BEAMJIT, a Maze of Twisty Little Traces

A walk-through of the prototype just-in-time (JIT) compiler for Erlang.

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Who am I?

- Senior researcher at the Swedish Institute of Computer Science (SICS) working on programming tools and distributed systems.

What this talk is About

A brief introduction to the BEAM just-in-time compiler followed by a walk-through of last year's development.

Outline

Just-In-Time (JIT) Compilation

- Decide at runtime to compile "hot" parts to native code.
- Fairly common implementation technique
  - Python (Psyco, PyPy)
  - Smalltalk (Cog)
  - Java (HotSpot)
  - JavaScript (SquirrelFish Extreme, SpiderMonkey)

BEAM: Specification & Implementation

- BEAM is the name of the Erlang VM.
- A register machine.
- Approximately 150 instructions which are specialized to approximately 450 macro-instructions using a peephole optimizer during code loading.
- Hand-written C (mostly) directly threaded interpreter.
- No authoritative description of the semantics of the VM except the implementation source code!

Project Goal

- Goals:
  - Do as little manual work as possible.
  - Preserve the semantics of plain BEAM.
  - Automatically stay in sync with the plain BEAM, i.e. if bugs are fixed in the interpreter the JIT should not have to be modified manually.
  - Have a native code generator which is state-of-the-art.
- Plan:
  - Parse and extract semantics from the C implementation.
  - Transform the parsed C source to C fragments which are then reassembled into a replacement interpreter which includes a JIT-compiler.

HiPE vs JIT

Why would Erlang need a JIT-compiler, we already have HiPE?

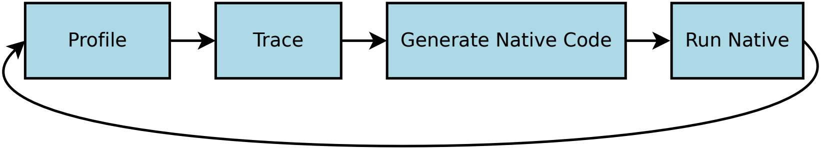
- Cross module optimization.
- Native-code much larger than BEAM-code.
- Tracing does not require switching to full emulation.
- Modules stay target independent, simplifies deployment:
  - No need for cross compilation.
  - Binaries not strongly coupled to a particular build of the emulator.

Tools

- LLVM – A Compiler Infrastructure, contains a collection of modular and reusable compiler and toolchain technologies. Uses a low-level assembler-like representation called LLVM-IR.
- Clang – A mostly gcc-compatible front-end for C-like languages, produces LLVM-IR.
- libclang – A C library built on top of Clang, allows the AST of a parsed C-module to be accessed and traversed.

Just-In-Time (JIT) Compilation as it Applies to BEAM

- Use light-weight profiling to detect when we are at a place which is frequently executed.
- Trace the flow of execution until we get back to the same place.
- Compile trace to native code.
- NOTE: We are tracing the execution flow in the interpreter, the granularity is finer than BEAM opcodes.



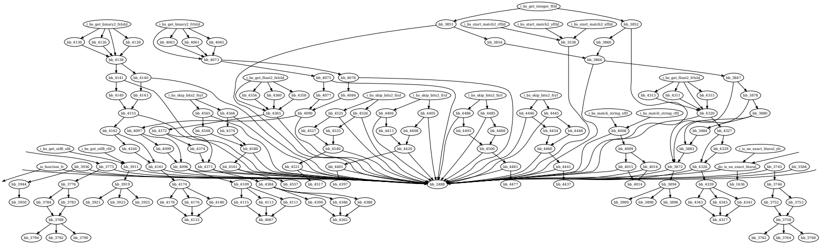
BEAMJIT: What is Needed?

- Three basic execution modes
  - Profiling
  - Tracing
  - Native
- Interpreter loop has to be modified to support mode switching:
  - Turn on/off tracing.
  - Passing state to/from native code.
- Native code generation: Need the semantics for each instruction.

Extracting the Semantics of the BEAM Opcodes

Use libclang to parse and simplify the interpreter source:

- Flatten variable scopes.
- Remove loops, replace by if + goto.
- Make fall-troughs explicit.
- Turn structured C into a spaghetti of Basic Blocks (BB), CFG – Control Flow Graph.
- Do liveness-analysis of variables.



