Debugging the Java HotSpot VM

Just-in-time compilers

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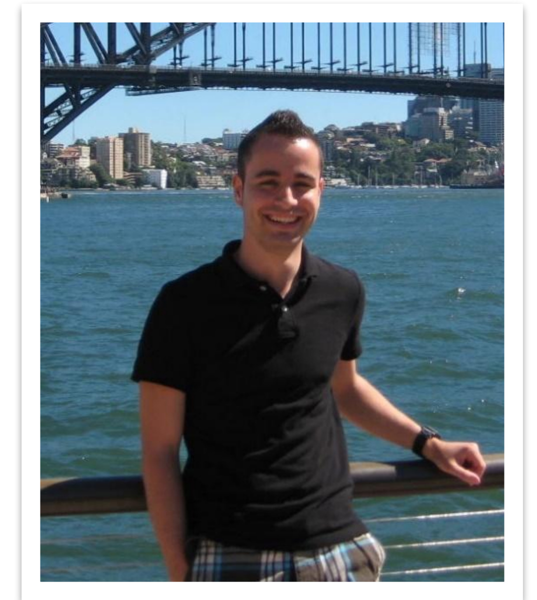
About me

- **Joined Oracle in 2014**
- **Software engineer in the Java HotSpot VM Compiler Team**
  - Based in Baden, Switzerland
- **German citizen**
- **Master's degree in Computer Science from ETH Zurich**
- **Worked on various compiler-related projects**
  - Currently working on future Inline Type support for Java



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Compiler team bug triaging

- **All incoming bugs** and RFEs are **triaged**
  - Labels, affects and fix version, priority (ILW), links, …
  - Initial triaging done by compiler triaging team (Rahul, Tobias)
  - Signoff by SQE engineer
- **OpenJDK bugs and sustaining bugs are not triaged**
- **Differentiate between test and product bugs**
  - All targeted product bugs are immediately assigned
  - If you get one, **how to debug?**

https://wiki.se.oracle.com/display/JPG/JVM+Compiler+Team
https://wiki.se.oracle.com/display/JPG/Compiler+Bug+Triaging
https://wiki.se.oracle.com/display/JPGRM/ILW+and+Priority+Mapping+of+Bugs

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How to debug the JIT compilers

- **Compilers are complex, unstable and hard to test**
  - Old bugs may be triggered by completely unrelated (even non-VM) changes
  - Several levels of abstraction: Java code, bytecode, IR, optimizations, code generation
- **The following slides show some tips and tricks**
  - Based on my experience
  - Not all steps are applicable to all problems
  - I‘m mostly using Ubuntu 20.04. on x86-64 with Eclipse

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How to debug the JIT compilers

Outline

1) Analyze the log files ⬅
2) Try to reproduce the problem
3) Find the change that introduced the problem
4) Basic analysis
5) Advanced analysis

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1) Analyze the log files

- **Look at the failure / test history in MDash**
  - Gather information from artifacts
  - Problem is project related? Ask experts for help.
- **hs_err_pid*.log contains lots of information**
  - Stack trace, current compilation, command line arguments, VM version, events, ...
  - Manually decode assembly instructions [1] or use hs_err decoder [2]
- **Test / application log file(s)**
  - jtreg, bigapps, console output, environment info
- **Core file**
  - Often contains not enough information

[1] https://www.onlinedisassembler.com/odaweb/
[2] http://jenkins.s0.javaplatfo1lhr.oraclevcn.com:999/kjdb_web/

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1) Analyze the log files: Failure types

- **Wrong result**
  - Wrong numeric value, impossible exception thrown, wrong branch taken, …
  - Severe and usually hard to debug
  - Might be security vulnerability
- **Crash or assertion**
  - During compilation, in compiled code, while deoptimizing, …
- **Performance issue**
  - Regression, test time out, endless loop, code cache exhaustion, …
  - Might be test bug or expected regression (correctness vs. performance)

