

Amalgamating Different JIT Compilations in a Meta-tracing JIT Compiler Framework

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Abstract

Most virtual machines employ just-in-time (JIT) compilers to achieve high-performance. Trace-based compilation and method-based compilation are two major compilation strategies in JIT compilers. In general, the former excels in compiling programs with more in-depth method calls and more dynamic branches, while the latter is suitable for a wide range of programs. Some previous studies have suggested that each strategy has its advantages and disadvantages, and there is no clear winner.

In this paper, we present a new approach, namely, the meta-hybrid JIT compilation strategy. It combines trace-based and method-based compilations to utilize the advantages of both strategies. Moreover, it is realized as a meta JIT compiler framework; thus, we can generate a VM with a hybrid JIT compiler that can apply different program parts by merely writing an interpreter with our framework.

We chose to extend a meta-tracing JIT compiler and supported the two compilations on it. As a prototype, we implemented a simple meta-tracing JIT compiler framework called BacCaml based on the MinCaml compiler by following RPython’s architecture.

We evaluated its performance by creating a small functional programming language with BacCaml and running microbenchmark programs. Furthermore, we performed a synthetic experiment to confirm that there are programs that run faster by hybrid compilation.

CCS Concepts: • Software and its engineering → Just-in-time compilers.

Keywords: JIT compiler, language implementation framework, meta-tracing JIT compiler, RPython

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1 Introduction

Just-in-Time (JIT) compilation is widely used in modern programming language implementations that include Java [16, 30], JavaScript [15, 17, 26], and PHP [1, 29] to name a few. There is a variety of JIT compilers that commonly identify “hot spots” or frequently-executed parts of a program at runtime, collect runtime information, and generate machine code. By compiling only frequently-executed parts of a program, the compilation is fast enough to be executed at runtime. By exploiting runtime information, compilers can execute aggressive optimization techniques such as inlining, type specialization and produce as efficient—sometimes more efficient—code as the that code generated with traditional static compilers.

JIT compilers can be classified by the strategy of selecting compilation targets, namely method-based and trace-based strategies. The method-based strategy involves using methods (or functions) as a unit of compilation, which has been used in many JIT compilers [12, 30, 37]. It shares many optimization techniques with traditional static compilers. The trace-based strategy involves using a *trace* of a program execution, which is a sequence of instructions during a particular run of a program, as a compilation unit [3, 6, 9, 15]. It effectively executes inlining, loop unrolling and type specialization.

Neither of the two strategies is better than the other; instead, each works better for different types of programs. While the method-based strategy works well on average, the trace-based strategy exhibits polarized performance characteristics. It works better for programs with many biased conditional branches and deeply nested function calls [3, 9, 15, 23]. However, this strategy can cause severe overheads when the path of an execution varies, which is known as the *path-divergence problem* [20, 21].

It seems straightforward to combine the two strategies, i.e., when compiling a different part of a program, using a

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strategy that works better for that part. However, the following questions need to be answered: (1) how can we construct such a compilation engine without actually creating two very different compilers, (2) how do the code fragments that are compiled by different strategies interact with each other, and (3) how can we determine a compilation strategy to compile a part of a program.

There are not many studies on these regards. To the best of our knowledge, only region-based compilation by HipHop Virtual Machine (HHVM) [29] and is the strategy that supports both strategies. HHVM is designed for PHP and Hack, and implemented by making a method-based compiler more flexible in selecting compilation targets. Lazy basic block versioning is provided by Higgs JavaScript VM. It is a JIT code generation technique working at the level of basic blocks, defining a basic block as a single-entry and single-exit sequence of instructions, and performs both strategies by combining type-specialized basic blocks.

We propose a *meta-hybrid JIT compiler framework* to combine trace- and method-based strategies, to study questions (1) and (2), while leaving question (3) for future work. One major difference from the existing hybrid compilers is that we design a *meta-JIT compiler framework*, which can generate a JIT compiler for a new language by merely writing an interpreter of the language. Moreover, we design it by extending a *meta-tracing* compilation framework by following the RPython's [9, 13] architecture.

We implemented BacCaml, a prototype implementation of our framework. Though its architecture is based on the RPython's, it is a completely different and much simpler implementation written in OCaml. We modified the MinCaml compiler [34] as the compiler backend.

Contributions and Organization. This paper has the following contributions.

- We propose a meta-hybrid JIT compiler framework that can apply both trace- and method-based compilation strategies, i.e., hybrid compilation strategy, to different parts of a program under a meta-JIT compiler framework.
- We present a technique to achieve method-based compilation with a meta-tracing JIT compiler by controlling the trace-based compiler to cover all the paths in a method.
- We identify the problem of interconnecting code fragments compiled by the different strategies, and present a solution that involves dynamically switching the usage of call stacks.
- We implemented a prototype of our framework called BacCaml, and confirmed that there are programs where the hybrid compilation strategy for our framework performs better.

The rest of this paper is organized as follows. In Section 2, we give an overview of method JIT, tracing JIT, and meta-tracing JIT compilation which serve as the underlying techniques of our framework. In Section 3, we present our hybrid compiler framework after discussing the advantages and disadvantages of tracing- and method-based strategies. In Section 4, we introduce a technique that enables method-based compilation with a meta-tracing JIT compiler. Afterwards, we explain the problem and solution of combining code fragments compiled by two compilation strategies. In Section 5, we evaluate the basic performance of the current BacCaml implementation. In Section 6, we report on a synthetic experiment in order to confirm usefulness of the hybrid strategy. In Section 7, we discuss related work. Finally, we conclude the paper in Section 8.

2 Background

Before presenting the concept and implementation of our meta-hybrid JIT compiler framework, we briefly review the following compilation techniques which are essential of our framework; method-based compilation, trace-based compilation, and meta-tracing JIT compilation.

