Experiences with Multi-threading and Dynamic Class Loading in a Java Just-In-Time Compiler

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Outline

- **Overview of J9/TestaRossa**
- **Brief overview of our paper**
  - Class loading/unloading
  - Profiling in a multi-threaded environment
  - Code patching
- **Focus on code patching**
  - Because it's cool!
- **Summary**

J9 virtual machine

- **High performance production Java VM from IBM**
- **Java 1.4.2 and Java 5.0 compliant**
- **Common code base for J2SE and J2ME products**
- **Support on 12 different processor/OS platforms**
- **Used in hundreds of IBM products including**
  - Websphere Application Server (WAS 6.x)
  - Rational Application Developer (RAD)
  - DB2
  - XML parsers

TR (TestaRossa) JIT compiler

- **Just-In-Time (JIT) compiler for J9 VM**
- **Fast startup time**
- **Adaptive compilation : multiple optimization levels**
- **Target ‘hot spots’ with higher opt level**
- **Classical and Java-specific optimizations**
- **Speculative optimizations**
  – Low overhead PDF (profiling) framework
  – Code patching in many scenarios

Program characteristics

Benchmark	Loaded Classes	Unloaded Classes	Number of threads
SPECjvm98			
compress	383	0	1
jess	523	0	1
db	378	0	1
javac	537	0	1
mpegaudio	431	0	1
mtrt	404	0	2
jack	429	0	1
SPECjbb2000	1098	0	8*
Trade6	11639	341	>> 10

- Middleware programs load order of magnitude more classes
- Memory leak: classes must be unloaded on an ongoing basis
- Lots of active threads executing tons of code: no method-level hotspots
- Target only jvm/jbb: ignore critical correctness/performance issues!

The One Page Paper Overview

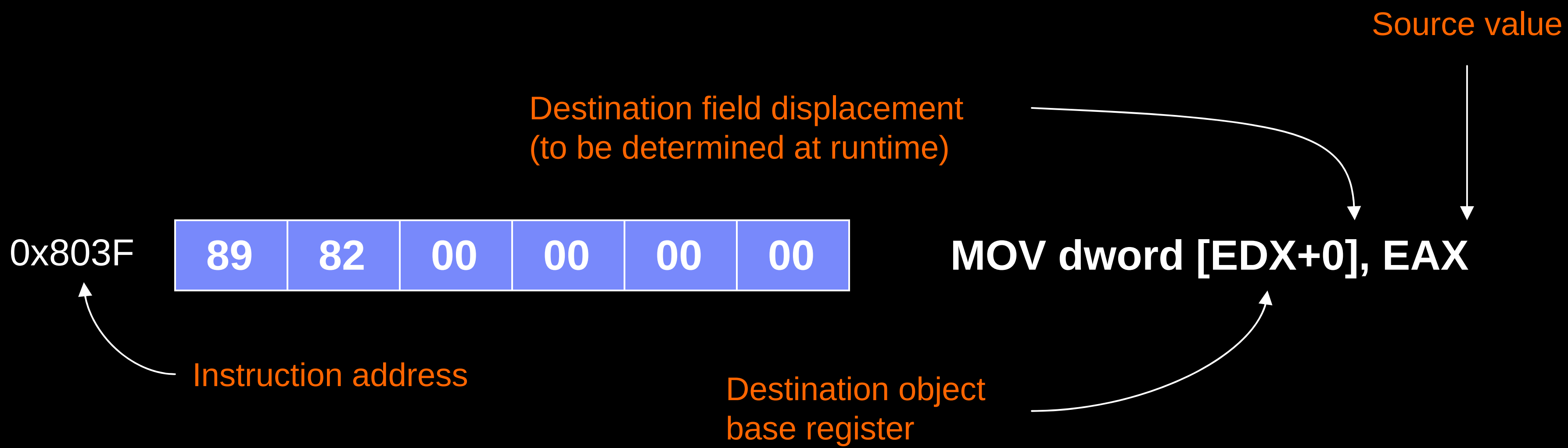
- **Class loading and unloading**
  - Unloading a class requires significant clean-up
  - Danger of class references materialized in the code
- **Profiling when there are a lot of threads**
  - Must ensure timely recompilation and good scalability
- **Code patching**
  - Resolution, efficient dispatch, recompilation, speculative optimizations
  - Tricky stuff

Code Patching Overview

- **Code patching scenarios, from easy to hard**
  1. All threads stopped (scalability suffers)
  2. Single site, many active threads
  3. Multiple sites, many active threads
- **Patch site alignment problems**
- **Trade-offs impact designs on each platform**
  - e.g. number of PIC slots

