Deegen: a Meta-compiler Approach for High Performance VMs at Low Engineering Cost

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Dynamic Languages

- JavaScript, Python, PHP, Ruby, Lua, many more…
- High productivity thanks to dynamic typing.
- But also poor runtime performance on a naive VM implementation.
- And building a good VM is hard…

What does the state-of-the-arts do?

- To get a state-of-the-art VM…
- Need an ~~interpreter.~~

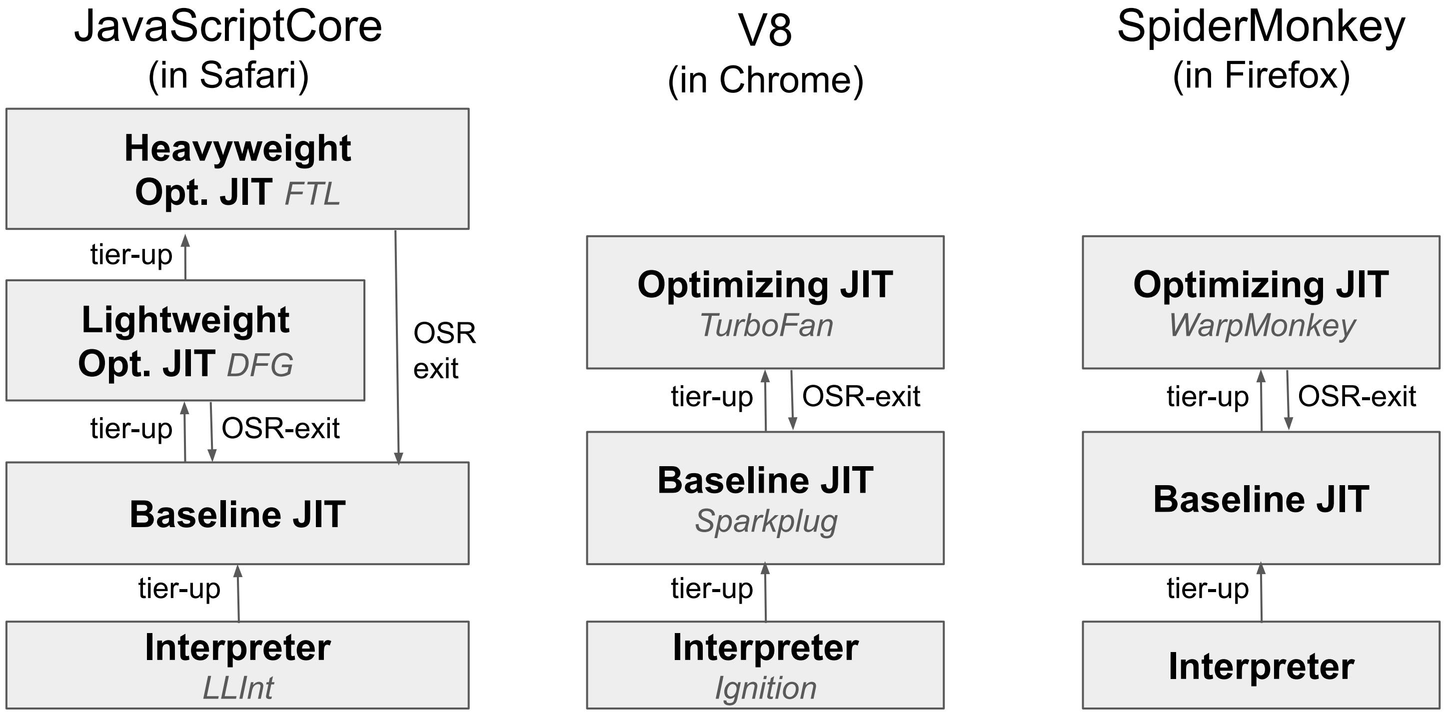
  optimized interpreter

- Need a ~~JIT compiler.~~

  multi-tier JIT compiler

- Compilation happens at runtime, so compilation time matters!
  - Baseline JIT: generate code fast
  - Optimizing JIT: generate fast code

What does the state-of-the-art do?



* OSR-exit: the process of bailing out from speculatively optimized JIT'ed code and fallback to interpreter / generic JIT'ed code, also known as deoptimization

But… what does it cost?

But… what does it cost?

- Optimized interpreter
  - Handroll assembly
- Baseline JIT
  - Handroll assembly
  - Handroll assembler
  - Tier-up logic
- Optimizing JIT
  - Handroll assembly
  - Handroll assmbler
  - Tier-up logic
  - OSR-exit logic
  - Optimization pipeline

Huge engineering cost
(V8/JSC: US $100M+)
Lots of code duplication
(across tiers and across architectures)
Subtle VM bugs
(and JIT bugs are notoriously exploitable)
High dev. expertise requirement

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But wait a minute…

LLVM can generate assembly

LLVM can generate machine code from assembly

So can we replace the handrolled parts with LLVM?

So… Can we use LLVM in dynamic language VMs?

- Obviously, I'm not the first to have this idea
  - Unladen Swallow (for Python, inactive since 2010)
  - Rubinius (for Ruby, inactive since 2020)
  - LLVMLua (for Lua, inactive since 2012)
  - …
- Many attempts, but limited outreach to mainstream use
- Why?