2.1 Method-Based JIT Compilation Technique

JIT compilation is a commonly used technique in VM-based languages, including Smalltalk-80 [12], SELF [37] and Java [2, 30]. It performs the same compilation processes as the back-end of the ahead-of-time compilers but does only to a small set of methods during an execution of a program. The compiled methods are “hot spots” in the execution as they are usually chosen from frequently-executed ones by taking an execution profile. In addition to the standard optimization techniques that are developed for the ahead-of-time compilers, it performs more optimization techniques by exploiting profiling information. One of those techniques is *aggressive inlining*, which selectively chooses inline method bodies only to the ones frequently executed. By not inlining methods that are rarely executed, it can inline more nested method calls.

2.2 Trace-Based JIT Compilation Technique

Tracing optimization was initially investigated by the Dynamo project [3] and was adopted for implementing compilers for many languages such as Lua [31], JavaScript [15], Java trace-JIT [16, 23] and the SPUR project [6].

Tracing JIT compilers track the execution of a program and generate a machine code with hot paths. They convert a sequential code path called *trace* into native code while interpreting others [10]. “Trace” is a straight-line program; therefore, every possible branch is selected as the actually-executed one. To ensure that the tracing and execution condition is the same, a *guard* code is placed at every possible point (e.g., if statements) that go in another direction. The

```

def interp(bytecode):
    stack = []; sp = 0; pc = 0
    while True:
        jit_merge_point(reds=['stack', 'sp'],
                       greens=['bytecode', 'pc'])
        inst = bytecode[pc]
        if inst == ADD:
            v2, sp = pop(stack, sp)
            v1, sp = pop(stack, sp)
            sp = push(stack, sp, v1 + v2)
        elif inst == JUMP_IF:
            pc += 1; addr = bytecode[pc]
            if addr < pc: # backward jump
                can_enter_jit(reds=['stack', 'sp'],
                             greens=['bytecode', 'pc'])
            pc = addr

```

Figure 1. Example interpreter definition written in RPython.

guard code determines whether the original condition is still valid. If the condition is false, the machine code’s execution stops and falls back to the interpreter.

2.3 Meta-Tracing JIT Compilation Technique

Typically, tracing JIT compilers record a representation of a program; however, a meta-tracing JIT compiler traces the execution of an *interpreter* defined by a language builder. Meta-tracing JIT compilation is just tracing compilation: in the sense that it compiles a *path* of a base-program, even if it has conditional branches. If it has, the compiled code will contain *guards*, each of which is a conditional branch to the interpreter execution from that point.

RPython [9, 10], a statically typed subset of Python programming language, is a tool-chain for creating a high-performance VM with a trace-based JIT compiler. It requires a language builder for implementing a bytecode compiler and interpreter definition for the bytecode. Our prototype BacCaml is based on RPython’s architecture. Before describing the details of BacCaml, let us give an overview of RPython’s meta-tracing JIT compilation.

To leverage the RPython’s JIT compiler, an interpreter developer should annotate to help identify the loops in the *base-program* that is going to be interpreted. Figure 1 shows an example of an interpreter defined by a language developer. The example uses two annotations, *jit_merge_point* and *can_enter_jit*. *jit_merge_point* should be put at the top of a dispatch loop to identify which part is the main loop, and *can_enter_jit* should be placed at the point where a back-edge instruction can occur (where meta-tracing compilation might start).

Algorithms 1 and 2 illustrate the meta-tracing JIT compilation algorithm in pseudocode. The procedure *JitMetaTracing* takes the following arguments: *rep* – a representation for the interpreter and *states* – the state of the interpreter just in starting to trace. A meta-tracing JIT compiler records the execution and checks the operands in the executed operations. It uses *red* and *green* colors for recognizing runtime information. The color *red* means “a variable in a base language”;

Algorithm 1: JitMetaTracing(rep, states)

input : Representations of an interpreter itself
input : States (e.g., virtual registers and memories) of an interpreter itself
output: The resulting trace of the hot spot in a base-program

```

1 entry_states ← states;
2 repeat
3   residue ← []; // Data to store the result
4   op ← rep.current_operation(states);
5   if op = conditional branch then
6     if op has red variables then
7       guard ← op.mk_guard(states);
8       residue.append(guard);
9     eval(op, states, residue);
10  else if op = function call to f then
11    inline f;
12  else
13    eval(op, states, residue);
14 until op != jit_merge_point ∧ entry_states != states;
15 return residue;

```

Algorithm 2: Eval(op, states, residue)

```

1 if op has red variable then
2   op.const_fold(states);
3   residue.append(op);
4 else
5   op.execute(states);

```

hence, red variables are used for calculating the result of a base-program. The color *green* indicates “a variable in an interpreter”, then the compiler will optimize this variable by constant-folding or inlining. If all the operands in one operation are green, the operation is only used for calculation in an interpreter, and therefore the compiler executes it. If at least one variable is red, the compiler recognizes the operation is in a base-program and writes to the *residue*.

One significant advantage of a meta-tracing JIT compilation strategy depicted by RPython is that it is more comfortable to write interpreters in comparison to the abstract-syntax-tree (AST) rewriting specialization in Truffle. In [24], Marr and Ducasse stated that a significant difference between RPython and Truffle is the number of optimizations a language implementer needs to apply in order to reach the same level of performance. In their experiments, SOM [19] built with RPython achieves excellent performance without adding many optimizations. On the other hand, SOM built with Truffle without any additional optimizations performs one order of magnitude worse than the meta-tracing. By adding some optimizations, SOM with Truffle reaches the same level as that of SOM with RPython. According to the result, they concluded that the meta-tracing strategy has significant benefits from an engineering perspective [24].

3 Approach

This section explains the trade-offs between trace- and method-based compilation and introduces our approach to solve the problem.

3.1 Trade-Offs Between Trace-Based Compilation and Method-Based Compilation Strategies

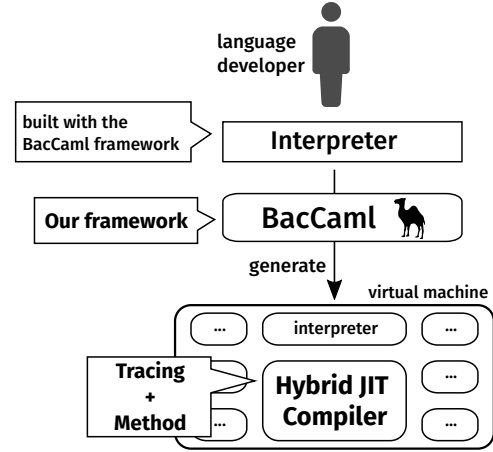
The advantages of the method-based compilation strategy are the following: First, the same optimization techniques used in AOT can be applied for method-based compilation. Thus, it can leverage existing AOT compiler engines such as GCC [35] and LLVM [14]. Second, a compilation unit has the complete control flow of a target method. Therefore, method-based compilation can be applied not only for various types of programs and also for programs that are not suitable for trace-based compilation [23, 24].

