New Compiler Optimizations in the Java HotSpot™ Virtual Machine

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Goal of This Talk

Learn how new dynamic compiler optimizations make Java-based programs run faster

Agenda

- Background
- Synchronization Optimizations
- Escape Analysis
- Tiered Compilation and Other Optimizations
- Future Plans
- Conclusion

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- **Background**
- Synchronization Optimizations
- Escape Analysis
- Tiered Compilation and Other Optimizations
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Brief Introduction to the Java HotSpot VM

- Sun Microsystems' flagship Java™ Virtual Machine implementation (JVM) for the desktop
- Roots in Smalltalk and Self
- Focus on object-oriented optimizations
  - Deep inlining
  - Class Hierarchy Analysis
  - Virtual call inlining
- Aggressive optimization
- Dynamic deoptimization

Brief Introduction to the Java HotSpot VM

- Two flavors: client and server
- Same infrastructure
- Java HotSpot client compiler focuses on compile speed
- Java HotSpot server compiler focuses on peak performance
    - More later on eliminating this distinction

Brief Introduction to the Java HotSpot VM

- Rest of this talk focuses on new optimizations being done by the client and server compilers
- Should largely be unnoticeable to the Java programmer
- May still be useful to understand more of inner workings of underlying Java virtual machine implementation

Agenda

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Escape Analysis

Tiered Compilation and Other Optimizations

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Locking in the Java Programming Language

- In Java language, every object is potentially a monitor
  - `synchronized` keyword
- All modern Java VMs incorporate lightweight locking
  - Avoid associating an OS-level mutex/condition variable pair with each Java-based object
  - Use atomic operations to enter and exit monitor
  - Fall back to heavyweight OS locks if contended
- Differences in encodings and protocols
- Effective because most locking is uncontended

Locking in the Java Programming Language

- In Java SE 5.0, **`java.util.concurrent`** locks introduced
  - New locks and primitives for building new locks
  - These optimizations do not apply to this class of locks

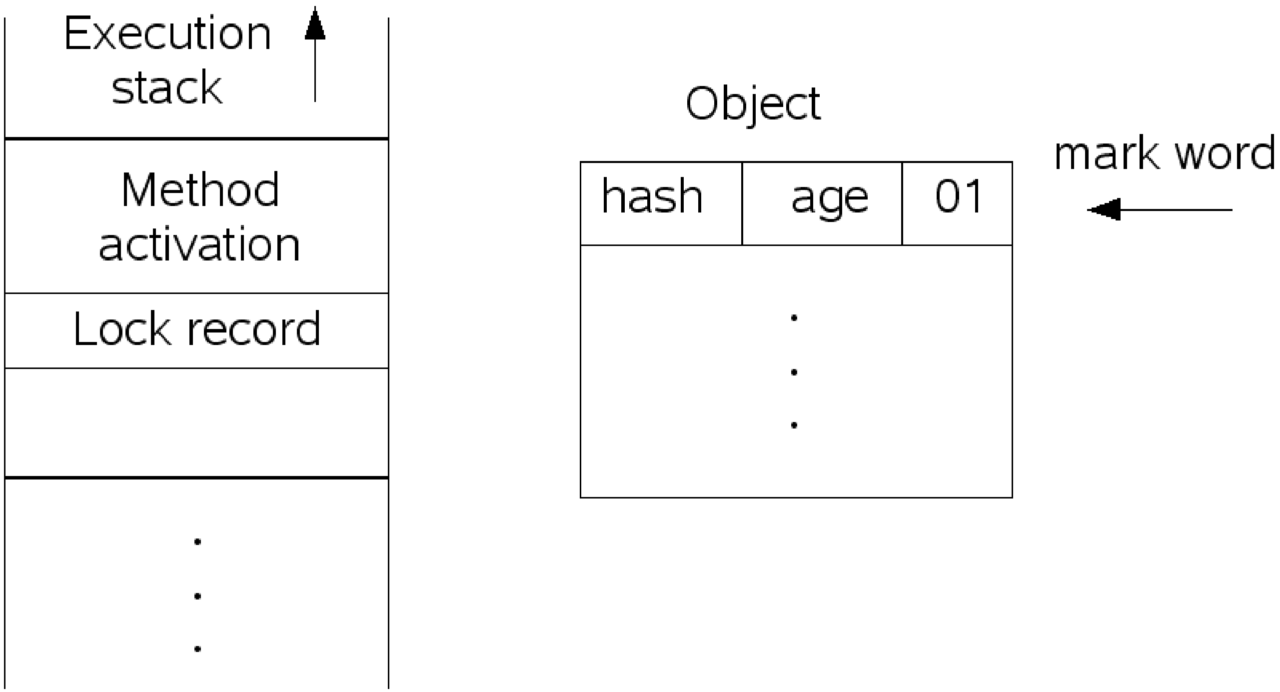
Overview of Lightweight Locking in Java HotSpot VM