Quoted from *Unladen Swallow Retrospective*

Post-mortem by one of the main Unladen Swallow developers:

high compilation cost

> Unfortunately, LLVM in its current state is really designed as a static compiler optimizer and back end. LLVM code generation and optimization is good but expensive. The optimizations are all designed to work on IR generated by static C-like languages. Most of the important optimizations for optimizing Python require high-level knowledge of how the program executed on previous iterations, and LLVM didn't help us do that.

code duplication
➜ maintenance cost to keep tiers in sync

no support for dynamic-type-related opts.

no support for inline caching

(into official CPython)

> no longer the case. If the merge were to have gone through, it is likely that it would have been disabled by default and ripped out a year later after bitrot. Only a few developers seemed

link: https://qinsb.blogspot.com/2011/03/unladen-swallow-retrospective.html

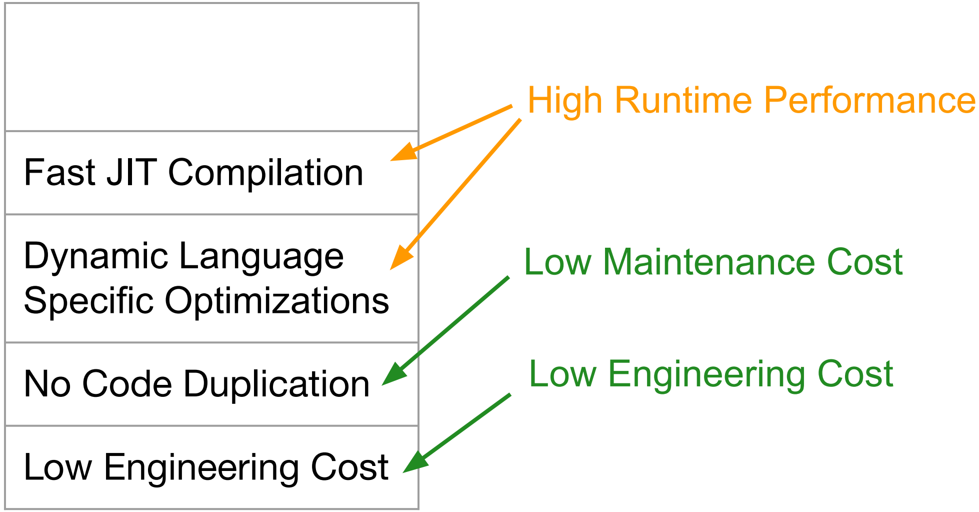
The Problems with LLVM

- LLVM produces good code, but compilation is slow, terribly slow
    - But for a JIT, fast compilation is critical
- No direct support for the important domain-specific optimizations
    - Inline Caching / Self-Modifying Code (dynamic patching)
    - Dynamic Type Related Optimization
    - Hot-cold Splitting
    - Tiering-up / OSR-Exit
    - …

Even worse, some are fundamentally undoable at LLVM IR level without major changes to LLVM!

- Cannot fully solve the engineering cost & code duplication problem
    - Still need to write interpreter in assembly for best performance
    - Still need to manually implement each JIT tier using LLVM APIs
    - Still need to keep all tiers in sync

An Ideal Dynamic Language VM Should Have…



An Ideal Dynamic Language VM Should Have…

	State-of-the-Art VM (JSC/V8/SpiderMonkey…)
Fast JIT Compilation	✅
Dynamic Language Specific Optimizations	✅
No Code Duplication	❌
Low Engineering Cost	❌

An Ideal Dynamic Language VM Should Have…

	State-of-the-Art VM (JSC/V8/SpiderMonkey…)	LLVM-based VM
Fast JIT Compilation	✅	❌
Dynamic Language Specific Optimizations	✅	❌
No Code Duplication	❌	⭕
Low Engineering Cost	❌	⭕

* I am aware of prior meta-VM approaches like Truffle or PyPy. I don’t have the time to cover them in this talk, but I’m sure you will reach your conclusion after the talk :)