However, when a method-based compiler compiles a method with many biased branches, the compiled code includes cold spots of the method. This makes compilation time longer than when applying trace-based compilation strategy. Furthermore, it requires well-planned inlining to a method for reducing the overhead of a function call. When it applies aggressive inlining to a method with deeply-nested function calls, the compiled code's size increases, leading to longer compilation time.

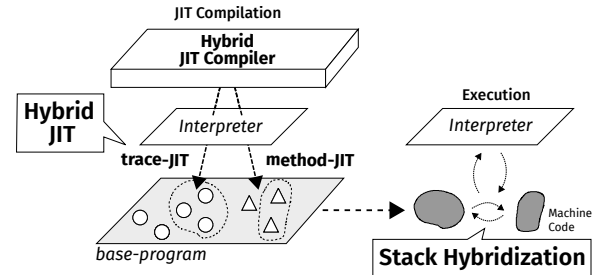
The trace-based compilation strategy, however, can apply many optimization techniques [8], including constant-subexpression elimination, dead-code elimination, constant-folding, and register allocation removal [7], since compilation code represents only one execution path. Thus, this strategy gets better results with specific programs with branching possibilities or loops [4, 21]. Moreover, it can execute aggressive function inlining at low cost, since a trace-based JIT compiler tracks and records the execution of a program so that a resulting trace will include an inlined function call [16]. This leads to reducing overheads of a function call and creating chances for further optimization. However, this strategy performs worse at programs with complex control flow because of the mismatch between tracing and execution [21]. In contrast, method-based compilation performs better in such programs.

3.2 Meta-Hybrid JIT Compiler Framework

We propose a *meta-hybrid JIT compiler framework* to overcome the trade-offs explained above, and the prototype implementation namely BacCaml. The framework is a *meta-JIT compiler framework*; therefore, a language developer can generate a VM with a hybrid JIT compiler by writing interpreter definition. A generated JIT compiler is a hybrid of the trace- and method-based compilations as it can select an execution path or a function as a compilation unit. The compiled code from the two types of strategies can work together in a single execution.



(a) A virtual machine generation with our meta-hybrid JIT compiler framework.



(b) A runtime overview of a generated hybrid JIT compiler.

Figure 2. The overviews of our meta-hybrid JIT compiler framework.

The basic idea of achieving hybrid compilation is realizing method-based compilation by extending a (meta-) tracing compiler and mixing them. Since a trace has no control flow and inlines a function, we create our method-based compilation by customizing the tracing JIT compilers' features to cover all the paths in a method. Therefore, our meta-hybrid JIT compiler framework shares its implementations between the two trace- and method-based compilers. Details are explained in Section 4.1.

In addition to the leverage strength of the two JIT compilation strategies, we aim to resolve the path-divergence problem by selectively applying method-based compilation to the functions that cause the problem trace compilation to the other parts of a program. Since this proposal focuses on combining the different two strategies, dynamically selecting a suitable strategy depending on target programs' structure is left as future work.

Figure 2 gives an overview of our meta-hybrid JIT compiler framework. As shown in Figure 2a, when a language developer writes interpreter definition with the framework, the framework can generate a VM with a hybrid JIT compiler. Figure 2b overviews our hybrid compilation and runtime by our framework. At runtime, the generated hybrid

JIT compiler applies different strategies to different parts of a base-program. Further, machine codes generated from different strategies can move back and forth with each other by *Stack Hybridization*, which is illustrated in Section 4.4.

4 Mixing The Two Compilation Strategies in Meta-Level

In this section, we first describe how to construct method-based compilation based on (meta-) trace-based compilation. We then explain how to cooperate with them in a meta JIT compiler framework. In this work, we merely aim at achieving *simple* method compilation; i.e., advanced optimization techniques used in existing method JIT compilers are left for future work.

4.1 Method-Based Compilation by Tracing

To construct method-based compilation by utilizing a trace-based compilation, we have to cover all paths of a function. In other words, we need to determine the *true path* and decrease the number of guard failures that occur to solve the path-divergence problem when applying trace-based compilation.

We propose *method JIT by tracing* by customizing the following features of trace-based compilation: (1) trace entry/exit points, (2) conditional branches (3) loops, (4) function calls. In the following paragraphs, we explain in detail how to “trace” a method by modifying these features. Note that method JIT by tracing is more naive than other state-of-the-art method-based JIT compilers, since this method-based compilation is designed for applying for programs with complex control flow, which causes performance degradation problem in a trace-based compilation, and we apply a trace-based compilation for other programs. Thus, the trace-based compiler is the primary compiler, and the method-based compiler is the secondary compiler in our system.

Trace entry/exit points. Trace-based JIT compilers [15, 16] generally compile loops in the base-program; therefore, they start to trace at the top of a loop and end when the execution returns to the entry point. To assemble the entire body of a function, we modify this behavior to trace from the top of a method body until a return instruction is reached (see Algorithm 3).

