LLVM for a Managed Language
What we've learned

Sanjoy Das, Philip Reames
{sanjoy,preames}@azulsystems.com

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Who are we?

Azul Systems

- We make scalable virtual machines
- Known for low latency, consistent execution, and large data set excellence

The Project Team

Bean Anderson
Philip Reames
Sanjoy Das
Chen Li
Igor Laevsky
Artur Pilipenko
What are we doing?

We’re building a production quality JIT compiler for Java[1] based on LLVM.

[1]: Actually, for any language that compiles to Java bytecode
Design Constraints and Liberties

- Server workload, targeting peak throughput
- Compile time is less important
  - We already have a “Tier 1” JIT and an interpreter
- Small team, maintainability and debuggability are key concerns
An “in memory compiler”

- LLVM is not the JIT, it’s the optimizer, code generator, and dynamic loader
- The JIT magic’y stuff lives in the runtime
  - High quality profiling information already available
  - Has support for re-profiling and re-compiling methods
  - Has support for “deoptimization” (discussed later)
  - Same with compilation policy, code management, etc..
An existing runtime with a *flexible internal* ABI

(within reason and with cause)
Architectural Overview

- A “high level IR” embedded within LLVM IR
- Callbacks from mid level optimizer passes to the runtime
- Record and replay compiles outside of the VM
Embedding a high level IR

- Starting off, we have “high level” operations represented using calls to known abstraction functions

  ```
  call void @azul.lock(i8 addrspace(1)* %obj)
  ```

- Most of the frontend lowers directly to normal IR

- Abstraction inlining events form the boundaries of each optimization phase
Why an embedded HIR?

- We didn’t really want to write another optimizer
- A split optimizer seemed likely to suffer from pass ordering problems.
  - So does an embedded one, but at least it’s easier to change your mind

Over time, we’ve migrated to eagerly lowering more and more pieces.
The Java Virtual Machine Runtime

Bytecode

The Bytecode Frontend

Record

LLVM IR

Record

Runtime Information via callbacks

obj file

LLVM’s Mid Level Optimizer

LLC

Architecture (artistic rendition)
Architecture (artistic rendition)
Code Management

● Generate and relocate object file in memory

● Most data sections are not relocated into permanent storage
  ○ Notable exception: .rodata*
  ○ Data sections like .eh_frame, .gcc_except_table, .llvm_stackmaps are parsed and discarded immediately after

● Runtime expects to patch code (patchable calls, inline call caches)
Optimizing Java
Java is not C

- All memory accesses are checked
  - Null checks, range checks, array store checks
  - Pointers are well behaved
- No undefined behavior to “exploit”
- Data passed by reference, not value
- `s.m.Unsafe` implies we’re compiling both C and Java at the same time
int sum_it(MyVector v, int len) {
    int sum = 0;
    for (int i = 0; i < len; i++)
        sum += v.a[i];
    return sum;
}

if (v == null) {
    throw new NullPointerException();
}

a = v.a;
if (a == null) {
    throw new NullPointerException();
}
if (i < 0 || i > a.length) {
    throw new IndexOutOfBoundsException();
}
sum += a[i]
Very few custom passes needed

Focus on improving existing passes

- lots of small changes
- mostly around canonicalization
Speculative Optimization

- Overly aggressive, “wrong” optimizations:
  - Speculatively prune edges in the CFG
  - Speculatively assume invariants that may not hold forever
  - Often better to “ask for forgiveness” than to “ask for permission”

- Need a mechanism to fix up our mistakes ...
int f() {
    // No subclass of A overrides foo
    return this.a.foo();
}

int f() {
    return A::foo(this.a);
}
void f() {
    this.a.foo();
    this.a.foo();
}

A new class B is loaded here, which subclasses A and implements foo
Might now be an instance of B
Any call can invalidate speculative assumptions in the caller frame

invoke `@A::foo()`

(normal return path)

Exception Flow

Interpreter `@ invokevirtual a.foo()`

The runtime ensures we “return to” the right continuation.
Speculative Optimization: Deoptimizing

● Deoptimize(verb): replace my (physical) frame with N interpreter frames, where N is the number of abstract frames inlined at this point

● We can construct interpreter frames from abstract machine state

● Abstract Machine State:
  ○ The local state of the executing thread (locals, stack slots, lock stack)
    ■ May contain runtime values (e.g. my 3rd local is in %rbx)
  ○ Writes to the heap, and other side effects
Deoptimization: What the Runtime Needs

- The runtime needs to map the N interpreted frames to the compiled frame
- The frontend needs to emit this “map”, and LLVM needs to preserve it
- This map is only needed at call sites
- Call sites also need to be something like “sequence points”
Deoptimization State: Codegen / Lowering

Four step process

1. \((\text{deopt args}) = \text{encode abstract state at call}\)