Outline

BEAMJIT Evolution

- Evolution since last year
  - Mk. I (EUC'12)
  - Mk. Ib
  - MK. II
  - MK. III
  - Mk. IV (EUC'13)

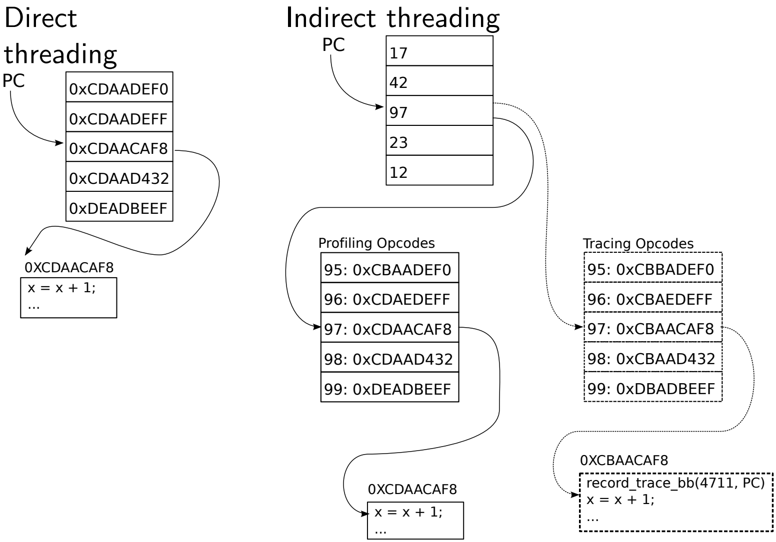
BEAMJIT Mk. I: Profiling

- First step in figuring out what to JIT-compile
  - Let Erlang compiler insert profile instructions at places which can be the head of a loop.
  - Count the number of times a function is executed.
  - Trigger tracing when count is high enough.
  - Eventually everything is compiled, this is BAD.
- Requires implementing (by hand) the profile-instruction in the interpreter.

BEAMJIT Mk. I: Tracing

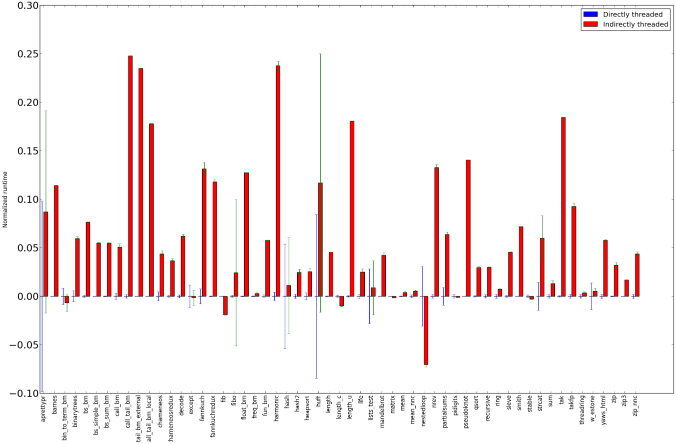
- Switch to a new version of the interpreter, generated from the CFG.
- For each basic block we pass through, record basic block identity and PC.
- Abort trace if too long.
- If we reach the profile instruction we started the trace from – We have found a loop!

BEAMJIT Mk. I: Profiling to Tracing Mode Switch



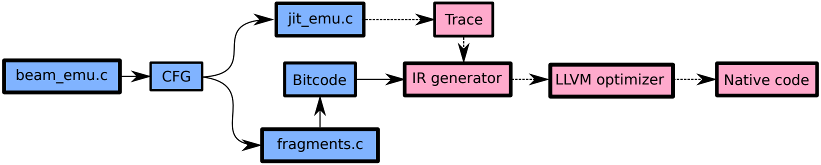
- Have two implementations of each opcode.
- Switch the table of opcodes.

BEAMJIT Mk. I: Cost of Indirect Threading



BEAMJIT Mk. I: Native-code Generation

- Glue together LLVM-IR-fragments for the trace.
- *Guards* are inserted to make sure we stay on the traced path.
- Hand the resulting IR off to LLVM.
- Fragments are extracted from the CFG as C-source, compiled to IR using clang (at build-time) and loaded during system initialization.



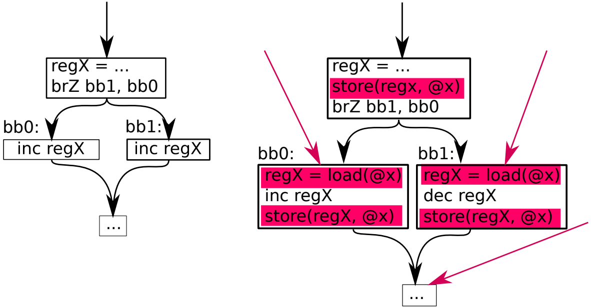
BEAMJIT Mk. I: Calling Native Code

- Interpreter → Native:
  - Interpreter: Copy live variables to a structure.
  - Native: Load vars into temporaries.
- Native → Interpreter:
  - The reverse.
  - Jump to the BB to continue from.