Conditional branches. When handling a conditional branch, trace-based JIT compilers convert a conditional branch into a guard instruction and collect instructions that are executed. When execution method-based compilation, however, we must compile both sides of conditional branches. To achieve this, a tracer that records executed instructions must return to the branch point and restart tracing the other side as well. As shown in Algorithm 4, the tracer in our constructed method-based JIT compiler has to trace both then and else sides so that it *backtracks* to the beginning of a conditional branch when it reaches the end of one side and

Algorithm 3: JitMetaMethod(rep, states, residue)

```

input : Representations of an interpreter itself.
input : States (e.g., virtual registers and memories) of an
        interpreter itself.
input : An array data structure that records an executed
        instruction.
output: The trace of a target method in a base-program
1 if op = method_entry then
2   residue ← [];
3   do
4     if op = conditional_branch then
5       | TraceCond (rep, states, residue);
6     else if op = loop_entry then
7       | TraceLoop (rep, states, residue);
8     else if op = function_call_to_f then
9       | TraceFunction (rep, states, residue);
10    else
11      | eval(op, states, residue);
12    op ← rep.get_next(op);
13  while op != return;
14  return residue;
15 else
16  | return;

```

Algorithm 4: TraceCond(rep, states, residue)

```

1 regs, mems ← [], [];
2 do
3   regs.store(states.get_reg());
4   mems.store(states.get_mem());
5   trace_then ← JITMETAMETHOD(states);
6   states.restore(regs, mems);
7   trace_else ← JITMETAMETHOD(states);
8   // construct if exp including trace_then and
   trace_else
9   trace_ifexp ← begin
10    if op.const_fold(states) then
11      | trace_then;
12    else
13      | trace_else
14  residue.append(trace_ifexp);
15  op ← rep.next_of(op);
16 while op != return;

```

continues to trace the other side. Before starting to trace one side, the tracer stores its states (e.g., the data stored in the tracer’s virtual registers and memories) in already prepared arrays. For just backtracking, the tracer *restores* those states and continues to the other side.

Figure 3a shows an example describing how the tracer for method-based compilation works. On the left side, node A is the method entry, nodes B – C – D form a conditional branch, and node E is the end of this method. The tracer starts to trace at A. On reaching a conditional branch (B), the tracer then stores its state and follows one side (B – C – E – G – H). On reaching *return* instruction (H), the tracer

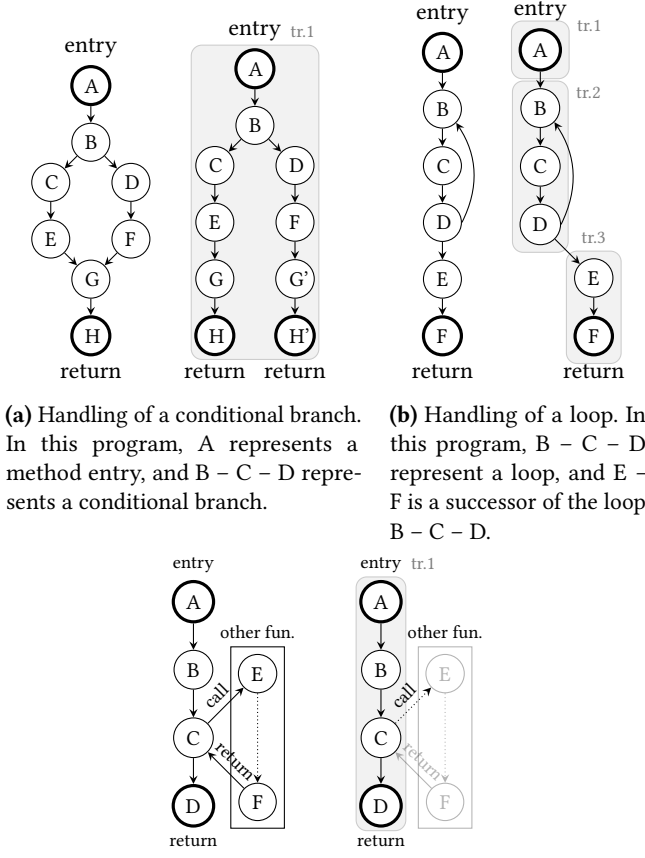


Figure 3. Examples how our method-based compilation works. Each left-hand side is the control-flow of a target base-program that represents one method, and each right-hand side is a result. “entry” and “return” means the entry point and exit point of a target method, respectively.

finally backtracks to B and resumes to trace the other side (B - D - F - G - H) by restoring the already saved data.

There is a risk of an exponential blow-up of compiled code when tracing a program that has many nested conditionals. To avoid generating too big native code, when the compiler detects too many branches in a target program part, our system stops the method-based compiler to trace. Instead, our system switches to apply trace-based compilation for such a program.

Loops. Our method-based compiler does not handle loops specially. While a trace-based compiler compiles loops as a straight-line path, our method-based compiler compiles not only the body a target loop, but also the successors of it.

Algorithm 5 illustrates how the tracer for method-based compilation traces a loop. When the tracer finds the entry point, it starts to analyze the body of a function to find a

Algorithm 5: TraceLoop(rep, states, residue)

```

1 op ← rep.get_op();
2 do
3   if op = back-edge to the entry then
4     residue.append(jump to entry);
5   else if op = loop-exit then
6     loop_after_state ← rep.next_of(op).get_states();
7     loop_after_trace ← JITMETAMETHOD(rep,
8       loop_after_state);
9     residue.append(jump to loop_after_trace);
10    residue_loop_after.append(loop_after_trace);
11  else
12    eval(op, states, residue);
13  op ← rep.next_of(op);
14 while op != return;
15 residue.append(residue_loop_after)

```

Algorithm 6: TraceFunction(rep, states, residue)

```

1 do
2   if op = function call to f then
3     residue.append(call to f); // not following but
4     // leaving the instruction “call f”
5     // continue to trace successors
6   while op != return;

```

back-edge and loop-exit instruction. When the tracer traces a back-edge, as with a trace-based compilation, leaves an instruction to jump to the entry. When the tracer leaves a loop-exit instruction, it also traces the destination of a loop-exit instruction and leaves a jump instruction to go to the outside of this loop.

Figure 3b shows an example of how to handle a loop. In this example, our method-based compiler compiles a single loop into three trace parts. The first one (tr.1) is up to the loop entry, the second one is the loop itself (tr.2) of the loop, and the third one is the successor of the loop (tr.3).

Function calls. Whereas a trace-based JIT compiler will inline function calls, our method-based JIT compiler will not inline, but emit a call instruction code and continue tracing. We don’t inline function because our method-based compilation is designed to apply only for programs with the path-divergence problem. If a target program needs inlining, we will apply trace-based compilation for it, since trace-based compilation can automatically perform function inlining. Thus, our method-based compilation is so naive that it is not equivalent to other method-based JIT compilers.