- First word of every object is the mark word
- Used for synchronization and garbage collection
  - Also holds identity hash code if computed
- Low two bits of mark word indicate synchronization state
  - 01 > unlocked
  - 00 > lightweight locked
  - 10 > inflated (heavyweight locked)
  - 11 > marked for GC

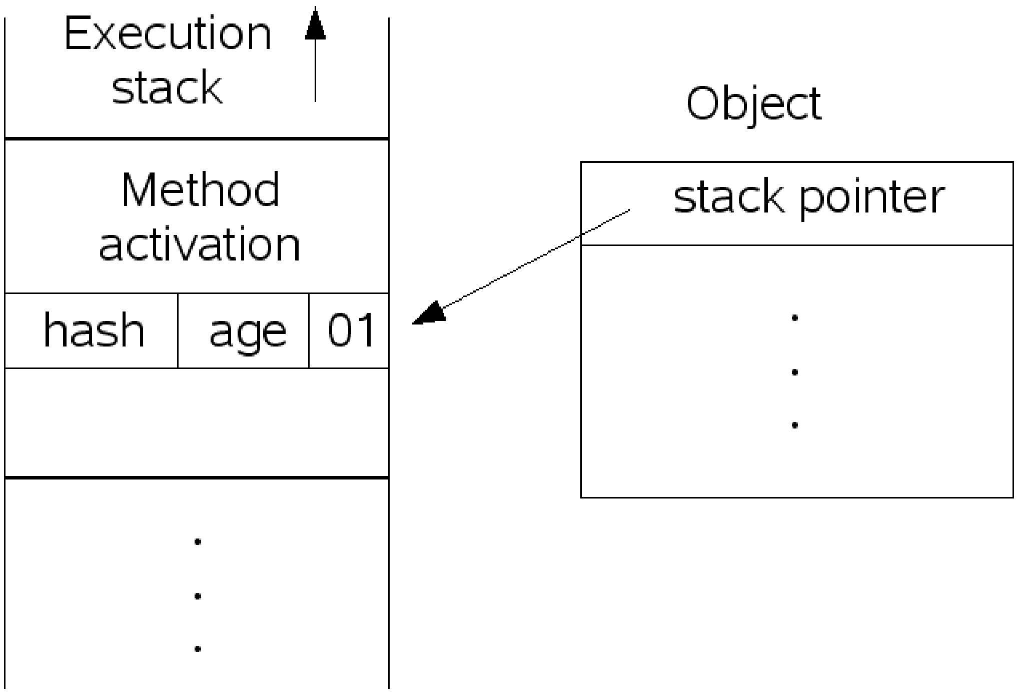
Overview of Lightweight Locking in Java HotSpot VM

- When object locked, mark word copied to stack into lock record
  - Displaced mark
- Atomic compare-and-swap (CAS) instruction used to make object point to on-stack lock record
- If CAS succeeds, thread owns lock
  - If fails, lock inflated–contention
- Lock records track which objects locked by the currently-executing method
  - Can walk stack of a thread to iterate locked objects

Locking Diagram



Locking Diagram



Overview of Lightweight Locking in Java HotSpot VM

- When object unlocked, CAS used to put displaced mark back in object
  - If fails, contention occurred
  - Notify waiting threads that monitor has exited

Observations

- Even atomic instructions can be relatively expensive on multiprocessors
- Most locking not only uncontended, but also performed by the same thread repeatedly
  - cf. Kawachiya et al, “Lock Reservation”, OOPSLA 2002
- Make it cheaper for a single thread to reacquire a lock
  - Trade-off of making it more expensive for another thread to acquire the same lock

Biased Locking

- First lock of an object biases it toward the thread which locked it
    - New encoding in mark word of object
- Subsequent locks and unlocks by same thread are very cheap
    - No atomic operations
    - Load-and-test to make sure still biased toward current thread
- Bias revoked if another thread locks same object
    - Expensive for individual objects