An Ideal Dynamic Language VM Should Have…

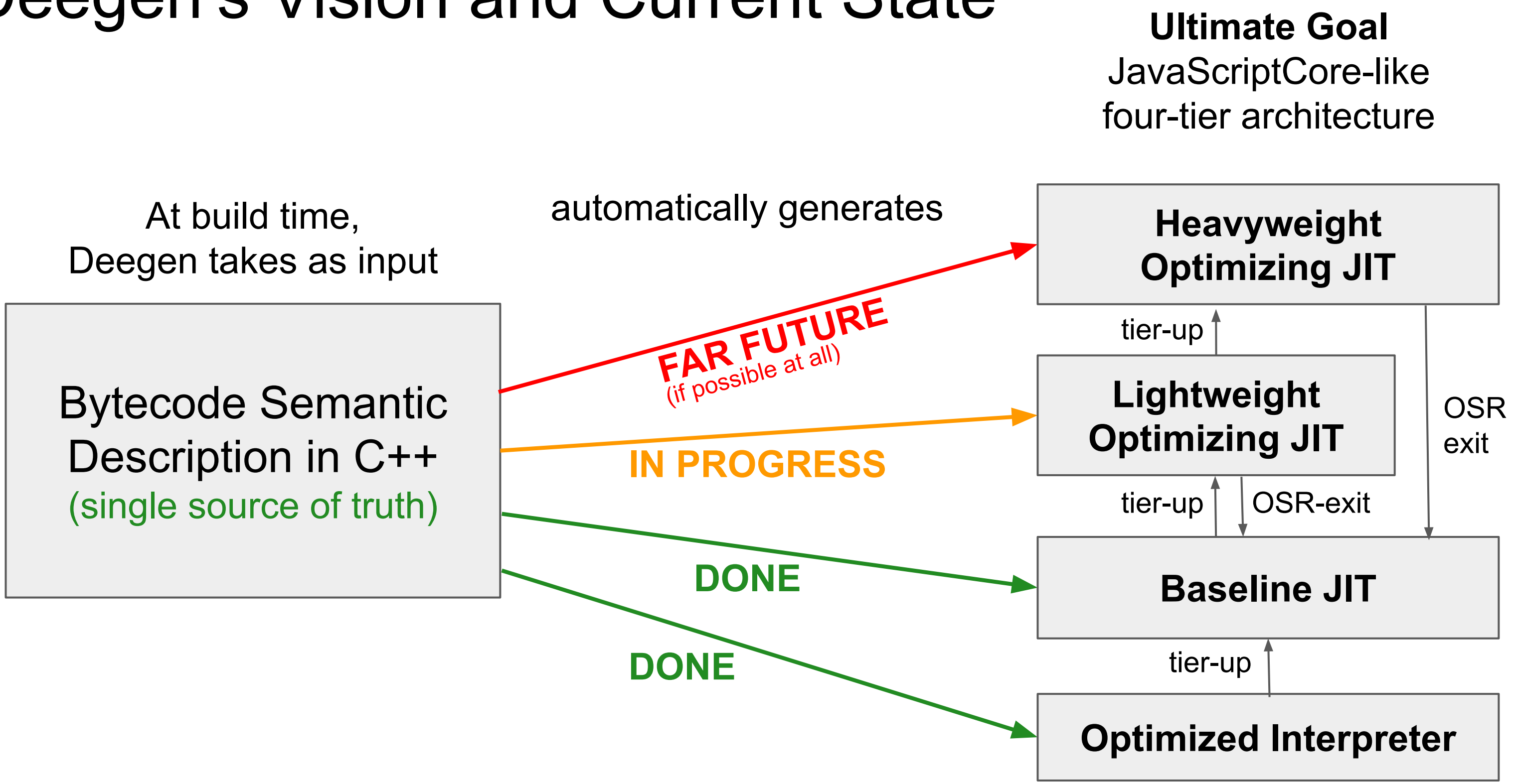
	State-of-the-Art VM (JSC/V8/SpiderMonkey…)	LLVM-based VM	VM Generated By Deegen
Fast JIT Compilation	✅	❌	✅
Dynamic Language Specific Optimizations	✅	❌	⭕ [note]
No Code Duplication	❌	⭕	✅
Low Engineering Cost	❌	⭕	✅

[Note]: We are in the progress of implementing more and more optimizations for Deegen, so that we can eventually turn the ⭕ into a proud ✅ in the future :)

Deegen's Core Idea

- Use LLVM at build time to automatically generate the VM
  - Enjoy the benefits of LLVM, not its slowness
  - At runtime, generated JIT uses *Copy-and-Patch* to generate machine code
- All VM tiers generated from a single source of truth (bytecode semantics in C++)
  - High-performance VM with low engineering cost
  - No more code duplication, VM tiers automatically in sync
- Exotic domain-specific optimizations done via ASM-level transform
  - However, only reorder and remove assembly basic blocks
  - So Deegen only needs bare minimal ASM knowledge (jump instructions only)
  - Transparent to language implementers, happens at build time