To remain a function call in a resulting trace, we have to inform which part is represented to a base-program function call in an interpreter definition. Therefore, we need to implement the specific interpreter style shown in the left-hand side of Figure 4 (we call this style *host-stack style* here). By writing in host-stack style, the tracer can detect which part is a base-program’s method invocation and leave a call

```

if opcode == CALL:
    addr = self.bytecode[pc]
    pc += 1
    # push a return addr to
    # 'user-stack'
    ret_addr = W_IntObject(pc)
    user_stack.push(ret_addr)
    if addr < pc:
        can_enter_jit(..)
        # jump to a callee function
        pc = t
    elif opcode == RETURN:
        v = user_stack.pop()
        # restore already pushed
        # return addr
        addr = user_stack.pop()
        user_stack.push(v)
        if addr < pc:
            can_enter_jit(..)
            # jump back to the caller
            # function
            pc = addr

if opcode == CALL:
    addr = self.bytecode[pc]
    # call the 'interp'
    # recursively
    res = self.interp(addr)
    user_stack.push(res)
    pc += 1
elif opcode == RETURN:
    # return a top of
    # 'user-stack'
    return user_stack.pop()

```

(a) Example interpreter written in host-stack style. (b) Example interpreter written in user-stack style.

Figure 4. Interpreter definition styles. For managing a return address/value, left-hand side style uses a host-language’s (system provided) stack, but right-hand side uses a developer-prepared stack data structure.

instruction in a resulting trace. Figure 3c shows how the tracer compiles a function call. In this example, the tracer eventually generates one trace, including a call instruction (tr.1).

In trace-based compilation, however, a meta-tracing JIT compiler can work efficiently in a specific way as shown in the right-hand side of Figure 4 (we call this *user-stack style* here).

In the next section, we organize why we need the two different two stack styles.

4.2 The Two Stack Styles

A compiler implemented by a meta-tracing JIT compiler framework has two options to represent a call-stack, namely the host-stack and the user-stack. Those two options are chosen based on the way of implementing function call/return operation in the interpreter. The host-stack style interpreter, which can be found in PyPy [33] and Topaz [36], uses the host-language’s function call/return for the base-language’s call/return. The user-stack style interpreter, as in Pycket [5] and Pyrlang [22], manages return addresses of the base-language’s function calls in a user-defined data structure in the interpreter.

Each of the two compilation strategies requires one of those two stack styles. Concretely, the method-based compilation requires the host-stack style, whereas the trace-based compilation prefers the user-stack style. While this causes the combination problem explained in the next section, we describe the relationship between the compilation strategies

```

# Example sum function
def sum(n):
    if n <= 1: return 1
    else: return n + sum(n-1)

sum(10000)

```

Figure 5. Example non-tail recursive function and its compiled trace in PyPy.

and the stack styles after explaining the differences between them.

Method-based compilation requires the host-stack style. The method-based compilation requires to confine the compilation target to one function/method¹ in a base-program, which means the compiler needs to leave a function call operation in the base program as a function call instruction in the compiled code and continue compilation of the subsequent operations in the caller function.

With a host-stack style interpreter, since the function call operation is implemented as a call to the interpreter function (i.e., *res = self.interp(addr)*) in Figure 4a), it is easy to leave the function call as it is and to continue compiling the subsequent operations.

With a user-stack style interpreter, however, the function call operation is implemented by manipulating the interpreter’s program counter (i.e., *user_stack.push(ret_addr); pc = t* in Figure 4b). To compile this into a function call machine instruction and continue compilation of the subsequent operations on the caller’s side, the compiler needs to trace the interpreter with the state after returning from the callee function without running the callee function. It is not easy, if not impossible.

Trace-based compilation prefers the user-stack style. The trace-based compilation prefers a user-stack style interpreter to successfully compile programs that heavily use recursive calls and to support languages that provide operators to manipulate call stacks (e.g., first-class continuations).

When a base-program with a (non-tail) recursive call (e.g., *sum(n)* in Figure 5) runs, it roughly performs a repetition of function calls followed by a repetition of function returns. A tracing compiler can compile the traces into two loops with a user-stack style interpreter, respectively correspond to the call/return repetitions. This is because the user-stack style interpreter realizes the base function call/return as jumps.

¹Even with function inlining, and the compiler must stop inlining at some point.

However, with a host-stack style interpreter, a tracing compiler can either terminate compilation upon the function call operation in the interpreter or inline the call operation. The former will yield very short compiled code fragments, which entails a significant amount of overheads. The latter can work well when nested levels of calls are not deep. When the nested levels get more in-depth, it can lead to code bloat. Figure 5 shows the compilation of a non-tail recursive function in PyPy, which uses the host-stack style interpreter. The sequence below the horizontal bar is the intermediate compiled code, where we can see that the compiler performs function inlining. For functions with a larger body, this approach will cause code bloating or limited levels of inlining.

4.3 Combination Problem

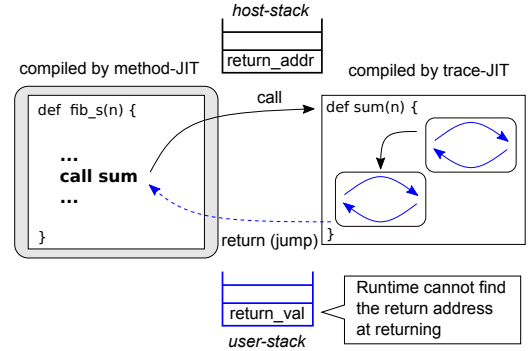
The reason why we cannot naively combine them is the following: the two compilations require different interpreter implementation styles in function calls. Trace-based compilation requires the *user-stack style*, while method-based compilation requires the *host-stack style*. In other words, different types of compilations use different stack frames for optimizing function calls. Because of this gap, the runtime cannot call back and forth between native codes generated from the two compilations. Trace-based compilation inlines a function call; therefore, there is no function call instruction in the resulting trace. Whereas method-based compilation “leaves” a function call instruction in the resulting trace. We explain this problem by using Figure 6. Figure 6a shows an example that a method-compiled function calls a trace-compiled function, and Figure 6b shows an example that a method-compiled function calls a trace-compiled function.