Bias Revocation

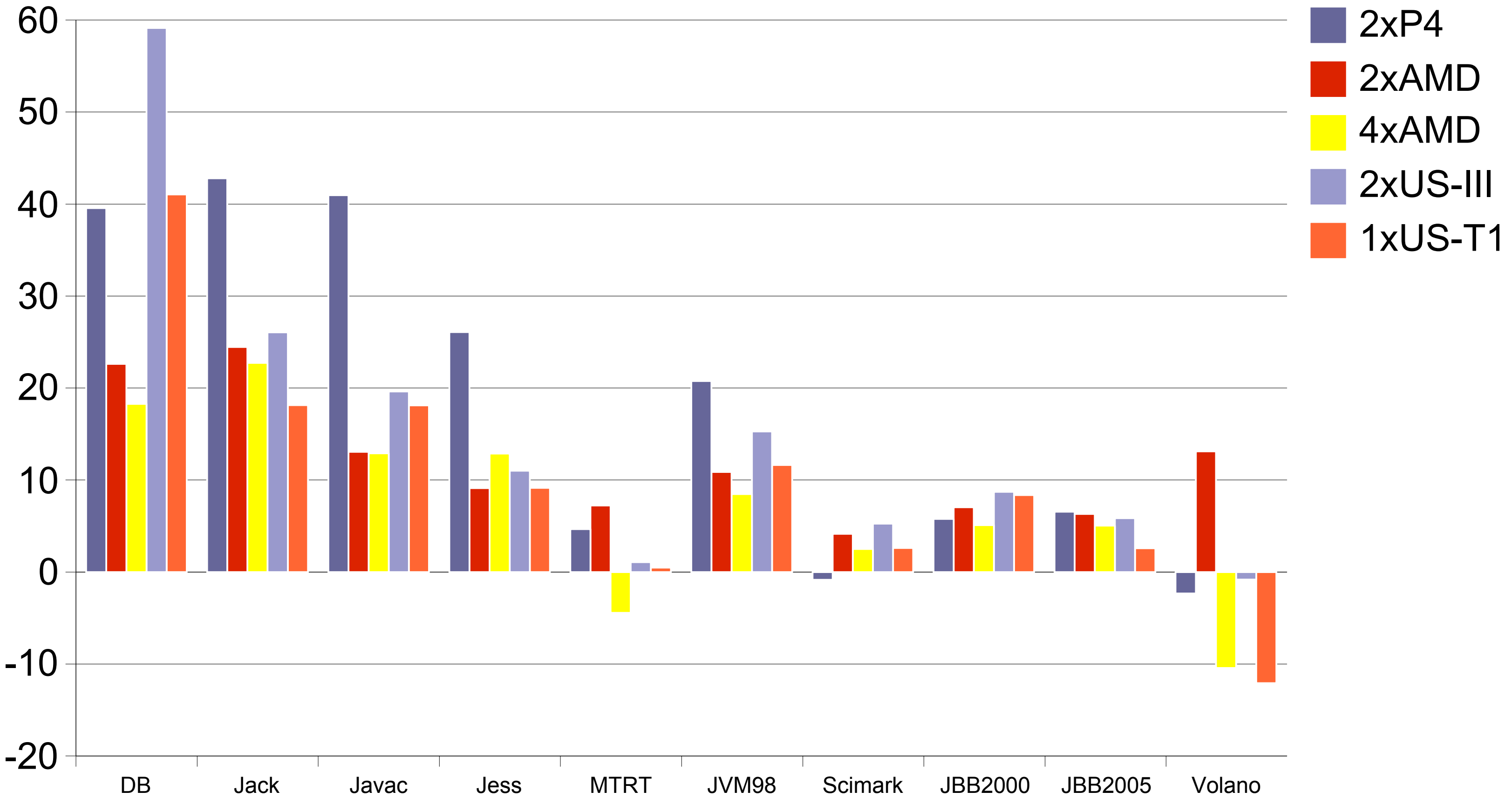
- Stop thread owning the object’s bias
- Walk stack enumerating lock records
- Fill in lock records for object, if any
- Update object’s mark word
  - Point at highest lock record if currently locked
  - Write in unlocked value if not currently locked
- Continue with normal CAS-based locking
- Obviously fairly expensive

Bulk Rebiasing and Revocation

- Detect if many revocations occurring for a given data type
- Try invalidating all biases for objects of that type
  - Allows them to rebias themselves to a new thread
  - Amortizes cost of individual revocations
  - Multiple such bulk rebias operations permitted
- If individual revocations persist, disable biased locking for that data type
- Minimize the downside of the optimization while retaining the benefits

Results

Percentage Increase/Decrease in Benchmark Scores



Source: Sun Microsystems, Inc.