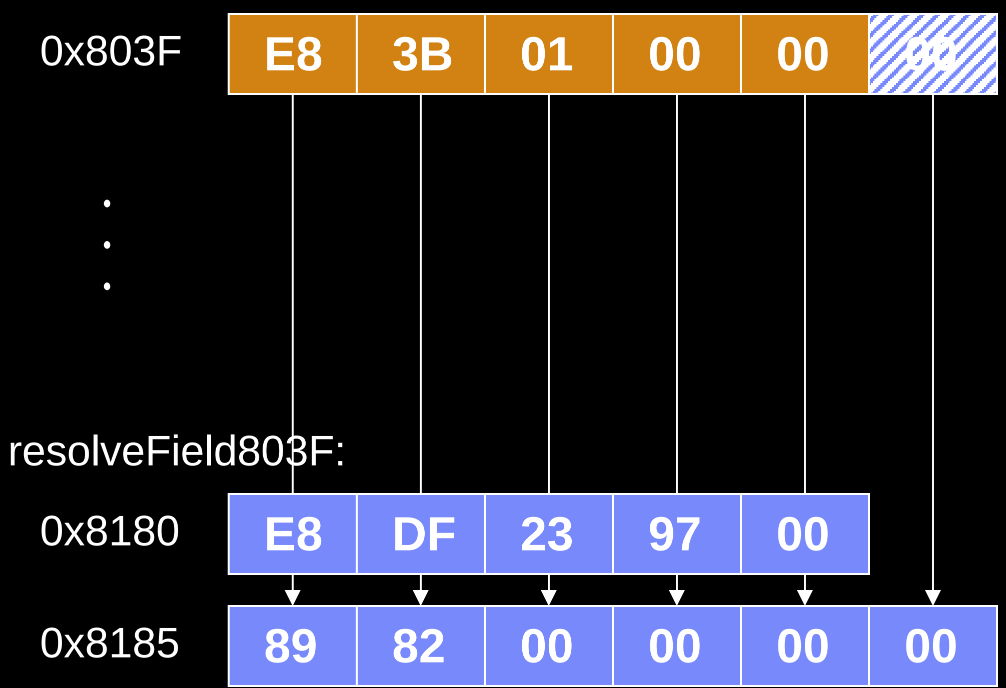
Code Patching Example: Intel IA32 Field Resolution

- **Store to unresolved field**
  – Field offset unknown at compile-time
- **When writing instruction, offset initialized to 0**
  – Opcode, operand bytes assume largest offset (4B)



Code Patching Example Cont…

- **Resolution by site-specific generated code**
  - Calls a VM function to resolve the field



MOV dword [EDX+80],EAX

CALL resolveField803F

Instruction bytes are copied to a site-specific resolution code out-of-line from the main instruction sequence…

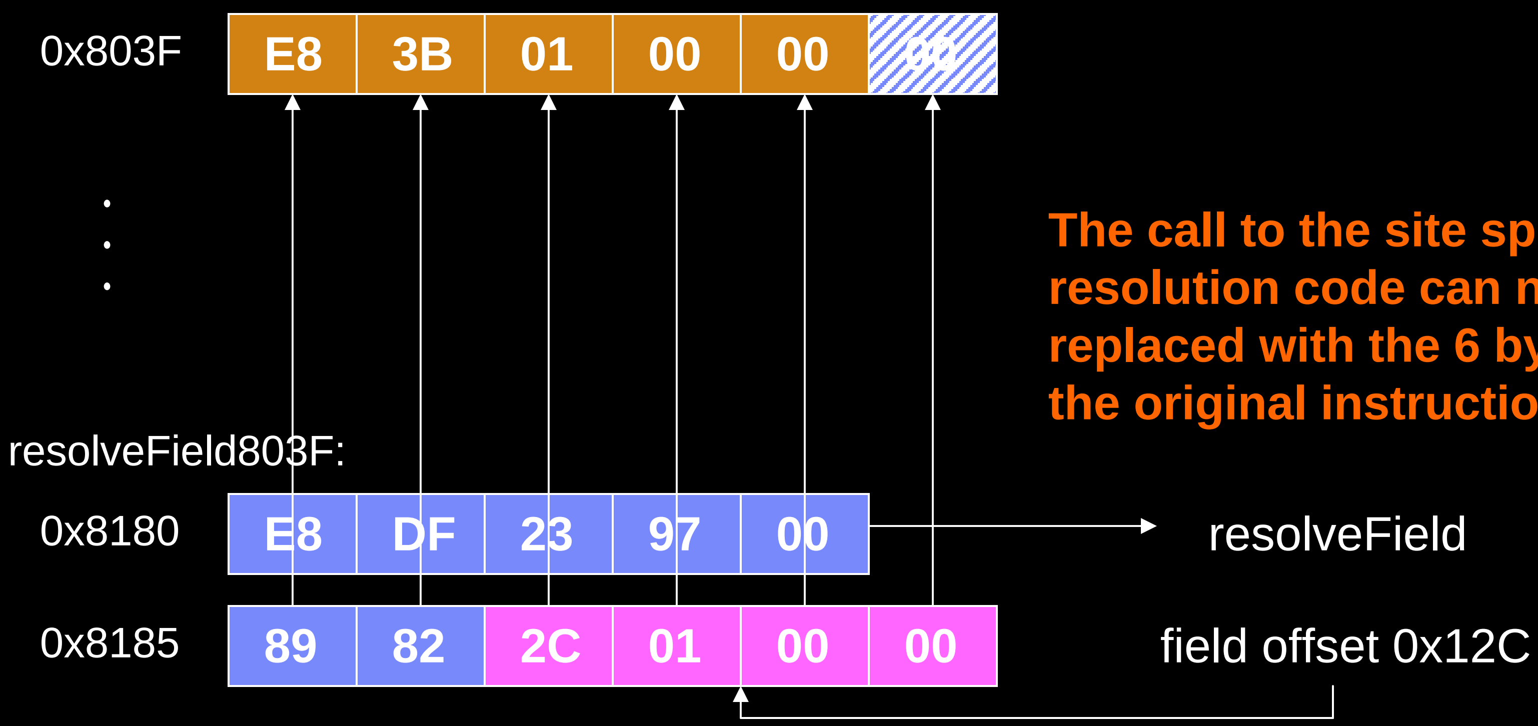
…and the original bytes are overlaid with a 5 byte CALL instruction that reaches the site-specific resolution code