Deegen's Vision and Current State



Evaluating Deegen in Practice

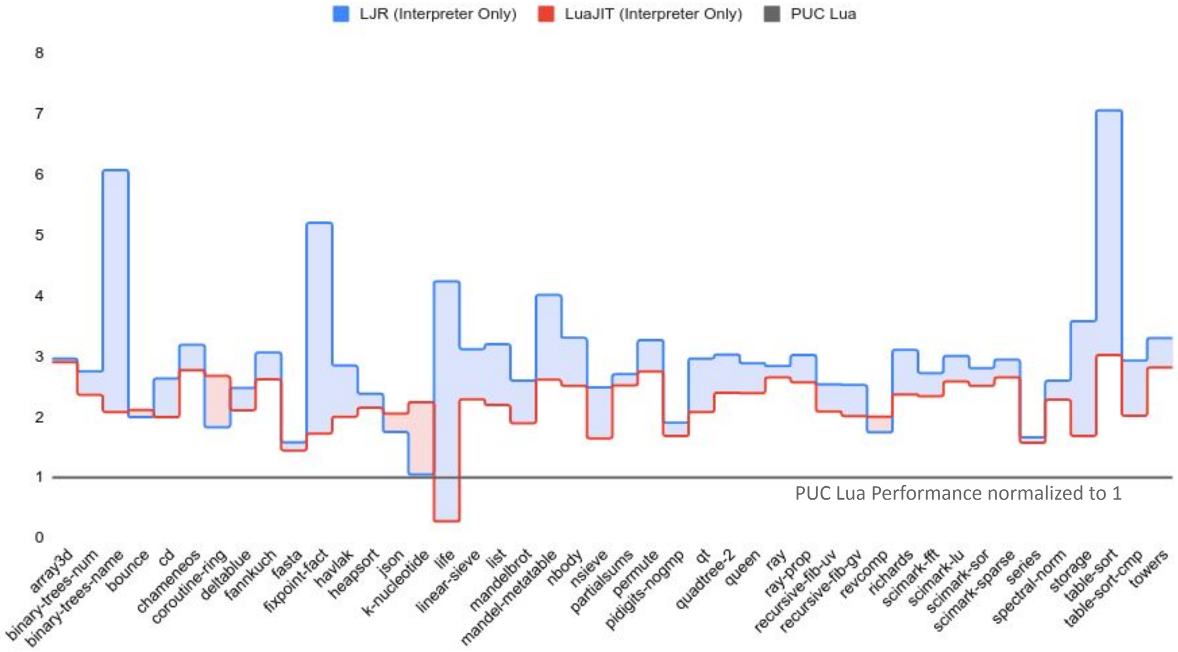
- Use Deegen to generate a VM for a dynamic language!
- First target: Lua
- Why Lua?
  - Industrial language with many real use cases
  - Supports almost any dynamic language features you can find
    - Including exotic ones like stackful coroutines
  - Nevertheless, small and simple
  - LuaJIT: natural friend (to reuse components) and rival (to outperform!)

LuaJIT Remake

- Standard-compliant VM for Lua 5.1
- Reuses several LuaJIT components
  - Frontend lexer & parser
  - Bytecode generator (Lua code ➪ Bytecode)
- Bytecode execution engine generated automatically by Deegen
  - Optimized interpreter
  - Baseline JIT compiler
- VM design not identical
  - Most importantly, we have inline caching optimization (powered by Deegen)

Interpreter Performance (No-JIT mode)

- LJR interpreter outperforms LuaJIT interpreter on 39/44 benchmarks
- Avg: 31% faster than LuaJIT interpreter, 179% faster than PUC Lua

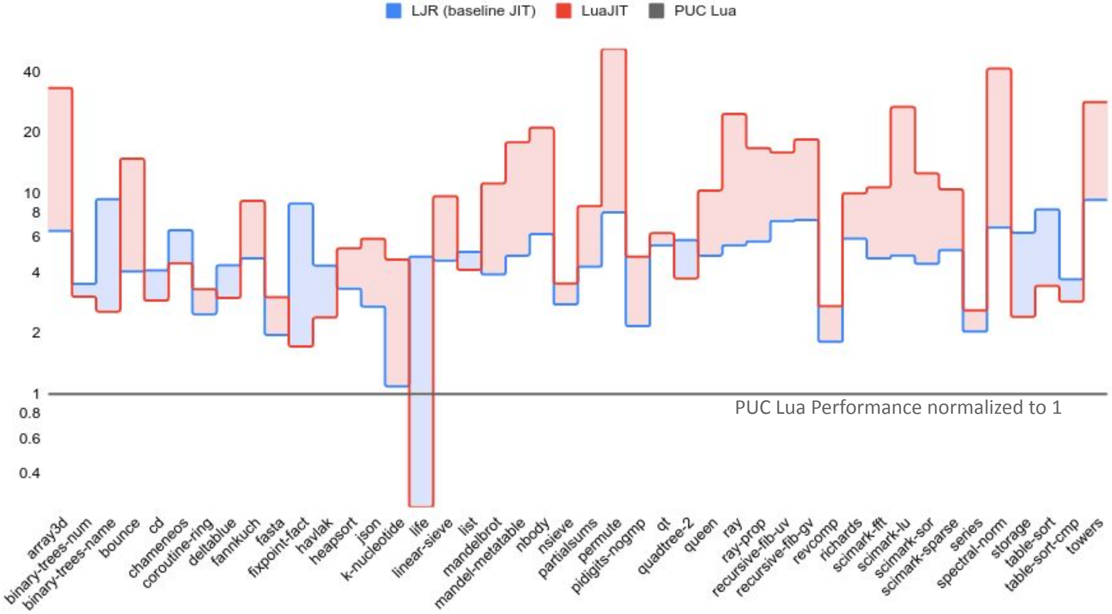


Baseline JIT Startup Delay

- Baseline JIT
  - 1st priority: generate code fast
  - 2nd priority: generate fast code
- Startup delay: How fast can the JIT generate code?
- Average throughput over 44 benchmarks:
  - 1.62GB/s machine code generated (single-threaded)
  - 19.1M/s Lua bytecode processed (single-threaded)
- Fair to claim that startup delay is negligble
- However, still want interpreter, because of memory overhead
  - On average, 91 bytes machine code per Lua bytecode