In the case that `fib_s` (compiled by method-based compilation) calls `sum` (compiled by trace-based compilation) as shown in Figure 6, the runtime puts a return address in the host-stack. In `sum`, the return value and return address are stored in the user-stack. On returning from `sum`, since the semantics of `return` is defined as shown in Figure 4, the runtime attempts to find a return address from a user-stack. However, the return address is stored in a host-stack, and the runtime cannot return to the correct place.

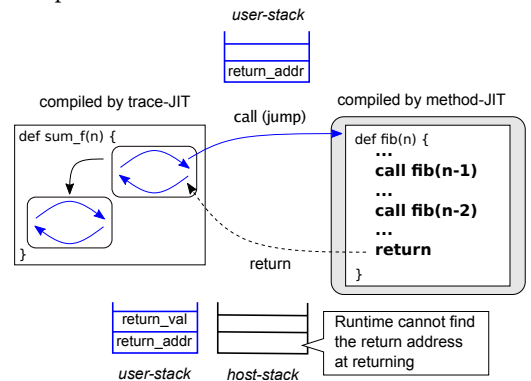
In the case shown in Figure 6b, `sum_f` (compiled by trace-based compilation) calls `fib` (compiled by method-based compilation), however the runtime puts its return address in the user-stack. When runtime returns from `fib`, it then attempts to find the return address from the host-stack, but it fails to find the address and results in runtime-error because the return address is pushed to the user-stack.

4.4 Stack Hybridization

To overcome this problem, we also present *Stack Hybridization*, a mechanism to bridge the native codes generated from different strategies. Stack Hybridization manages different kinds of stack frames, and generates machine code that can be mutually executed in trace-JIT and method-JIT contexts.



(a) Calling a trace-compiled code from a method-compiled function.



(b) Calling a method-compiled function from a trace-compiled code.

Figure 6. Example of Combination Problem. Gray background code is compiled by method JIT, and blue lined code is compiled by tracing JIT.

To use Stack Hybridization, a language developer needs to write an interpreter in the specific way: (1) For executing a call instruction in the base language, developers put a special flag to indicate which stack frame is used in a self-prepared stack data structure. (2) For executing a return, they have to branch to the return instruction of the base language corresponding to the call by checking the already pushed flag.

Roughly speaking, the interpreter handles the call and return operations in the following ways:

- When it calls a function under the trace-based compilation, it uses the user-stack; i.e., it saves the context information in the stack data structure, and iterates the interpreter loop. Additionally, it leaves a flag “user-stack” in the user-stack.
- When it calls a function under the method-based compilation, it uses the host-stack; i.e., it calls the interpreter function in the host language. Additionally, it leaves a flag “host-stack” in the user-stack.
- When it returns from a function, it first checks a flag in the user-stack. If the flag is “user-stack”, it restores the

context information from the user-stack. Otherwise, it returns from the interpreter function using the host-stack.

To support behaviors, we introduce an interpreter implementation style, which enables to embed both styles into a single interpreter and switch its behavior depending on the flag. Figure 7 shows a sketch of special syntax to support Stack Hybridization. The important syntaxes are `is_mj` pseudo function, and US/HS special flags. US means a flag “user-stack”, and HS means a flag “host-stack”.

`is_mj` is used for selecting suitable CALL definitions at compilation time. This pseudo function returns true under method-based compilation context, otherwise false. The host-stack styled definition should be placed in the then branch, and the user-stack styled definition is placed in the else branch as shown in the left of Figure 7. Then, the meta-hybrid JIT compiler traces the then branch in the context of trace-based compilation, but traces the else branch under method-based compilation context.

US and HS mean trace- and method-based compilation contexts, respectively. These special variables are used for detecting JIT compilation context dynamically when executing RETURN at runtime (not compilation time).

When defining CALL in an interpreter, US or HS is placed at the top of a user-stack when language developers define CALL instruction. At compilation time, these flags are treated as *red* variable, so an instruction pushing US or HS flag is left in a resulting trace. The compiler also leaves the branching instruction (`if JIT_flg == HS: ... else: ...`) in a resulting trace when tracing RET. This enables to find a JIT compilation context, and cooperate resulting traces made from the different two strategies at runtime.

For example, there are two traces, one (A) is made from trace-based compilation and the other (B) is from method-based compilation. When a function call from A to B is occurred, a flag US is pushed to a user-defined stack. When executing a RET instruction in B, the control executes a suitable definition by writing as shown in the right of Figure 7.

5 Evaluation

In this section, we evaluate the basic performance of BacCaml’s trace-based and method-based compilers. We first briefly introduce the current status of BacCaml, and how we took the data of microbenchmark programs. Next, we show the results of evaluation for BacCaml by running microbenchmark programs.

5.1 Setup

Implementation. We implemented the BacCaml meta-hybrid JIT compiler framework based on the MinCaml compiler [34]. MinCaml is a small ML compiler designed for education-purpose. MinCaml can generate native code almost as fast as other notable compilers such as GCC or

```

if instr == CALL:
    addr = bytecode[pc]
    # branch considering by
    # a JIT ctx.
    if is_mj():
        # push JIT flag (HS) to
        # `user-stack`
        user_stack.push(HS)
        ret_val = interp(addr)
        user_stack.push(ret_value)
    else:
        # push JIT flag (US) to
        # `user-stack`
        user_stack.push(US)
        user_stack.push(pc+1)
        pc = addr

elif instr == RETURN:
    ret_val = user_stack.pop()
    # get JIT ctx. flag from
    # `user-stack`
    JIT_flg = user_stack.pop()
    # check the JIT ctx. and branch
    if JIT_flg == HS:
        return ret_val
    else:
        ret_addr = user_stack.pop()
        user_stack.push(ret_val)
        pc = ret_addr

```

Figure 7. A sketch of an interpreter definition with Stack Hybridization. Some hint functions (e.g., `can_enter_jit` and `jit_merge_point`), and other definitions are omitted for simplicity. US and HS represents user-stack and host-stack, respectively.