BEAMJIT Mk. I: Performance

- Depressing performance.
- Running in pure interpreting mode, 6-7 times slower.

```
x = ...;
if (x != 0)
    x = x+ 1;
else
    x = x - 1;
...
```

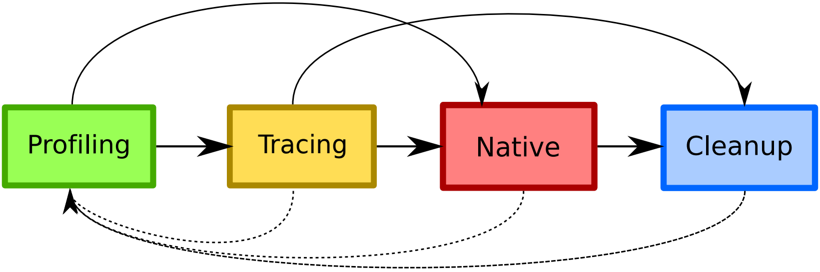


BEAMJIT Mk. Ib: First Useful

- First version that could compile OTP without crashing and pass the test suite.
- Make profiler time-aware.
- Measure execution intensity by including timestamp, count is incremented if the function was executed recently, reset otherwise.
- Blacklist locations which:
  - Never produce a successful trace.
  - Where we leave the trace without executing the loop at least once.
- GC traces when they are no longer needed.
- Minor performance improvements.

BEAMJIT Mk. II: Make it Easy for the Compiler

- Modify the interpreter loop as little as possible.
- Have separate trace interpreter.
- Limit entry to the interpreter at instruction boundaries.
- Have separate *cleanup*-interpreter to continue execution to the next instruction boundary.

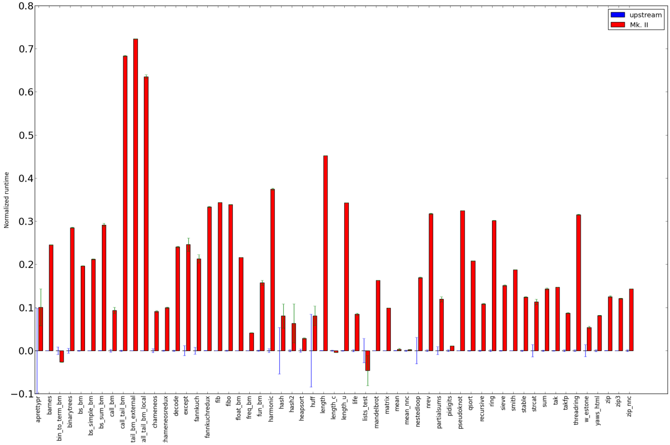


BEAMJIT Mk. II: Implementation Tricks

- Use liveness information from the CFG.
- Package native-code as a function where the arguments are the live variables.
- The cleanup-interpreter is a set of functions, one for each BB, which tail-recursively calls the next BB. Arguments are the live variables.

BEAMJIT Mk. II: Performance

- Performance not stellar.
- Sensitive to placement in source-code.
- Should be possible to optimize further.



BEAMJIT Mk. III: Trace-Along

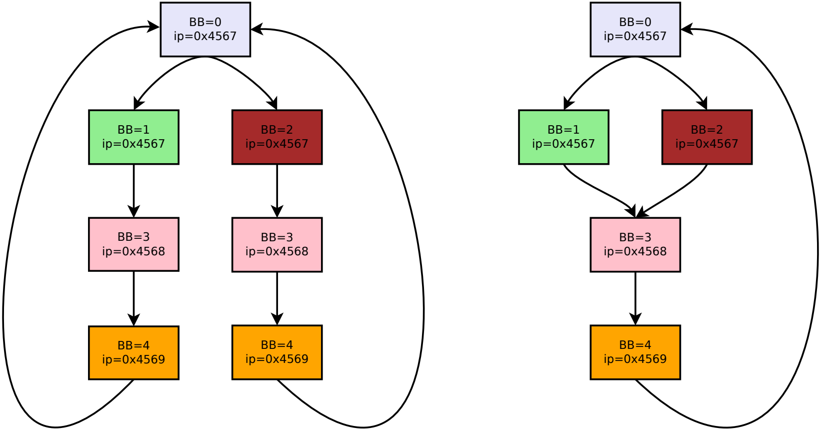
- Appears that we quite often compile a trace which is not representative.
- Ensure that we have a representative trace: Trace-Along
  - Follow along a previously created trace.
  - Abort trace if we diverge.
  - Generate code when succeeded multiple times.