Results

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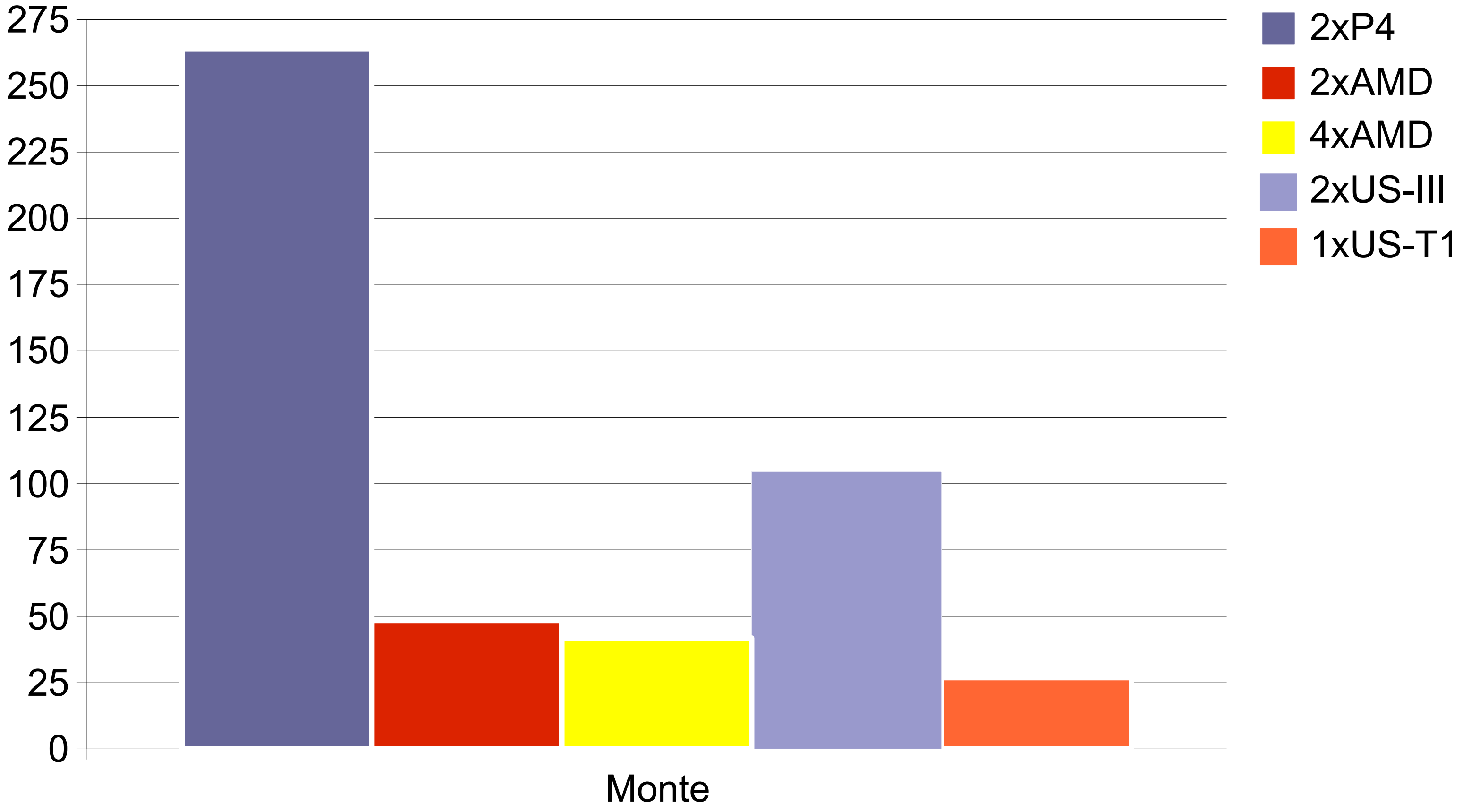

Source: Sun Microsystems, Inc.