OCamlOpt. We did not extend RPython itself because the implementation of RPython is too huge to comprehend. As an initial step, we created a subset of RPython on a compiler with reasonable implementation size ².

We also created a small functional programming language, namely MinCaml--, with the BacCaml framework for taking microbenchmark. It is almost same to MinCaml, but limited to unit, boolean and integer variables ³.

Methodology. We attempted to run all of MinCaml’s test programs ⁴ and shootout ⁵ benchmark suite by MinCaml-- and BacCaml before taking microbenchmark. Then, we selected all programs that can be successfully worked in them. The names of microbenchmark programs are shown in the X-axis of Figure 8.

When taking microbenchmark, we set a threshold for starting JIT compilation at a lower-than-normal value to simplify the situation. Basically, we set 100 as a threshold to determine whether starting JIT compilation or not. Therefore, this microbenchmark can arrive at a steady-state by attempting at most 50 iterations. Thus, we ran each program 150 times, and the first 50 trials were ignored to exclude the warm-up.

Since BacCaml is a prototype, we convert a resulting trace to Assembly, compile it by GCC at the compilation phase. The compiler then dispatches the control to the machine code by using dynamic loading in the execution phase. Particularly, trace-generation and compilation processes consume much time (approximately 80 % of a warm-up phase), so using a

²BacCaml itself is written in OCaml, and its implementation can be accessed at GitHub (<https://github.com/prg-titech/BacCaml>)

³MinCaml-- is also available at GitHub (<https://github.com/prg-titech/MinCaml>)

⁴<https://github.com/esumii/min-caml/tree/master/test>

⁵<https://dada.perl.it/shootout/>

JIT native code generation framework such as libgccjit⁶ or GNU Lightning⁷ is left as future work.

We ran all the microbenchmarks on Manjaro Linux with Linux kernel version 5.6.16-1-MANJARO and dedicated hardware with the following modules; CPU: AMD Ryzen 5 3600 6-Core Processor; Memory: 32 GB DDR4 2666Mhz PC4-21300.

In the Figure 8a and Figure 8b, \boxplus means BacCaml's tracing JIT, \blacksquare means BacCaml's method JIT, \boxtimes means BacCaml's interpreter-only execution, \square means MinCaml (AOT), and \boxminus means BacCaml's hybrid JIT (mixing tracing and method JIT).

Threats to Validity. There are the following threats to validity in our evaluation (including the experiment in the next section). Our method-based compilation is naive, then the inference which trace-based compilation is faster than method-based compilation has a possibility to be overturned by a full-fledged method-based compilers. This is actually true not only to our method-based compiler, but also for our trace-based compiler when compared against the state-of-the-art trace-based compilers like PyPy.

5.2 Results of Standalone JIT Microbenchmark

For comparing the standalone performance of trace- and method-based compilation strategies, we first applied both strategies separately for programs written in MinCaml--, and compared the performances of MinCaml-- with JIT with an interpreter-only execution of MinCaml-- and the MinCaml ahead-of-time compiler.

Before showing data, we explain the limitations of our method-based compilation. Compared to other state-of-the-art method JIT compilers, our method-based compilation does not inline them. It is because our method-based compilation is designed to be applied to only programs with the path-divergence problem. In other words, it is a fallback strategy when trace-based compilation does not work well.

The results are shown in Figure 8a and 8b. Note that Figure 8a is normalized to the MinCaml (lower is better), but Figure 8b is to the interpreter-only execution (higher is better).

Figure 8a illustrates the performances of the two JIT compilations comparing to the elapsed time of MinCaml-- (AOT). In these results, our trace-based compilation (\boxplus) was from 1.12 to 12.4x slower than MinCaml (AOT) (\square) in programs which have straight-forwarded control flow (fib-tail, sum, sum-tail, square, square-tail, fact, ary, prefix_sum). Our trace-based compilation was effective on such programs since almost all executions are run on compiled straight-line traces. However, it performs from 38.5 to 42.1x slower than other strategies in programs with complex control flow (fib, ack, tak, sieve), since these programs cause the path-divergence problem. In Figure 8b, our trace-based compilation was from

6.02 to 31.92x faster than interpreter-only in programs with straight-line control flow. However, it was still from 1.44 to 2.68x faster than interpreter-only in programs with the path-divergence problem, since most of the execution was done on the interpreter.

On the other hand, our method-based compilation (\blacksquare) was from 1.16 to 6.52x slower than MinCaml (AOT) in Figure 8a. Besides, from Figure 8b, our method-based compilation also performs from 15.04 to 37.8x faster than interpreter-only. From these results, most execution ran on a resulting trace. Our strategy prevented the path-divergence problem since our method-based compilation covered the entire body of a method.

Overall, our trace-based compilation was about 1.10x faster in programs with straight-line control flow but about 11.8x slower in programs with complex control flow than our method-based compilation. According to those results, we can say that trace-based compilation's performance depends on the control flow of a target program (when fitted to trace-based strategy, its performance was better than method-based strategy). Still, a method-based strategy works well on average. Therefore, we argue that combining the two strategies is vital for further speedup on JIT compilation.

6 Hybrid JIT Experiment

In this section, we demonstrate the result of an experiment for a hybrid JIT compilation strategy. This experiment aims to confirm if there are programs that are faster with a hybrid strategy than standalone strategies. This experiment was also performed by the same implementations used in Section 5.

6.1 Setup

Methodology. We first synthesized two types of functions, one is suitable for trace-based compilation, and the other is for method-based compilation according to the result shown in Section 5. Then, we applied hybrid JIT compilation for them; trace-based compilation is applied for a program with straight-line control flow, and method-based compilation is applied for a program with complex control flow. Finally, we compared the performance with standalone JIT strategies (tracing JIT only and method JIT only) and BacCaml's interpreter-only execution.

According to the result shown in Section 5.2, we chose sum, fib, and tak from the microbenchmark programs. It is because sum is faster in trace-based compilation than in method-based compilation, and fib and tak are faster in method-based compilation than a trace-based compilation. Then we manually synthesized those functions for preparing test programs, namely sum-fib, fib-sum, sum-tak and tak-sum, that shown in Figure 9.