Baseline JIT Execution Performance

- Baseline JIT vs Optimizing JIT: unfair comparison
- However, LJR still managed to outperform LuaJIT on 13/44 benchmarks
- Avg: 34% slower than LuaJIT, 360% faster than PUC Lua



Bytecode Semantic Definition Example

```
void Add(TValue lhs, TValue rhs) {
  if (!lhs.Is<tDouble>() || !rhs.Is<tDouble>()) {
    ThrowError("Can't add!");
  } else {
    double res = lhs.As<tDouble>() + rhs.As<tDouble>();
    Return(TValue::Create<tDouble>(res));
  }
}
```

Deegen API

Defined by user, but understood by Deegen

Bytecode Semantic Definition Example, Continued

```
void AddContinuation(TValue /*lhs*/, TValue /*rhs*/) {
  Return(GetReturnValueAtOrd(0));
}
void Add(TValue lhs, TValue rhs) {
  if (!lhs.Is<tDouble>() || !rhs.Is<tDouble>()) {
    /* we want to call metamethod now */
    HeapPtr<FunctionObject> mm = GetMMForAdd(lhs, rhs);
    MakeCall(mm, lhs, rhs, AddContinuation);
    /* MakeCall never returns */
  } else {
    double res = lhs.As<tDouble>() + rhs.As<tDouble>();
    Return(TValue::Create<tDouble>(res));
  }
}
```

Arbitrary runtime call, not understood by Deegen

Deegen API

Control transfers to continuation functor when call returns

Bytecode Specification Language

```
DEEGEN_DEFINE_BYTECODE(Add) {
  Operands(
    BytecodeSlotOrConstant("lhs"),
    BytecodeSlotOrConstant("rhs")
  );
  Result(BytecodeValue);
  Implementation(Add);
  Variant(
    Op("lhs").IsBytecodeSlot(),
    Op("rhs").IsBytecodeSlot()
  );
  Variant(
    Op("lhs").IsConstant<tDoubleNotNaN>(),
    Op("rhs").IsBytecodeSlot()
  );
  Variant(
    Op("lhs").IsBytecodeSlot(),
    Op("rhs").IsConstant<tDoubleNotNaN>()
  );
}
```

Deegen understands the type system, and will do optimizations using this info

Also supports static quickening based on type assumption (not shown)

User-Friendly Bytecode Builder API

```
bytecodeBuilder.CreateAdd({
  .lhs = Local(1),
  .rhs = Cst<tDouble>(123.4),
  .output = Local(2)
});
```

Actual Disassembly of AddVV bytecode

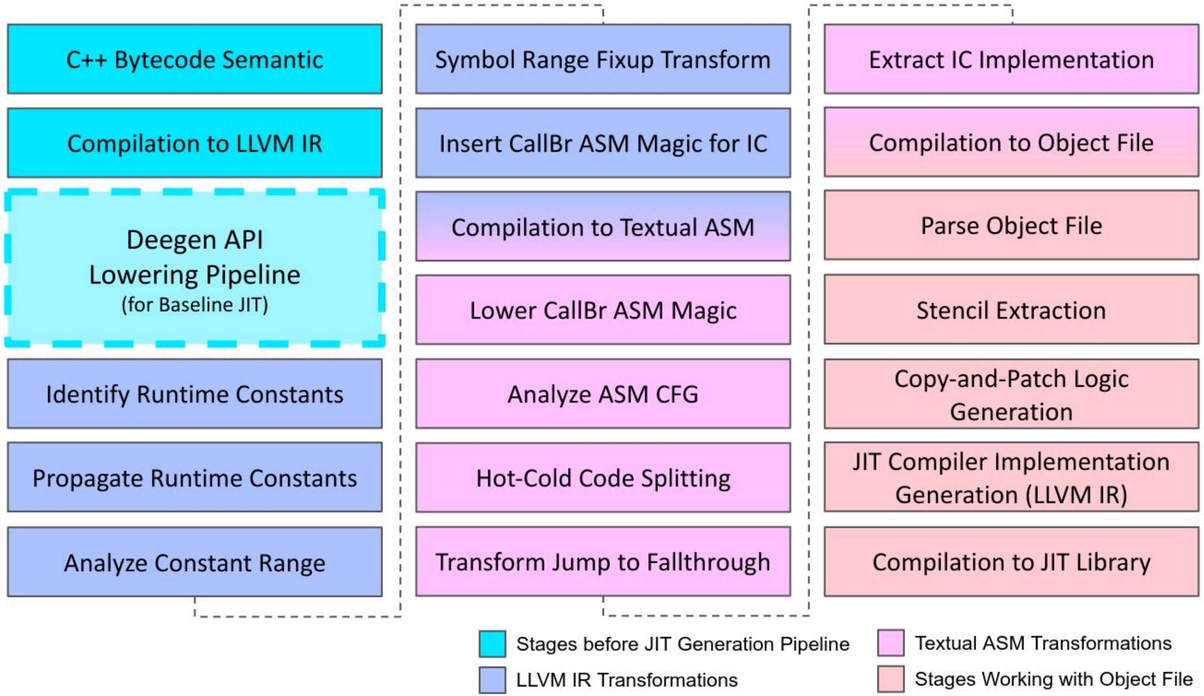
```
__deegen_interpreter_op_Add_0:
    # decode 'lhs' from bytecode stream
    movzwl      2(%r12), %eax
    # decode 'rhs' from bytecode stream
    movzwl      4(%r12), %ecx
    # load the bytecode value at slot 'lhs'
    movsd       (%rbp,%rax,8), %xmm1
    # load the bytecode value at slot 'rhs'
    movsd       (%rbp,%rcx,8), %xmm2
    # check if either value is NaN
    # Note that due to our boxing scheme,
    # non-double value will exhibit as NaN when viewed as double
    # so this checks if input has double NaN or non-double value
    ucomisd     %xmm2, %xmm1
    # branch if input has double NaN or non-double values
    jp          .LBB0_1
    # decode the destination slot from bytecode stream
    movzwl      6(%r12), %eax
    # execute the add
    addsd       %xmm2, %xmm1
    # store result to destination slot
    movsd       %xmm1, (%rbp,%rax,8)
    # decode next bytecode opcode
    movzwl      8(%r12), %eax
    # advance bytecode pointer to next bytecode
    addq        $8, %r12
    # load the interpreter function for next bytecode
    movq        __deegen_interpreter_dispatch_table(,%rax,8), %rax
    # dispatch to next bytecode
    jmpq        *%rax
.LBB0_1:
    # branch to automatically generated slowpath (omitted)
    jmp         __deegen_interpreter_op_Add_0_quickening_slowpath
```