CALL resolveField

original instruction bytes

Code Patching Example Cont…

- **'resolveField' determines field offset at runtime**



The call to the site specific resolution code can now be replaced with the 6 bytes from the original instruction…

Code Patching Example Cont…

- **BUT there's a problem…**
  – Atomic updates needed to guarantee other threads execute correct code
  – X86 can only patch 2^N bytes atomically: example needs 6B
- **Solution: atomically overlay a thread barrier (self loop)**
  – JMP -2 instruction for X86, similar on other platforms
- **Guarantee all processors observe barrier before patching**
  – Only one thread resolves the field
  – MFENCE, CLFLUSH instructions for X86

Code Patching Example Cont…

0x803F | EB | FE | 01 | 00 | 00 | 00

JMP -2 ; spin loop

.
.
.

resolveField803F:

0x8180 | E8 | DF | 23 | 97 | 00

0x8185 | 89 | 82 | 2C | 01 | 00 | 00

Spin loop prevents other threads from executing instruction as its being patched

Atomically inserted with LOCK CMPXCHG instruction followed by a memory fence

If the CMPXCHG failed, then branch to 0x803F: another thread put in the self-loop already

Code Patching Example Cont…

0x803F	89	82	2C	01	00	00

.
.
.

resolveField803F:

0x8180	E8	DF	23	97	00	
0x8185	89	82	2C	01	00	00

Field offset copied into original instruction (spin loop still present)

Followed by memory fence

Finally, spin loop removed with single 2-byte write

We're done! …or are we?

Code Patching Example: Still not correct

- **Patched bytes can't straddle patching boundary**
  - Not all instruction stores guaranteed to be atomically visible
  - Patching boundary is address that can't be straddled by code locations being patched…empirically:
    - 8-bytes on AMD K7 or K8 cores
    - 32-bytes on Intel Pentium 3
    - 64-bytes on Intel Pentium 4 and EM64T
- **Insert NOPs to align patchable instructions**
  - e.g. spin loop JMP-2 instruction can't straddle patching boundary
  - Increases code footprint by 1-2% on AMD: need more NOPs
  - Extra NOPs can have surprising performance effects (!)