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2) Try to reproduce the problem

- **Use exact same configuration**
  - Compilers are highly dependent on the architecture
  - VM build, host, test, command line arguments, jtreg version
  - Only then try to narrow problem down with own build or different flags
- **Write shell script to run test multiple times (days)**
  - Some failures are extremely rare
  - Use re-run command generated by test suite (for example, jtreg or UTE)
  - May require running multiple tests on the same VM (AgentVM mode)

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2) Try to reproduce the problem

- **Find other instances of the same problem**
  - Search JIRA / Mach5 for error message, stack trace or test (suite)
  - Phone Home tool [1]
- **Check if C1 or C2 problem**
  - Try with `–Xint`, `-XX:TieredStopAtLevel=1` and `-XX:-TieredCompilation`
- **Replay compilation via `–XX:+ReplayCompiles`**
  - Requires replay_pid*.log generated during crash
  - Mighty tool, if it works (~60% of the cases)
  - Simplify replay file by removing inlining statements (can be scripted)

[1] http://phonehome.se.oracle.com:8080/Ph-Dashboard/PHSearchAction

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2) Try to reproduce the problem

- **Only reproduces on a specific machine?**
  - Set `-XX:+PrintFlagsFinal` and compare output between machines
  - Could be due to different GC settings or processor features affecting all compilation phases due to ergonomic flag settings (for example, `-XX:UseAVX`)
  - C/C++ compiler bug or undefined behavior?
- **Try to write a reproducer**
  - May use inlining and profile information from replay file as guidance
  - Then simplify as much as possible
  - Helps with analysis and to avoid later regressions
  - Personal experience: **Don't give up early!** It may take a while but it's worth it.

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3) Find the change that introduced the problem

- **Find build** that introduced the problem
  - Binary search with reproducer on VM builds
  - Be careful, other changes may only hide the problem!
- **Look at list of compiler changes** for that build

```
project = JDK AND resolution = Fixed AND component = hotspot AND Subcomponent =
compiler AND fixVersion = "9" AND "Resolved In Build" = bXX ORDER BY resolved DESC
```

  - May want to exclude test bugs and OpenJDK bugs

```
… AND (labels is EMPTY OR labels not in (teststabilization, testbug, noreg-self,
noreg-doc, openjdk))
```

- **Analyze the change** or ask author for help

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4) Basic analysis: Simplification

- **Try to narrow problem down to a single compiled method**
  - Useful flags:
    `-XX:+PrintCompilation`, `-XX:+PrintInlining`, `-XX:CompileCommand=quiet`,
    `-XX:CompileCommand=exclude/dontinline/inline,*`
  - Use compiler directives for more fine-grained control
- **Simplify IR and generated code by disabling optimizations**
  - Example C2 flags to disable:
    `-XX:-OptimizePtrCompare`, `-XX:-OptoPeephole`, `-XX:LoopUnrollLimit=0`, `-XX:LoopMaxUnroll=0` ,
    `-XX:-SuperWordLoopUnrollAnalysis`, `-XX:-UseCountedLoopSafepoints`,
    `-XX:-UseLoopPredicate`, `-XX:-LoopUnswitching`, `-XX:-UseSuperWord`, `-XX:-SubsumeLoads`,
    `-XX:-OptimizeStringConcat`, `-XX:-SplitIfBlocks`, `-XX:-RangeCheckElimination` ,
    `-XX:-PartialPeelAtUnsignedTests`
  - Find more flags in `globals.hpp`, `c1/c2_globals.hpp`

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4) Basic analysis: Hints

- **Inlined method is intrinsified?**
  - Disable intrinsic via `-XX:DisableIntrinsic=_Name`
- **Wrong numeric value in Java code?**
  - Could be a concurrency issue or a missing sign extension
  - Run with GC verification flags to find bad oops
- **Performance problem?**
  - Profile application to find responsible method (for example, by using JFR)
  - Enable debug output for C2 optimizations and compare to baseline
  - Compare generated assembly code to baseline

