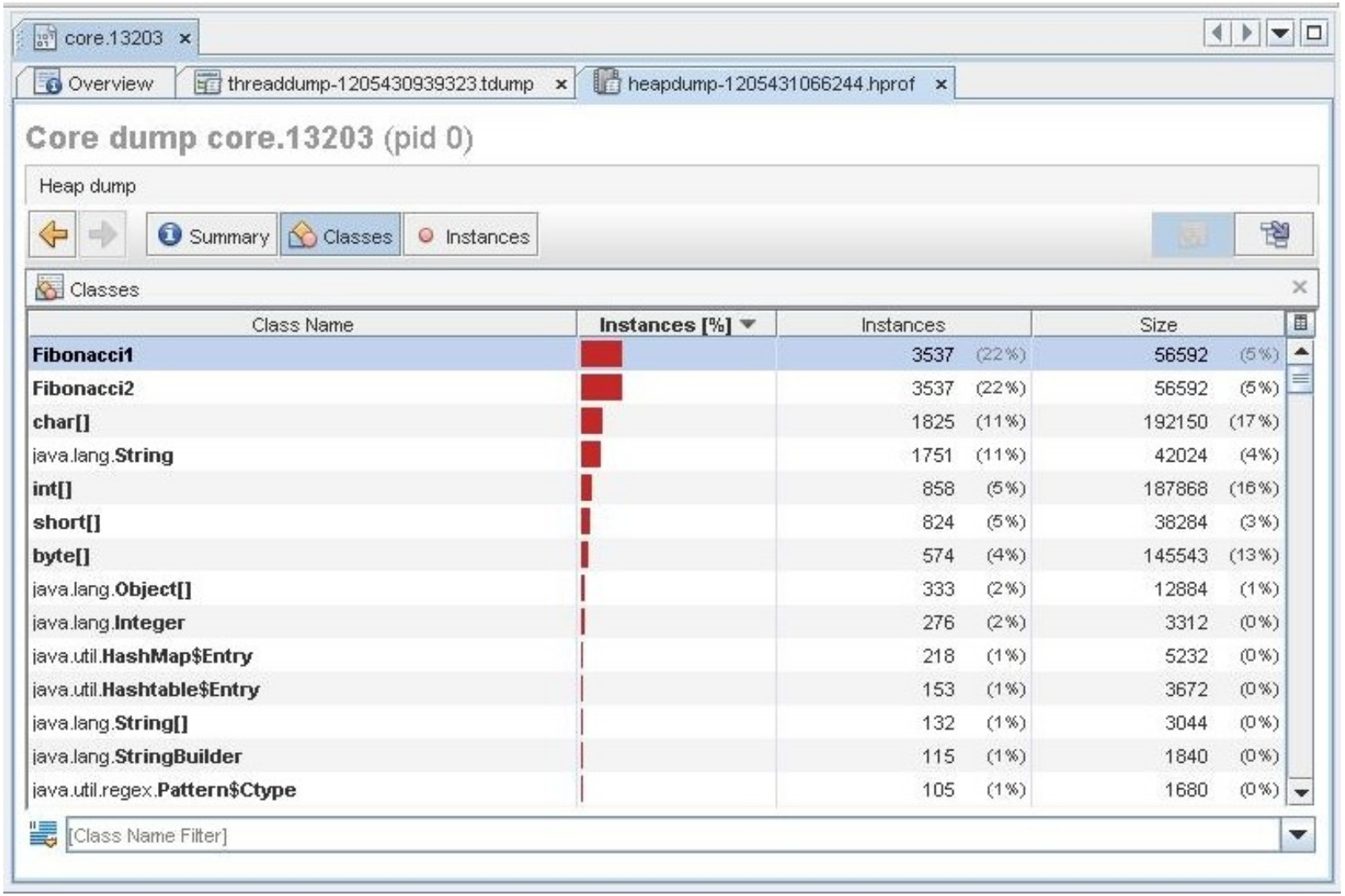
```
javax.realtime.RealtimeThread t@18: (state = IN_JAVA)
 - Fibonacci2.computeFib() @bci=17, line=35
    (Interpreted frame)
 - Deterministic.computeFibs(int, int) @bci=35, line=99
    (Interpreted frame)
 - Deterministic$RealTimeFibonacciLoops.run() @bci=90,
    line=184 (Interpreted frame)

java.lang.Thread t@1: (state = BLOCKED)
 - java.lang.Object.wait(long) @bci=-977304266
    (Interpreted frame)
 - java.lang.Object.wait(long) @bci=0 (Interpreted frame)
 - java.lang.Thread.join(long) @bci=38, line=1302
    (Interpreted frame)
 - java.lang.Thread.join() @bci=2, line=1355
    (Interpreted frame)
 - Deterministic.main(java.lang.String[]) @bci=1428, line=409
    (Interpreted frame)
```

jmap -heap Sample Output

```
Immortal memory block:
   capacity = 33554432 (32.0MB)
   used     = 33554424 (31.99MB)
   free     = 8 (8B)
   99.99997615814209% used
RT Collected Heap:
   capacity = 67108864 (64.0MB)
   used     = 67101344 (63.99MB)
   free     = 7520 (7.34375KB)
   99.98879432678223% used
Scoped memory block 1:
   capacity = 16777216 (16.0MB)
   used     = 7838344 (7.47MB)
   free     = 8938872 (8.52MB)
   46.720170974731445% used
Scoped memory block 2:
   capacity = 16777216 (16.0MB)
   used     = 7788872 (7.43MB)
   free     = 8988344 (8.57MB)
   46.42529487609863% used
Unallocated scoped memory chunk:
   size = 33554432 (32.0MB)
Total unallocated scoped memory:
   size = 33554432 (32.0MB)
```



VisualVM Heap Dump Screenshot



Conclusion

- DTrace is a fantastic tool to monitor the Solaris OS/Java RTS stack
  - Low impact on real-time behavior
  - Generic scheduling overview
  - Focused tracing
  - Precise measurement
- It's up to you to write THE script that will solve your problem
  - Your imagination is the limit
- But sometimes DTrace is not enough
  - Troubleshooting tools updated for Java RTS
    - `jstack`
    - `jmap`
    - Visual VM

THANK YOU

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