Summary

- Biased locking improves uncontended synchronization performance
    - Still a fairly aggressive optimization
- Have attempted to minimize any performance penalties of biased locking
    - `-XX:-UseBiasedLocking` to disable completely
- Please provide feedback on Mustang forums
    - `http://mustang.dev.java.net/`

Summary

- Additional optimizations in Java Platform, Standard Edition 6 (Java SE 6) to improve contended synchronization performance
- Escape analysis and lock coarsening further improve synchronization speed
    - More later

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Escape Analysis

- **Problem:** In general, when compiling and optimizing a method, we must assume that other threads and methods called can make arbitrary changes to any Java-based object

Escape Analysis

- Problem: In general, when compiling and optimizing a method, we must assume that other threads and methods called can make arbitrary changes to any Java-based object
- For objects allocated in a method these assumptions can be relaxed if we can prove that it does not ESCAPE the code being compiled

Non-Escaping Objects

- Allocated in the method being compiled
- Are not a subclass of Thread
- Do not have a finalizer
- Are not stored to a static field or a field of an escaped object
- Are not passed as an argument to a method call unless we know that the called method does not cause it to escape

Escape Example

```
class Escape1 {
  Integer val;
  Escape1 next;
  Escape1(Integer v) { val = v;}

  void example() {
    Integer i1 = new Integer(1);
    Integer i2 = new Integer(2);
    Integer i3 = new Integer(3);
    Escape1 e1 = new Escape1(i1);
    Escape1 e2 = new Escape1(i2);
    Escape1 e3 = new Escape1(i3);

    e1.next = e2;
    next = e2;  //  e2 and i2 escape via “this”
    e2.next = e3;  // e3 and i3 escape
  }
}
```

Optimization Possibilities

- Eliminate locking on the object
- Optimize field references
- In some cases can allocate object on the stack frame instead of the heap

Common Occurrences of Non-escaping Objects

- Autoboxing of method arguments (if called method is inlined.)
- Iterators over Collections
- StringBuilder objects created for String concatenation

Tracking Object Stores

- The analysis in the server compiler is based on:
  - J. Choi, M. Gupta, M. Serrano, V Sreedhar, S. Midkiff, Escape Analysis for Java, OOPSLA99, 1999

Tracking Object Stores

- For all ptr. values in a method, computes the set of objects that it could point to
- Initialize allocations to non-escaping and all other pointer values as escaping
- Mark anything a ptr. value could point to as escaping when it is:
  - Stored into a field of an escaped object
  - Passed as an argument to a method which causes the argument to escape

Tracking Object Stores

- The paper describes 2 algorithms:
  - Flow-insensitive—identifies objects which do not escape over the entire method
  - Flow-sensitive—identifies objects which do not escape over regions of a method
- The flow-sensitive algorithm requires more memory and may interact with other compiler optimizations

Tracking Object Stores

- The server compiler currently implements the flow-insensitive algorithm
- We have a prototype of the flow-sensitive version and are evaluating whether the extra complexity give sufficiently better code

Tracking Method Arguments

- If a called method is not inlined, we must track whether it causes any of its arguments to escape
- Without this tracking, we must make the pessimistic assumption that all arguments escape. This eliminated most of the optimization opportunities from escape analysis

Tracking Method Arguments

- Since a called method may not have been compiled yet, we can not rely on the compiler

Tracking Method Arguments

- We have a bytecode escape estimator which was implemented by two researchers from the Johannes Kepler University Linz as part of their work described in:
    - T. Kotzmann, H. Mössenböck, Escape analysis in the context of dynamic compilation and deoptimization, Proceedings of the 1st ACM/USENIX International Conference on Virtual Execution Environments, 2005 http://portal.acm.org/citation.cfm?doid=1064979.1064996

Tracking Method Arguments

- The escape estimator scans the bytecodes of a method and produces a conservative estimate of which arguments escape
- It also tracks whether the return value of the scanned method is an unescaped object
- Records the results of the scan for later use

Field Optimization Without Escape Analysis

```
class Escape2 {
  int fld1, fld2;

  Escape2(int v1, int v2) { fld1 = v1; fld2 = v2; }

  static void bigMethod() {
    ...  // a large method too big to inline
  }

  static int example(int v1, int v2) {
    Escape2  e1 = new Escape2(v1, 10);
    Escape2  e2 = new Escape2(v2, 5 - v1);

    bigMethod();// must assume fields of e1 & e2 can change

    return e1.fld1 + e2.fld1;  // need to reload values
  }
}
```