2. Wrap call in a statepoint, stackmap or patchpoint
   
   a. Warning: subtle differences between live through vs. live in

3. Run “normal” code generation

4. Read out the locations holding the abstract state from .llvm_stackmaps
Deoptimization State: Early Representation

- We need a representation for the mid-level optimizer
- statepoint, patchpoint or stackmap are not ideal for mid level optimizations (especially inlining)
- Solution: operand bundles
Deoptimization State: Operand Bundles

● “deopt” operand bundles (in progress, still very experimental)
  ○ call void @f(i32 %arg) [ “deopt”(i32 0, i8* %a, i32* null) ]
  ○ Lowered via gc.statepoint currently; other lowerings possible

● Operand bundles are more general than “deopt”
  ○ call void @g(i32 %arg) [ “tag-a”(i32 0, i32 %t), “tag-b”(i32 %m) ]
  ○ Useful for things other than deoptimization: value injection, frame introspection
Specific Improvements
Implicit Null Checks

- Despite best efforts (e.g. loop unswitching, GVN), some null checks remain
  - `obj.field.subField++`
- Standard Solution: issue an unchecked load, and handle the SIGSEGV
- Works because in practice `NullPointerException` exceptions are very rare
Implicit Null Checks

testq  %rdi, %rdi

je      is_null

movl    32(%rdi), %eax

retq

is_null:

movl    $42, %eax

retq

Legality: the load faults if and only if %rdi is zero

load_inst:

movl    32(%rdi), %eax

retq

is_null:

movl    $42, %eax

retq
Implicit Null Checks

- `.llvm_faultmaps` maps faulting PC’s to handler PCs
- Inherently a profile guided optimization
- Possible to extend this to checking for division by zero
- In LLVM today for x86, see `llc -enable-implicit-null-checks`
Optimizing Range Checks

- We’ve made (and are still making) ScalarEvolution smarter
- `-indvars` has been sufficient so far, no separate range check elision pass
- Java has well defined integer overflow, so SCEV needs to be even smarter
SCEV’isms: Exploiting Monotonicity

for (i = M; i <s N; i++)
{
    if (i <s 0) return;
    a[i] = 0;
}

The range check can fail only on the first iteration. i <s 0 ⇔ M <s 0

for (i = M; i <s N; i++ns w)
{
    if (M <s 0) return;
    a[i] = 0;
}
SCEV’isms: Correlated IVs

j = 0
for (i = L-1; i >= 0; i--)
{
    if (!(j < L)) throw();
    a[j++] = 0;
}

// backedge taken L-1 times
SCEV’isms: Multiple Preconditions

if (!(k < \_u L)) return;

for (int i = 0; i < \_u k; i++)
{
    if (!(i < \_u L)) throw();

    a[i] = 0;
}

Today this range check does not optimize away.
Partially Eliding Range Checks: IRCE

```java
for (i = 0; i < n; i++) {
    if (i < a.length)
        a[i] = 42;
    else throw();
}
```

```java
t = smin(n, a.length)
for (i = 0; i < t; i++)
    a[i] = 42;  // unchecked
for (i = t; i < n; i++) {
    if (i < a.length)
        a[i] = 42;
    else throw();
}
```
Dereferenceability

if (arr == null) return;

loop:
if (*condition) {
    t = arr->length;
    x += t
}

Subject to aliasing, of course.
Dereferenceability

- Dereferenceability in Java has well-behaved control dependence
  - Non-null references are dereferenceable in their first N bytes (N is a function of the type)
  - We introduced `dereferenceable_or_null(N)` to specify this

- Open Question: Arrays?
  - `dereferenceable_or_null(<runtime value>)`?
Aliasing

- We haven’t needed a language specific AA implementation yet; we use TBAA and struct TBAA to convey basic facts
- Fairly coarse so far; not heavily leveraging the Java type system
- We generalized `argmemonly` to non-intrinsics
  - Really helpful for high level abstractions
Constant Memory

- We use `invariant.load` for:
  - VM level final fields (e.g. length of an array)
  - Java level final fields (static final) of heap reference type
    - Primitive static finals can be directly constant folded
    - Instance finals are a bit tricky (forthcoming)
Constant Memory: Open problems

- Memory which “becomes constant”
  - Inlining allocation functions and \texttt{invariant.load}
  - final instance fields in Java

- Subtly different (?) representations for the same thing
  - The backend’s notion of \texttt{invariant.load} is different than the IR’s
  - TBAA’s notion of \texttt{isConstant} vs. \texttt{invariant.load}
Takeaways

- Embedded high level IR enables rapid development
- New support for operand bundles (i.e. deoptimization, frame introspection, frame interjection)
- Canonicalization required for effective optimization; per language work needed
- LLVM powerful building block for debuggable managed language compiler
Questions?