The Baseline JIT Tier

- Completely free for a language implementer:
  - No additional input required.
  - Everything generated automatically from the bytecode semantics.
- Features:
  - Extremely fast compilation speed
  - Good machine code quality (under design constraints of baseline JIT)
  - Almost all optimizations used in JavaScriptCore's baseline JIT

The Baseline JIT Tier

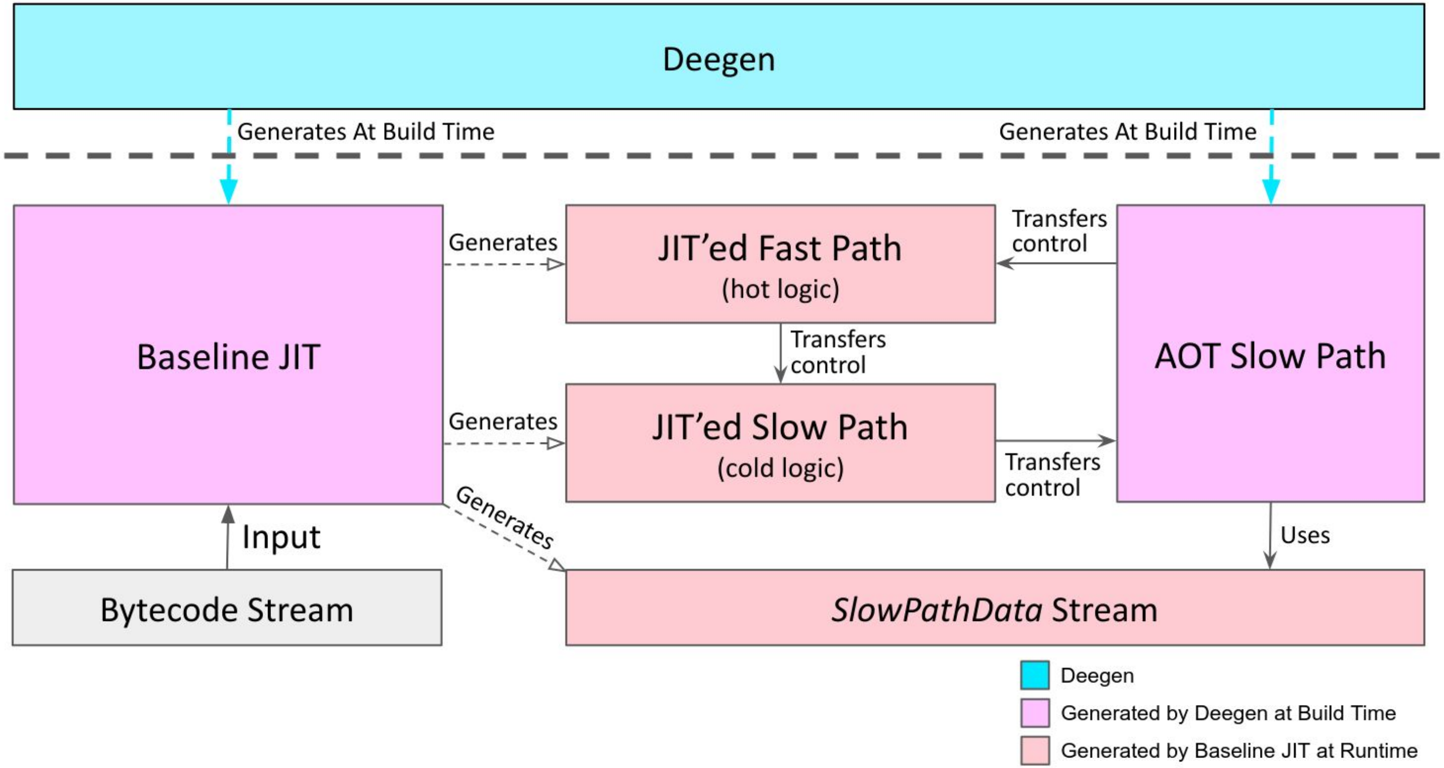
- Generated automatically via a sophiscated build-time pipeline