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4) Basic analysis: Hints

- **Problem related to String operations?**
  - Disable **Compact Strings**

    `-XX:-CompactStrings`
  - Disable **Indify String Concat**

    `-XDstringConcat=inline` or `-XDstringConcat=indy` or `-XDstringConcat=indyWithConstants`
  - Disable **String intrinsics**

```
-XX:DisableIntrinsic=_toBytesStringU, _getCharsStringU, _inflateStringC,
_inflateStringB, _compressStringC, _getCharStringU, _compressStringB, _compareToL,
_compareToU, _compareToLU, _compareToUL, _putCharStringU, _arraycopy, _indexOfL,
_indexOfU, _indexOfUL, _indexOfIL, _indexOfIU, _indexOfIUL, _indexOfU_char,
_equalsL, _equalsU, _hasNegatives, _encodeByteISOArray
```

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4) Basic analysis: Hints

- **Problem related to loop optimizations?**
  - Debug flags
    `-XX:+TraceLoopOpts -XX:+TraceSuperWord -XX:+TraceNewVectors`
  - Disable vectorization
    `–XX:-UseSuperWord`
  - Disable AVX
    `–XX:UseAVX=0`
  - Other flags
    `-XX:-RangeCheckElimination -XX:-PartialPeelLoop –XX:-UseLoopPredicate –XX:LoopMaxUnroll=0 –XX:-OptimizeFill …`

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4) Basic analysis: Hints

- **Physical memory corruption?**
  - Unlikely if failure showed up on multiple machines
  - Check RAM on machine
- **VM binary corrupted?**
  - Compare binary to sane build
- **Static C/C++ compiler bug or undefined behavior?**
  - Try with different version or disable optimizations
  - Overflow in C/C++ code? For example, `long == int` on Windows.
- **OS / kernel bug**
  - INTJDK-7624851: corruption of XMM registers with some Linux kernel versions

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5) Advanced analysis: Bytecodes

- **Print bytecodes during compilation**
  - Use `-XX:+CIPrintMethodCodes`
  - May use AsmTools (`jasm`) to create test from bytecodes
- **Disassemble class files**
  - `javap -c -p`
- **Debug method handles**
  - Use `-Djava.lang.invoke.MethodHandle.DUMP_CLASS_FILES=true`
- **Inspect object header layout**
  - http://openjdk.java.net/projects/code-tools/jol/

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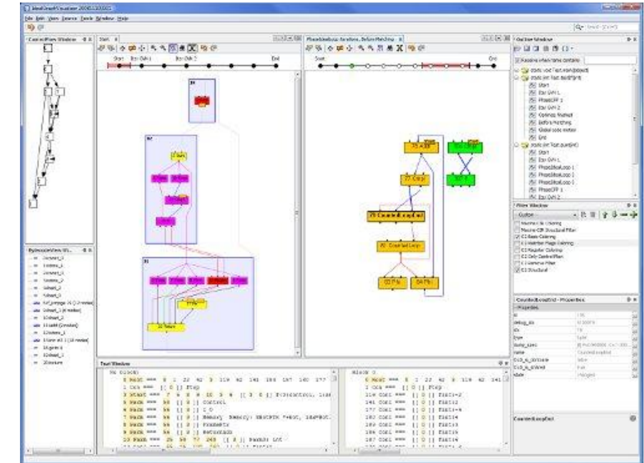
5) Advanced analysis: IR

- **Relies on simplification of reproducer in step 4)**
- **Dump ideal graph in text form**
  - Use `-XX:+PrintIdeal`
  - Hard to read but compact
- **Use Ideal Graph Visualizer**
  - Visual representation of IR
  - Supports several filters (customizable)
  - Use `-XX:PrintIdealGraphLevel=* -XX:PrintIdealGraphFile="foo.xml“`
- **Pro tip: Draw relevant parts on paper**