BEAMJIT Mk. IV: Multi-path

- We blacklist many locations where trace-along repeatedly fails to find a representative trace.
- Allow multi-path traces.
- Generate native code when the trace has not grown for N successive iterations.
- Slows down LLVM optimization and native code generation significantly.

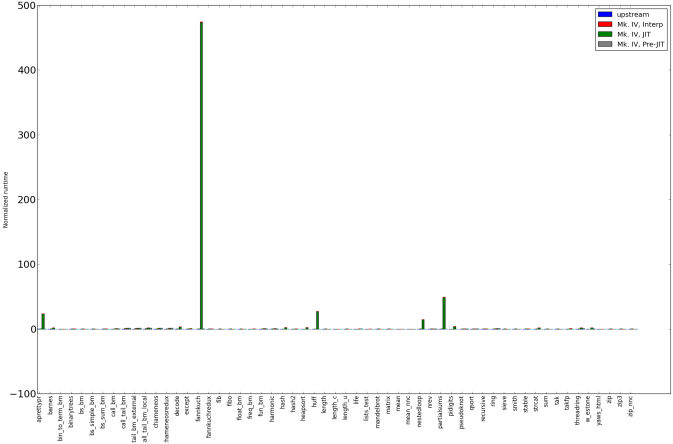
BEAMJIT Mk. IV: Trace Compression

- LLVM slowdown appears to be related to the size of the CFG.
- Inspection of traces shows loops and common segments.
- Compress traces to remove shared segments.

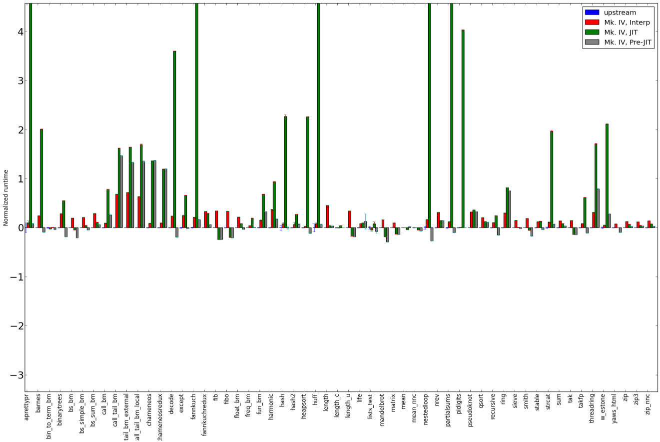


BEAMJIT Mk. IV: Performance

- Compilation overhead dwarfs everything else (-O2).
- Future work: Figure out which optimization passes are needed.



BEAMJIT Mk. IV: Performance (cont.)



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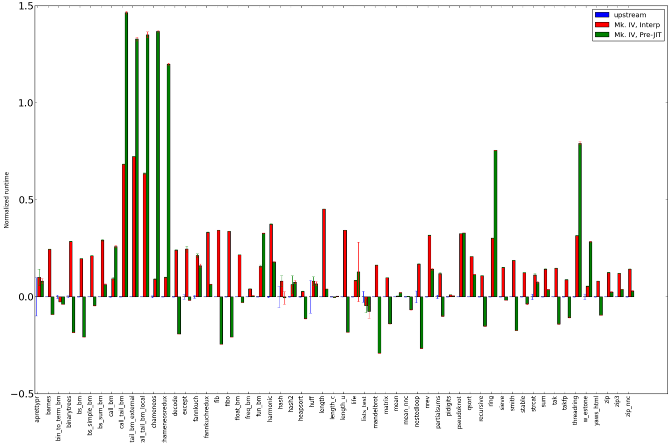
BEAMJIT Mk. IV: Performance (cont.)

- Guards costly.
- Not good where the common case cannot be on the fast path



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Future Work

- Do not fixate on finding loops
  - Allow traces which are runs rather than loops, ring benchmarks.
- Erlang-aware constant propagation:
  - Eliminate loads from code (constant at compile time).
  - Will eliminate loading of immediates.
  - Will eliminate many of the guards.
- Increase performance in plain interpreting mode.
- Run native-code generation in separate thread.
- Extend trace outside the main interpreter loop, inside BIFs.

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Outline

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Acknowledgements

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Questions?