The Baseline JIT Tier

- Use Copy-and-Patch to generate code.
- Inline Caching as the only high-level optimization
  - As it is the only high-level optimization that can be performed without sacrificing startup delay
- However, many low-level optimizations
  - Runtime-constant propagation (aka, binding-time analysis)
  - Self-modifying-code-based IC implementation for best perf
  - Inline Slab optimization for IC
  - Hot-cold splitting
  - Tail-jump elimination
  - …

Baseline JIT Architecture (except Inline Caching)



Example: generated code for Add

```
fast_path:
  0: f2 0f 10 8d ** ** ** **   movsd     $[1](%rbp), %xmm1
  8: f2 0f 10 95 ** ** ** **   movsd     $[2](%rbp), %xmm2
 10: 66 0f 2e ca               ucomisd   %xmm2, %xmm1
 14: 0f 8a ** ** ** **         jp        [3]
 1a: f2 0f 58 ca               addsd     %xmm2, %xmm1
 1e: f2 0f 11 8d ** ** ** **   movsd     %xmm1, $[4](%rbp)
--------------------------------------------------------------
slow_path:
  0: 41 bc ** ** ** **         movl      $[5], %r12d
  6: 4c 03 63 30               addq      0x30(%rbx), %r12
  a: e9 ** ** ** **            jmp       [6]
```

```
[1] lhsSlot * 8
[2] rhsSlot * 8
[3] slow_path
[4] outputSlot * 8
[5] slowPathDataOffset
[6] __Add_slowpath
```

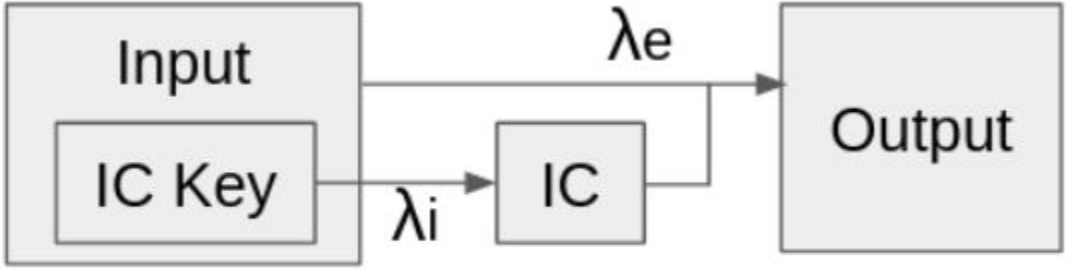
Inline Caching

- “The most important optimization” —JavaScriptCore dev
- Key observation: certain values can be well-predicted
  - For code `f()`, “`f`” likely holds the same function
  - Many objects are used like C structs, so a property access site (e.g., “`employee.name`”) likely to see objects with the same “structure”.
- Cache the seen value and computation result at use site (“inline” caching)
- If next time we see the same value, can skip redundant computation
  - For call, can skip the check that the object is indeed a function, and the load of the code pointer from the function
  - For object property access, combined with hidden class, can skip the hash table lookup and directly know where the property is

Inline Caching in Deegen

- Deegen understands calls, but not objects
  - Object semantics drastically differ per language
  - Impossible to provide a generic and ideal implementation
  - So should not be hardcoded by Deegen
- Call inline caching
  - Automatic in Deegen, no user intervention
- Object property inline caching
  - Achieved by Generic Inline Caching API
  - Requires user to use the API to express IC semantics

Generic Inine Caching API



λi : expensive but idempotent computation

λe: cheap computation based on the input and the result of the idempotent step

Computation eligible for inline caching can be characterized as above.

Generic Inine Caching API

- Idea: use C++ lambda to represent computation
- Body lambda
  - Represents the overall computation
- Effect lambda
  - Defined inside the body lambda, can have multiple
  - Represents an effectful computation
- That is, all computation in the body lambda must be idempotent. Effectful computation must be done within an effect lambda.

Inline Caching Example: TableGetById

- TableGetById
- Get a fixed string property from the table
- e.g., `employee.name`, `animal.weight`
- One of the most common operations on object.

```
void TableGetById(TValue tab, TValue key) {
  // Let's assume 'tab' is indeed a table for simplicity.
  HeapPtr<TableObject> t = tab.As<tTable>();
  // And we know 'key' must be string since the index of
  // TableGetById is required to be a constant string
  HeapPtr<String> k = key.As<tString>();
  // Call API to create an inline cache
  ICHandler* ic = MakeInlineCache();
  HiddenClassPtr hc = t.m_hiddenClass;
  // Make the IC cache on key 'hc'
  ic->Key(hc);
  // Specify the IC body (the function 'λ')
  Return(ic->Body([=] {
    // Query hidden class to get value slot in the table
    // This step is idempotent due to the design of hidden class
    int32_t slot = hc->Query(k);
    // Specify the effectful step (the function 'λ_e')
    if (slot == -1) {      // not found
      return ic->Effect([] { return NilValue(); }
    } else {
      return ic->Effect([=] { return t->storage[slot]; });
    }
  });
}
```