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5) Advanced analysis: Assembly

- **Opto assembly**
  - Requires debug build and supported by C2
  - Use `-XX:+PrintOptoAssembly`
- **Native assembly**
  - Requires `hsdis` disassembler to be on the library path
  - Use `-XX:+PrintAssembly`
- **Simplify assembly layout**
  - Use `-XX:-BlockLayoutRotateLoops -XX:-BlockLayoutByFrequency`

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5) Advanced analysis: GDB

- **Start with GDB or attach it while JVM is already running**
  - Use `slowdebug` build
  - On error `-XX:+ShowMessageBoxOnError`
  - On exception `-XX:AbortVMOnException=java.lang.AssertionError`
- **Ignore SIGSEGV signals**
  - They are used for VM internal purposes (for example, implicit null checks)
  - `(gdb) handle SIGSEGV nostop noprint`
- **Inspect C2 graph**
  - Dump nodes: `(gdb) p node->dump(1)`
  - Use watchpoints to track changes. For example, watch `node->_in[0]`

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5) Advanced analysis: GDB

- **Step through generated assembly**
  - Set breakpoint at nmethod entry point
  - Always use **hardware breakpoints** to avoid code modification
- **VM provides debug API**
  - See `debug.cpp`: `findpc(pc)`, `find_node(root, index)`
  - Methods can be called from GDB
- **Make sure that debug symbols are available**
  - Configure `--with-native-debug-symbols=external`
  - Unzip *.diz from existing build

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5) Advanced analysis: rr

- **Records and deterministically replays the execution**
  - `rr java -version`
  - `rr replay`
- **Allows reverse execution/debugging**
  - `(rr) reverse-cont`
  - May require some `-XX:SuppressErrorAt=…` statements
  - **Reverse debug dying subgraphs** by incrementally watching node input array
- **Default flag values may change when executing with rr**
  - Set flags manually (check what changed with `-XX:+PrintFlagsFinal`)

http://rr-project.org/

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More from my personal experience

- **It's not stupid if it works!**
  - Some failures are extremely intermittent and only reproduce on a remote machine
  - Log modification of node inputs and print stack trace to figure out location
  - Use `MacroAssembler::print_state64` or `stop` to print from compiled code
- **Don't hesitate to seek help if you get stuck**
- **Don't give up!**
  - Usually it takes just another hour - or week :)

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Documenting your progress

- **Set JIRA issues you are working on to “In Progress”**
  - Regularly give a status update in the comments
  - Update affects versions, labels, ...
- **Make sure the RFR/PR contains all required information**
  - You might have spent lots of time on the topic, reviewers didn’t
  - Also helps if you need to look at it again for a regression 6 months later ;)

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Questions?

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Live Debugging Session

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Bug 1: SIGFPE in C2 compiled code

```
# A fatal error has been detected by the Java Runtime Environment:
#
#  SIGFPE (0x8) at pc=0x00007f14c8aed2c5, pid=491680, tid=491681

[...]

---------------  T H R E A D  ---------------

Current thread (0x00007f14d0030dc0):  JavaThread "main" [_thread_in_Java, id=491681, stack(0x00007f14d7133000,0x00007f14d7234000)]

Stack: [0x00007f14d7133000,0x00007f14d7234000],  sp=0x00007f14d7232810,  free space=1022k
Native frames: (J=compiled Java code, A=aot compiled Java code, j=interpreted, Vv=VM code, C=native code)
J 293 c2 Test.test(II)I (4 bytes) @ 0x00007f14c8aed2c5 [0x00007f14c8aed2a0+0x0000000000000025]
j  Test.main([Ljava/lang/String;)V+12
v  ~StubRoutines::call_stub
V  [libjvm.so+0x9e13bb]  JavaCalls::call_helper(JavaValue*, methodHandle const&, JavaCallArguments*, Thread*)+0x5fd
V  [libjvm.so+0xec37c0]  os::os_exception_wrapper(void (*)(JavaValue*, methodHandle const&, JavaCallArguments*, Thread*), 
JavaValue*, methodHandle const&, JavaCallArguments*, Thread*)+0x36
V  [libjvm.so+0x9e0dba]  JavaCalls::call(JavaValue*, methodHandle const&, JavaCallArguments*, Thread*)+0x8e
V  [libjvm.so+0xa88a0e]  jni_invoke_static(JNIEnv_*, JavaValue*, _jobject*, JNICallType, _jmethodID*, JNI_ArgumentPusher*, 
Thread*)+0x188
V  [libjvm.so+0xa9e656]  jni_CallStaticVoidMethod+0x333
C  [libjli.so+0x4a2f]  JavaMain+0xbf7
C  [libjli.so+0xaca5]  ThreadJavaMain+0x27
```