Code Patching Example Cont…

- **Single byte NOP inserted to align spin loop site**
  – Patching infrastructure otherwise unaffected

0x803F	**90**						**NOP**
0x8040	**89**	**82**	**00**	**00**	**00**	**00**	**MOV dword [EDX+0], EAX**

First two bytes no longer straddle a patching boundary

Code Patching On Other Architectures

- **pSeries**
  - Uniform instruction length
  - Challenges:
    - Multiple instructions required for immediate addresses
- **zSeries**
  - Variable instruction length
  - Challenges:
    - Overcoming I-cache coherence costs, efficiency of atomic instructions

Summary

- **Middleware applications are highly multi-threaded and load and unload LOTS of classes**
  – Implications for patching, profiling, optimization design
- **Our paper describes**
  – Class unloading pain
  – Profiling correctly when lots of threads around
  – Code patching trickiness

Backup Slides

Contributions of Our Paper

- **Highlight issues relevant in a production JIT compiler running multi-threaded and/or large applications**
  - Class loading and unloading
  - Best code patching techniques vary by platform
  - Low overhead profiling with multiple active threads
- **Describe our solutions to these problems**

Class loading and CHTable

- **Class loading is not a 'stop the world' event**
  - Allows other Java threads to make progress while one thread loads a class
  - Allows compilation thread to compile while classes are being loaded
- **JIT compiler maintains a class hierarchy table**
  - Superclass/interface relationships are updated
  - Compensate for violated run time assumptions
  - All updates performed after acquiring CHTable lock
  - Compiler does not hold CHTable lock throughout a compilation
  - Compile-time CHTable queries must acquire CHTable lock

Class loading and CHTable

- **JIT compiler optimizations using class hierarchy table**
  - Guarded devirtualization
    - Conditionally convert virtual call to direct call
    - Assumption is registered in the CHTable
    - If assumption is violated, compensate at run time
    - Patch code to execute the backup code (virtual call)
  - Invariant argument pre-existence
    - Devirtualize virtual calls using an invariant parameter as a receiver
    - Re-compile the method containing devirtualized calls if assumption is violated
- **Class hierarchy might have changed while a compilation was in progress**
  - Acquire CHTable lock just before binary code is generated
  - Generate binary code
  - Compensate for any assumptions violated during the compilation
  - Release CHTable lock

Garbage collection and class unloading in the J9 VM

- **Class unloading : memory allocated for class is re-claimed and the class ‘dies’**
- **Class unloading done during garbage collection**
- **Garbage collection is a ‘stop the world’ event in J9**
  - Co-operative model (Java threads execute ‘yield points’ to check if GC is pending)
  - Java classes are also objects on the heap and can therefore be collected (and unloaded)
  - Class objects are never ‘moved’, i.e. a class is always at the same address throughout it’s lifetime
- **All classes in a class loader unloaded together**
- **A class is unloaded when**
  - No objects of that class type are ‘live’ on the Java heap
  - No loaded bytecodes explicitly refer to the class

Class unloading in the J9 VM

Impacts the JIT compiler significantly

- Class hierarchy table
- Profiling data
- Compilation issues
- Code memory reclamation
- Persistent data reclamation
- ‘Materialized’ references in generated code

Class unloading and ‘materialized’ references

```
Interface I { public void foo(); }

class C1 implements I
   {
   public void foo()  { System.out.println(“In C1.foo”); }
   }

class C2 implements I
   {
   public void foo() { System.out.println(“In C2.foo”); }
   }
```

Class unloading and ‘materialized’ references

```
public I createC1orC2(int x) {
   if (x % 2)
       return new C1();
   else
       return new C2();
   }

public void bar() {
   x++;
   I obj = this.createC1orC2(x);
   obj.foo();    // Polymorphic interface call
}
```

Class unloading and ‘materialized’ references

De-virtualized interface call conditionally

```
public void bar() {
   x++;
   I obj = this.createC1orC2(x);
   if (obj.class == C1)    // 'materialized' reference to C1
      C1.foo();    // called with obj as the receiver object
   else if (obj.class == C2)    // 'materialized' reference to C2
      C2.foo();   // called with obj as the receiver object
   else
        obj.foo(); // Polymorphic interface call
}
```

Class unloading and 'materialized' references

After replacing 'materialized' reference when C1 is unloaded

```
public void bar() {
  x++;
  I obj = this.createC1orC2(x);
  if (obj.class == -1)    // 'materialized' reference  to C1 changed
    C1.foo();    // called with obj as the receiver object
  else if (obj.class == C2)   // 'materialized' reference to C2
    C2.foo();   // called with obj as the receiver object
  else
     obj.foo(); // Polymorphic interface call
}
```

Class unloading and 'materialized' references

- **List of code locations containing 'materialized' references is maintained for each class**
- **Addition to the list is done both at compile time and at run time**
- **Only add to the list if the class loader of 'materialized' class is different from the class loader of some other class referred to in the constant pool**
  - Compare with class loader of method being compiled
  - Compare with class loader of super class/interface referred to in the constant pool
- **Patching can be done without any race conditions because all threads have yielded for a GC**