The Body Lambda

Value defined in body lambda
Treated as result from
idempotent computation

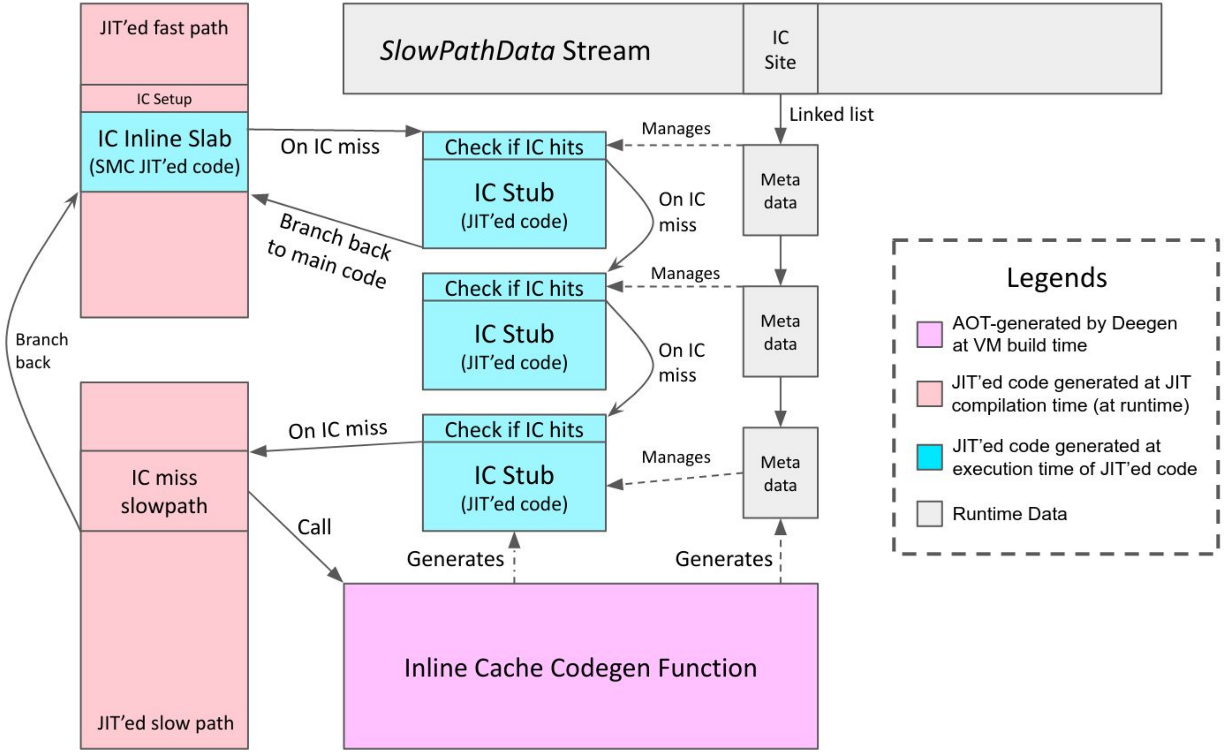
Two Effect Lambdas

Value defined outside,
sees fresh value every time

TableGetById: Interpreter Logic Disassembly

```
__deegen_interpreter_op_TableGetById_0_fused_ic_3:
    pushq    %rax
    movzwl   2(%r12), %eax              # decode the src slot from bytecode
    movq     (%rbp,%rax,8), %r9         # load the src TValue from stack
    cmpq     %r15, %r9                  # check if it is a heap entity
    jbe      .LBB5_9                    # if not, branch to slow path (omitted)
    movzwl   6(%r12), %r10d             # Decode the dst slot from bytecode
    movl     8(%r12), %edi
    addq     %rbx, %rdi                 # Get metadata struct (holding the inline cache for this bytecode)
    movl     %gs:(%r9), %ecx            # Load hidden class (safe as we have checked it's a heap entity)
    cmpl     %ecx, (%rdi)               # Check if inline cache hits
    jne      .LBB5_5                    # If not, branch to slow path (omitted)
    movslq   5(%rdi), %rax              # IC directly tells us the slot holding the property in the object
    movq     %gs:16(%r9,%rax,8), %rax   # Load that slot in the object
    movq     %rax, (%rbp,%r10,8)        # Store the result back to dst slot in the stack frame
    movzwl   12(%r12), %eax             # Dispatch to next bytecode
    addq     $12, %r12
    movq     __deegen_interpreter_dispatch_table(,%rax,8), %rax
    popq     %rcx
    jmpq     *%rax
```

Baseline JIT Inline Caching Design



Further Reading

- My Blog:
  - sillycross.github.io
- Blog post titles:
  - Building the fastest Lua interpreter automatically
  - Building a baseline JIT for Lua automatically
- LuaJIT Remake Github repo:
  - https://github.com/luajit-remake/luajit-remake