Field Optimization with Escape Analysis

```
class Escape2 {
  int fld1, fld2;

  Escape2(int v1, int v2) { fld1 = v1; fld2 = v2; }

  static void bigMethod() {
    ...  // a large method too big to inline
  }

  static int example(int v1, int v2) {
    Escape2  e1 = new Escape2(v1, 10);
    Escape2  e2 = new Escape2(v2, 5 - v1);

    bigMethod();  // cannot change fields of e1 & e2

    return e1.fld1 + e2.fld2; // returns v1 + (5 - v1) =  5
  }
}
```

Performance Results

- Lock elision provided no significant performance benefit over and above biased locking and lock coarsening (described later)
- Performance benefit of other optimizations made possible by escape analysis is continuing

Implementation Status

- Java SE 6 has escape analysis and lock elision in the server compiler
- It is off by default, it can be enabled with the -XX:+UseEscapeAnalysis flag
- Java SE 7 will have further optimizations
- There are currently no plans to release a client compiler with escape analysis

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Lock Coarsening

- Dynamically we often see a lock being released and immediately acquired
- Idea is to eliminate the closely separated release and acquire
- Doing this in non-loop code does not impact fairness
- Not obvious at source level as the locks are either synchronized methods or locks within the called method
- Inlining exposes the closely paired locks

Lock Coarsening

- Assume p is simple predicate (no exception possible) and S is a synchronized method
- Release from first call can be removed if acquire is removed from then and else path
- Release in then/else can be removed if acquire is removed from final call

```
S();
if (p)
   S();
else
   S();
S();
```

Lock Coarsening

- Release from first call can be removed if acquire/release is removed from then path
- Acquire is removed from final call

```
S();
if (p)
   S();
S();
```

Lock Coarsening

- Acquire/release could be removed from then path if we moved the release from initial call to after the then join point
- This case is not currently handled

```
S();
if (p)
   S();
```

Lock Coarsening—Results

- Removes 20% of all dynamic locks in single warehouse run of specjbb2000
- Improves score on specjbb2000 by 2%
- Scimark Monte Carlo subtest score improved by 60%!

Source: Sun Microsystems, Inc.

Array Copy Stubs

- System.arraycopy is heavily used in the JDK™ libraries as well as application code
- Compilers inlined System.arraycopy but they tended to be pessimistic about aliasing and alignment
- As a result performance was okay but not great

Array Copy Stubs

- In Mustang (and backported to 5.0u5) hand coded assembly stubs written for each type size assuming no overlap
- Compiler generates one simple test to decide
  - Overlap? Same code as previously
  - No Overlap? Call stub

Array Copy Stubs—Results

- System.arraycopy microbenchmarks
  - Slight degradation for small (1–4 elements)
  - > 100% improvement for modest number of elements (20+)
- 4% increase of specjbb2000 score on SPARC® hardware
- 1+% increase of specjbb2000 score on AMD64

Source: Sun Microsystems, Inc.

Tiered Compilation

- Client compiler is good at startup and short apps
  - Inferior performance for longer running apps
- Server compiler is good at long apps
  - Inferior startup performance
- Single JVM with both compilers
- Like an automatic transmission—
  - Startup with client compiler
  - Cruise with server compiler

Tiered Compilation—Issues

- Different calling conventions
  - A method compiled by client compiler can't call method created by server compiler or vice versa
- Different runtime interfaces
  - OopMaps were incompatible

Tiered Compilation

- Different calling conventions
  - Each compiler had separate code to describe calling conventions
- In Mustang shared code maps a signature into a description of the registers and/or stack slots used to pass parameters
- As a result methods generated by different compilers can call each other

Tiered Compilation

- Adapters convert from interpreter calling convention to compiled convention (i2c) and vice versa (c2i)
- Server compiler compiled adapters as separate code objects
- Server compiler used a separate thread for adapter compilation
- Client compiler built the code into the compiled Java method

Tiered Compilation

- In Mustang adapter code is generated by shared code
- A single adapter code object contains the i2c and c2i for each signature seen
- Reduction in generated code compared to client style of adapters
- Reduction in server compiler code and one less JVM thread