Class unloading and CHTable

- **Remove unloaded classes from superclasses/interfaces in CHTable**
- **Grouping unloading requests avoids excessive traversals over data structures**
  - Problematic scenario
    - Interface I is implemented by N classes
    - Each implemented class loaded by a different class loader (N class loaders)
    - Each class loader is unloaded and CHTable updates are performed independently
    - $O(N^2)$ to remove all implementors of I
    - We have seen N ~ 10,000 in customer applications

Class unloading and compilation

- **Asynchronous compilation**
  - Java threads queue methods for compilation and continue executing (in most cases)
- **Class containing a queued method could be unloaded before it is actually compiled**
  - Solution : Walk the compilation queue every time a class is unloaded and delete methods that belonging to the class
- **Class might be unloaded when a compilation is in progress**
  - Solution : Check if an unloaded class was used by the compilation in any manner; if so, abort the compilation

Class unloading and profiling

- Minimize work at run time and instead, move work to compile time as much as possible
- Profile data is for Java bytecodes that have been unloaded
  - Raw data is generated while program runs
  - Periodically, raw data is read and 'processed'
  - Bytecodes that generated raw data might have been unloaded
  - Solution : purge all raw data when class unloading occurs
  - What about 'processed' data for unloaded code ?
  - Solution : maintain bytecode address range for unloaded code and avoid returning information from compile-time queries for profiling information for bytecodes in that range
- Profile data contains references to unloaded classes
  - Keep track of unloaded classes' addresses
  - Avoid returning class whose address matched an unloaded class
- Alternatives
  - Cleanse profiling data as unloading occurs (costly at run time ?)

Class unloading and memory reclamation

- **Common tasks like serialization sometimes create class loaders with short lifetimes**
- **Unbounded memory increase over time (server applications can run for days)**
- **Re-claim code and data memory for compiled method(s) in unloaded class**
- **Problem : Might involve expensive searches each time at run time**
- **Solution : Maintain per-class loader information about compiled methods and persistent data**
  – Example : check if 'any' method belonging to an unloaded class loader was compiled

Profiling

- **When is profiling done**
  - Profile methods deemed to be 'hot' based on sampling
- **When a method is chosen to be profiled**
  - Compile the method with embedded profiling code
  - Execute the method body for a while collecting data
  - Recompile the method using profiling data

Profiling in the TR JIT

- **Loosely based on Jikes RVM approach**
  - Arnold et al (PLDI 2001)
- **Compiler creates a clone of the method to be profiled**
  - Clone contains the profiling code
- **Transition paths at equivalent points allow flow of control between two bodies**
  - Original method body executes more frequently

Profiling in the TR JIT (cont…)

- **Profiling approach**
  - Every M execution paths in the non-profiled version, transition to profiled version
  - Execute one execution path in the profiled version and transition back to non-profiled version
  - Do these steps N times
- **'M' is the profiling PERIOD**
  - 19, 29, 47… (increasing number of back edges)
- **'N' is the profiling COUNT**
  - 100, 625, 1250, 2500 … (increasing number of back edges)

Preliminaries

- **"Async checks"**
  - Inserted at each loop back edge to test if thread needs to yield to GC
  - Profiler uses async checks to mark loop back edges
- **"Execution Path"**
  - Starts at method entry or an async check
  - Ends at method entry or an async check
- **After one execution path is completed in profiled version, return to non-profiled version**
  - Ensures execution is not stuck in a loop in profiled version

Preliminaries (cont…)