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Bug 2: C2 compilation fails with assert

https://bugs.openjdk.java.net/browse/JDK-8176441

```
# A fatal error has been detected by the Java Runtime Environment:
#
#  Internal Error (/oracle/jdk/open/src/hotspot/share/opto/phaseX.cpp:1099), pid=505221, tid=505233
#  assert(false) failed: modified node was not processed by IGVN.transform_old()

[...]

Current CompileTask:
C2:   1226   30    b  4       custom.A8::unwrappedGeneratedCode (2223 bytes)

Stack: [0x00007fd2e6196000,0x00007fd2e6297000],  sp=0x00007fd2e62912a0,  free space=1004k
Native frames: (J=compiled Java code, A=aot compiled Java code, j=interpreted, Vv=VM code, C=native code)
V  [libjvm.so+0xf1629e]  PhaseIterGVN::verify_PhaseIterGVN()+0xa4
V  [libjvm.so+0xf16694]  PhaseIterGVN::optimize()+0x1a4
V  [libjvm.so+0xd22d8d]  PhaseIdealLoop::build_and_optimize(LoopOptsMode)+0x1879
V  [libjvm.so+0x6e5cb9]  PhaseIdealLoop::PhaseIdealLoop(PhaseIterGVN&, LoopOptsMode)+0xb3
V  [libjvm.so+0x6e5db4]  PhaseIdealLoop::optimize(PhaseIterGVN&, LoopOptsMode)+0x46
V  [libjvm.so+0x6da541]  Compile::Optimize()+0xa07
V  [libjvm.so+0x6d39ea]  Compile::Compile(ciEnv*, ciMethod*, int, bool, bool, bool, bool, DirectiveSet*)+0x1090
V  [libjvm.so+0x5d02ff]  C2Compiler::compile_method(ciEnv*, ciMethod*, int, bool, DirectiveSet*)+0x15b
V  [libjvm.so+0x6eea36]  CompileBroker::invoke_compiler_on_method(CompileTask*)+0x88e
V  [libjvm.so+0x6ed6c3]  CompileBroker::compiler_thread_loop()+0x3df
V  [libjvm.so+0x10b5239]  compiler_thread_entry(JavaThread*, Thread*)+0x69
V  [libjvm.so+0x10b0414]  JavaThread::thread_main_inner()+0x14c
V  [libjvm.so+0x10b02c0]  JavaThread::run()+0x124
V  [libjvm.so+0x10ac3d2]  Thread::call_run()+0x180
V  [libjvm.so+0xeb8290]  thread_native_entry(Thread*)+0x1e4
```

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Bug 3: Test fails with unexpected result

```
public static int[] test() {
  int[] result = new int[100];
  for (int i = 0; i < result.length; ++i) {
    result[i] = 42;
  }
  return result;
}
```

```
Exception in thread "main" java.lang.RuntimeException: Test failed: result[51] = 7
      at Test.main(Test.java:17)
```

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