Tiered Compilation

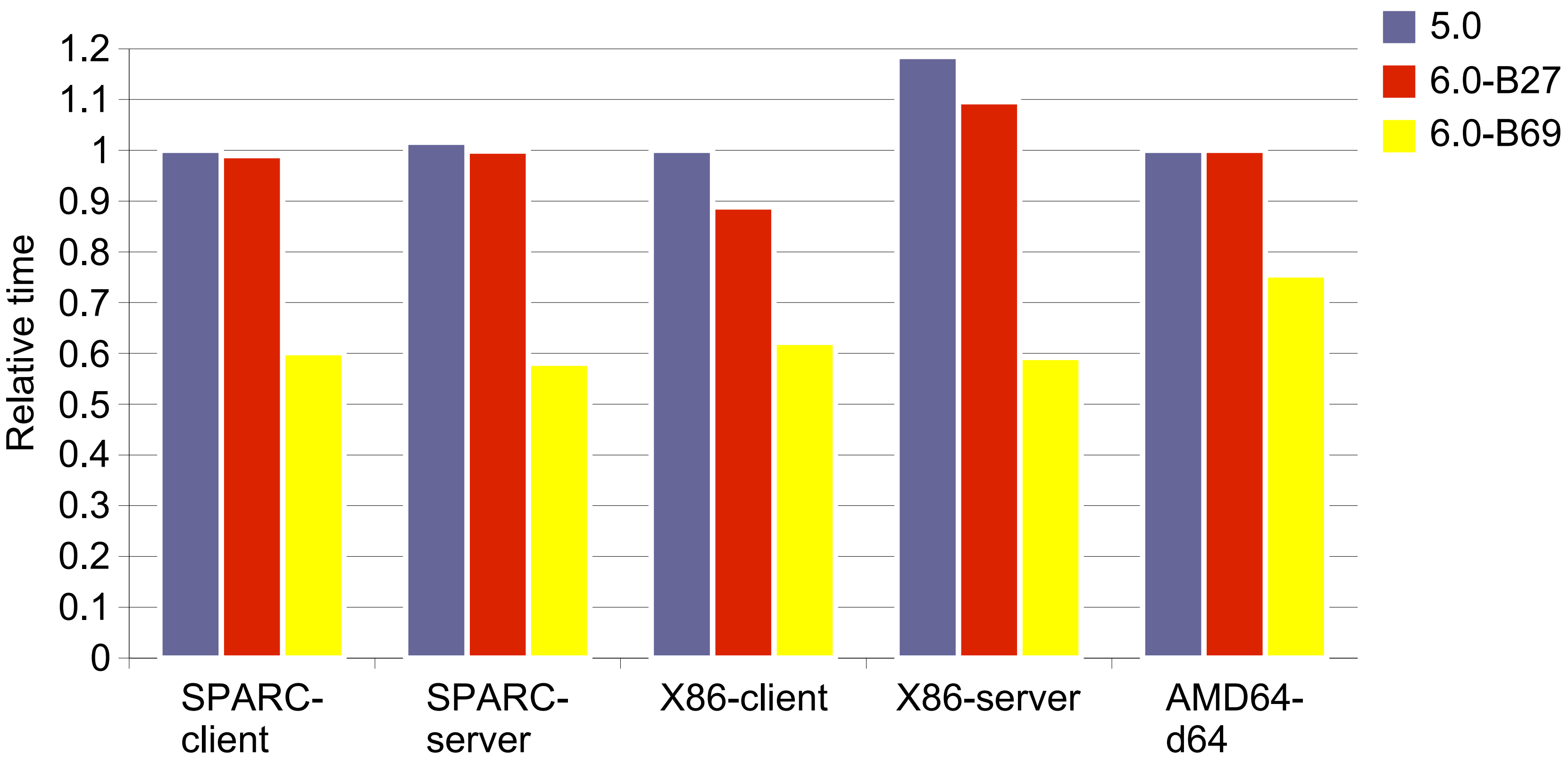
- Each compiler had distinct code for generating wrapper code for Java native methods
    - Transition from Java code to native and return requires precisely ordered thread state changes
- Client compiler code was straight forward and easy to modify
- Server code was difficult to understand and hard to get correct

Tiered Compilation

- In Mustang Java native method wrappers are produced by shared code
- Simple to modify
- Easy to experiment with new state transitions
- Better generated code