Execution Path

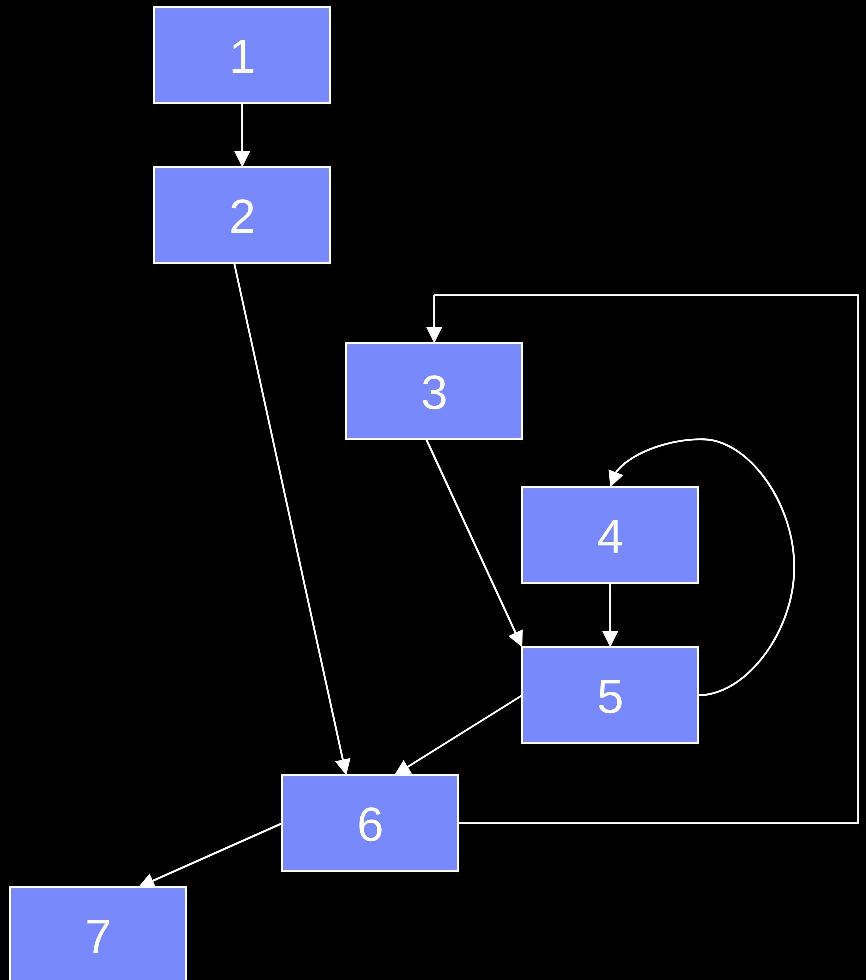
1->2->6

6->3->5

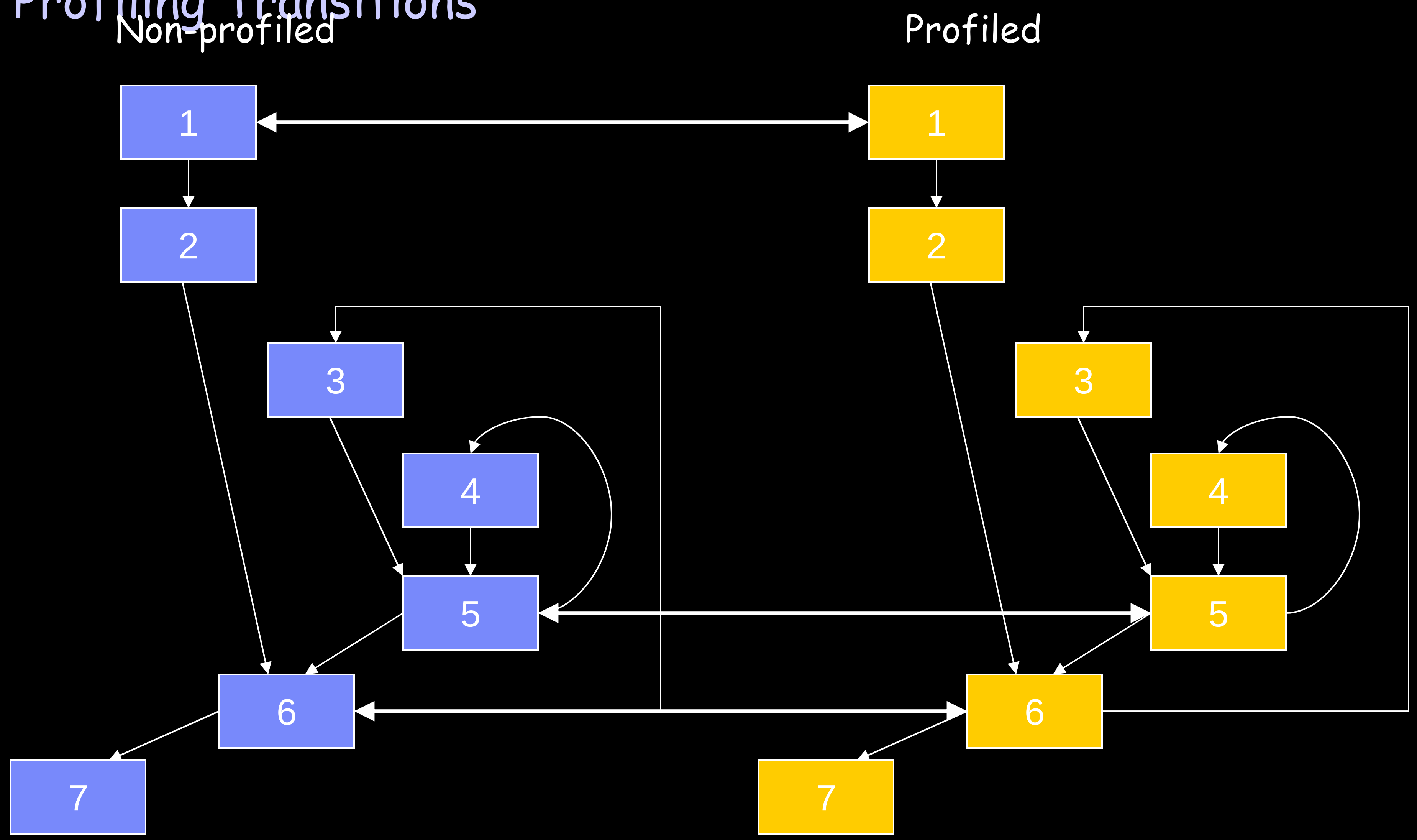
5->4->5

6->7…->1

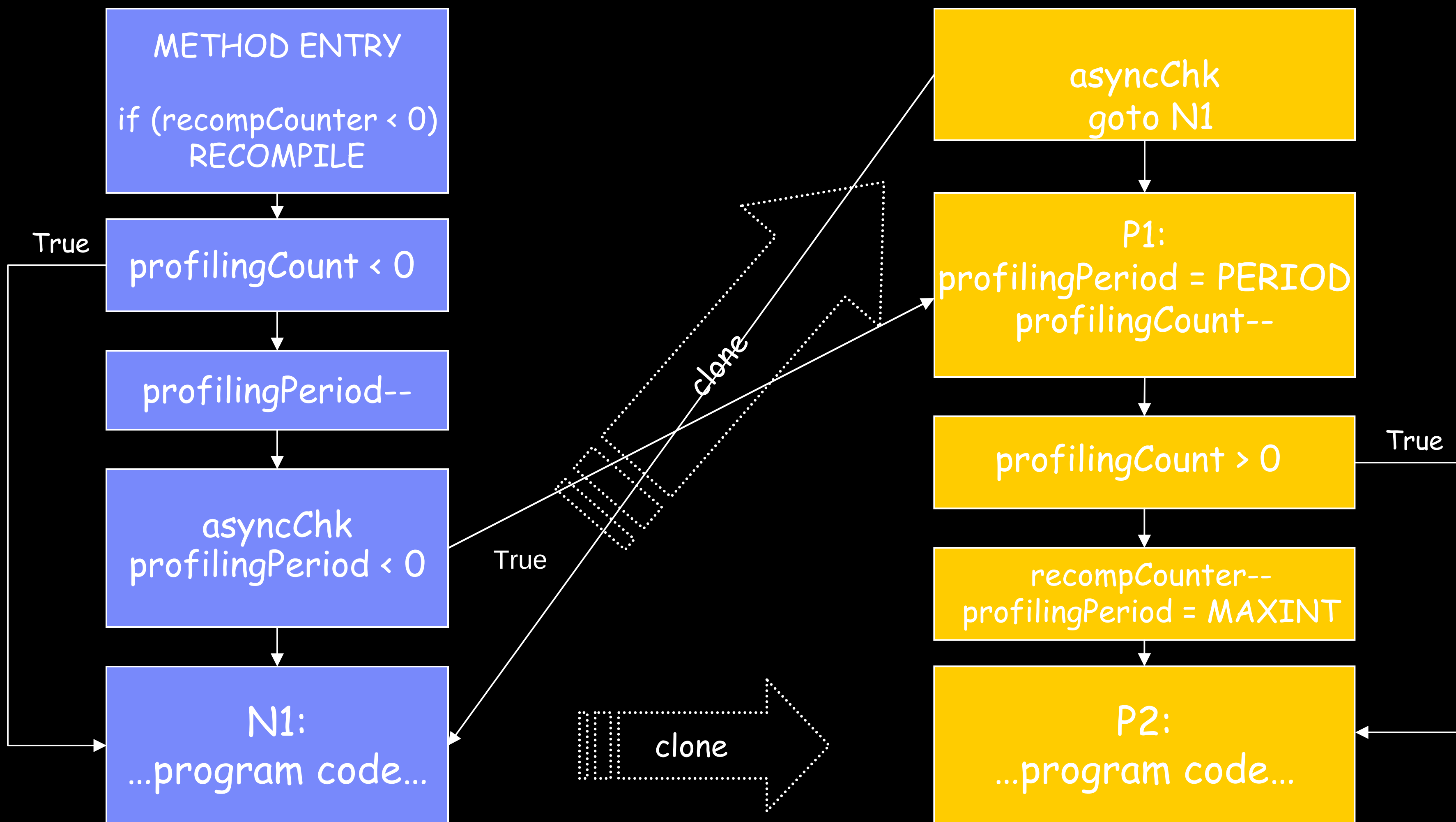
5->6



Profiling Transitions

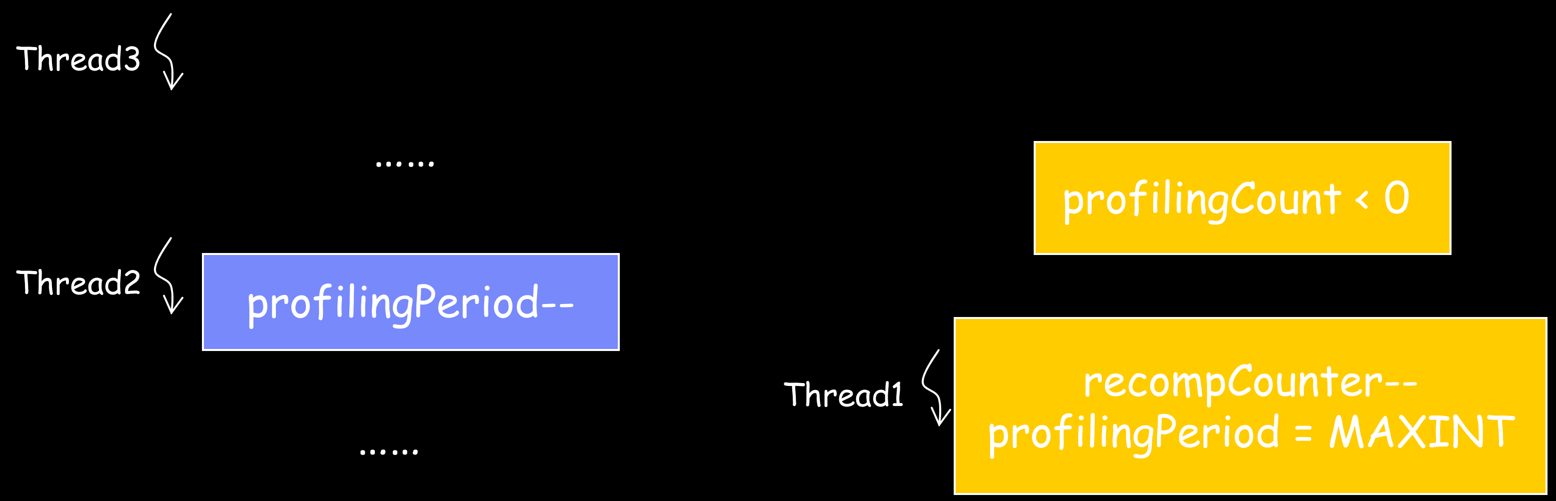


Profiling Transitions (cont…)



Effects of Multi-threading

- **Recompilation may not occur for a long time**



Initially

Thread1: count = 0 period = MAXINT

Thread2: period--

Thread3: at method entry

Thread Interaction

Thread3: set initial values

count = 29 period = 625

Thread3

……

Thread2

profilingPeriod--

……

profilingCount < 0

Thread1

recompCounter--
profilingPeriod = MAXINT

Thread1: read period (MAXINT)

Thread1:

period-- => period = MAXINT-1

Thread1:

count = 0 period = MAXINT

count = 29 period = MAXINT-1