Tiered Compilation

JNI Micro Benchmark



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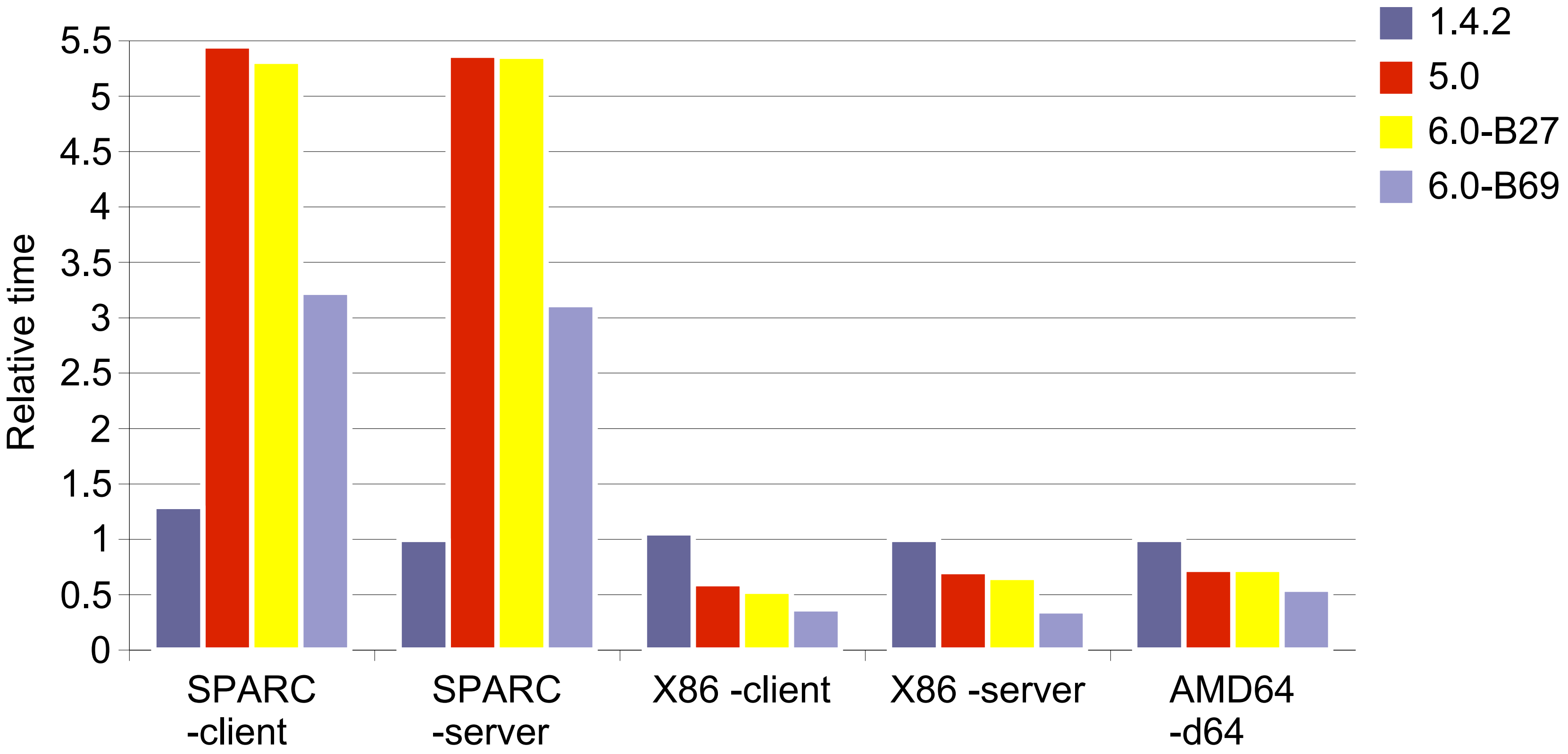
Tiered Compilation

JNI Micro Benchmark



Source: Sun Microsystems, Inc.

Tiered Compilation—Remaining Work

- Merging runtime stubs
  - IC miss handler
  - Deoptimization
  - Exception handling
- Policy decisions
  - When to deopt/recompile
  - When to collect profile data
- Client compiler for 64bit platforms

Conclusion

- More performance improvements coming
  - Finish tiered compilation
  - More use of escape analysis results
  - Faster call out to JNI
- Try it out
  - http://mustang.dev.java.net/

For More Information

BOF-0197 Java HotSpot VM Q&A

- Thursday 7:30 PM North Meeting Room 121/124/125

Q&A

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