transition won't occur for a long time!

Effects of Multi-threading

- **Poor scalability with increasing number of threads**
  - Multiple threads could transition to profiling code
  - Possibility of threads manipulating 'period' multiple times
  - Guarantee of profiling path being executed once every PERIOD paths no longer true
- **Imprecision in basic block profiling counts**
  - Multiple threads may manipulate basic block counts
  - Basic block counts may no longer reflect the hotness of an execution path

Profiling in the TR JIT

- **To improve scalability, use synchronization to access global 'period' and 'count' variables**
- **At Method Entry**
  - Synchronization is used to read global variables into thread-local storage
  - Basic block counters are also thread-local
- **At Method Exit**
  - Global variables are updated from thread-local storage at each method exit under synchronization
- **Adds overhead**
  - Each thread has now to allocate extra storage
  - Two locking operations introduce runtime overhead

Results

- **Statistics of stack usage and runtime overhead of synchronization in profiled methods**
  - Only period and count variables are allocated as thread-local
  - All counters are allocated as thread-local (including basic block counts)
- **Average stack usage increase was 14.7% across SPECjvm98 and SPECJbb2000**
- **Runtime overhead was negligible**

Stack usage

Results (cont…)

- Only _202_jess shows some overhead
  - Contains many small methods that get profiled
- Runtime overhead in the two multi-threaded benchmarks were negligible