For taking data, we used the same implementations and hardware employed in Section 5. We also took 150 iterations and ignored the first 50 trials to exclude warm-up.

⁶<https://gcc.gnu.org/onlinedocs/jit/>

⁷<https://www.gnu.org/software/lightning/>

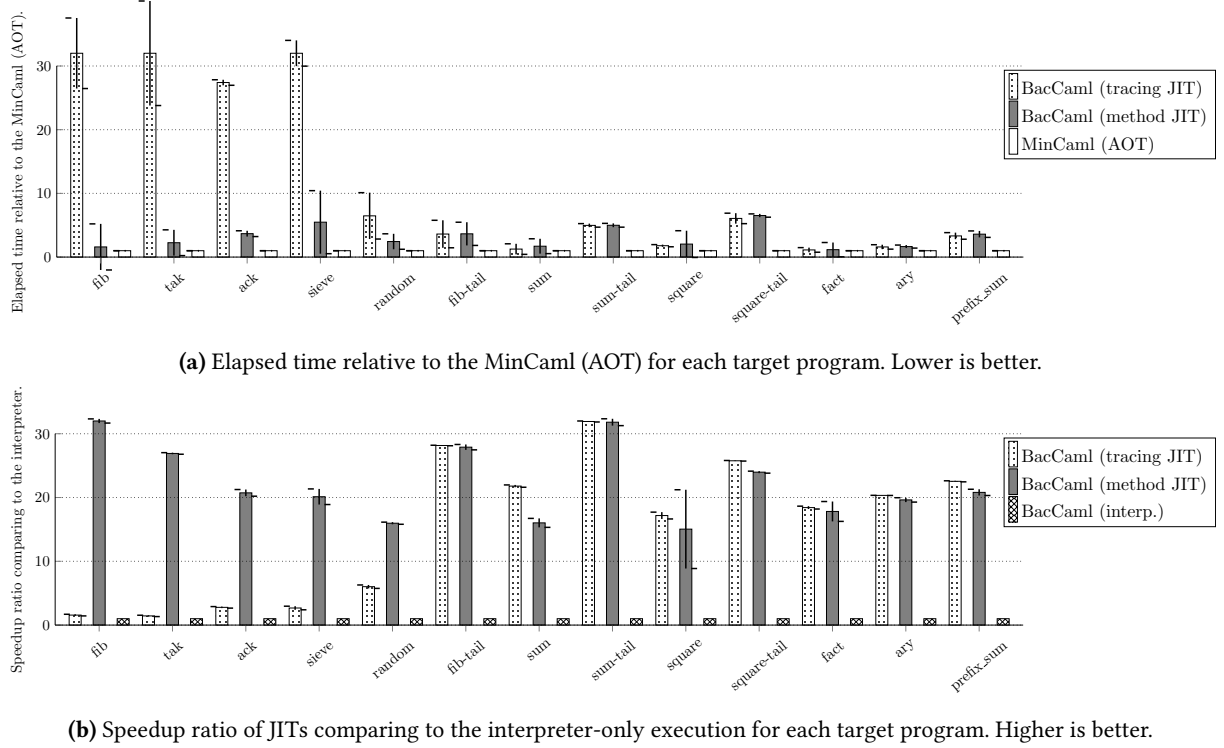


Figure 8. Results of standalone JIT microbenchmarking. The five programs on the left have a complex control flow, and the remaining programs have a straight control flow. The error bars represent the standard deviations.

Since the algorithm that decides to apply which compilation strategy to which part of a program is left for future work, we manually decided the program parts' strategies. In a hybrid JIT compilation strategy, we applied trace-based compilation to sum, and method-based compilation to fib and tak manually. Despite this, in other strategies, we used only a single strategy for those test programs. Specifically, we applied trace-based compilation to sum, fib and tak in a tracing JIT only strategy, and applied method-based compilation for them in a method JIT only strategy.

6.2 Results of Hybrid JIT Experiment

The results of the hybrid JIT experiment are shown in Figure 10. Overall, our hybrid compilation strategy (B) was from 1.01 to 2.17x faster than our method-based compilation-only. Our hybrid JIT strategy avoided the overhead of recursive function calls in sum when executing the native code generated from sum, since the recursive call part was inlined by trace-based compilation.

In contrast, our hybrid strategy was from 1.01 to 1.59x faster than the trace-based compilation-only in fib-sum and tak-sum. Moreover, our hybrid strategy was about 20x faster in sum-fib and sum-tak. This difference was caused by the structure of the target program's control flow. In fib-sum and tak-sum, fib and tak can be connected to the sum's recursive call and return parts. Otherwise, in sum-fib and sum-tak,

```

let rec fib n =
  if n <= 1 then 1 else
    fib (n-1) + fib (n-2) in

let rec sum i n =
  if i <= 1 then n else
    let m = fib 10 in
    sum (i-1) (n+m) in

print_int (sum 1000 0)

(a) sum-fib

let rec tak x y z =
  if x <= y then z else
    tak (tak (x-1) y z)
    (tak (y-1) z x)
    (tak (z-1) x y) in

let rec sum i n =
  if i <= 1 then n else
    let m = tak 12 6 4 in
    sum (i-1) (n + m) in

print_int (sum 100 0)

(c) sum-tak

let rec sum acc n =
  if n <= 1 then acc else
    sum (acc+n) (n-1) in

let rec fib n =
  if n <= 2 then sum 0 1000
  else
    fib (n-1) + fib (n-2) in

print_int (fib 20)

(b) fib-sum

let rec tak x y z =
  if x <= y then sum 1000 0
  else
    tak (tak (x-1) y z)
    (tak (y-1) z x)
    (tak (z-1) x y) in

print_int (tak 8 4 2)

(d) tak-sum

```

Figure 9. Target programs written in MinCaml-- used for the hybrid JIT experiment.

sum cannot be connected to entire fib and tak, since our trace-based compiler cannot cover entire body of fib and tak functions by the path-divergence problem.

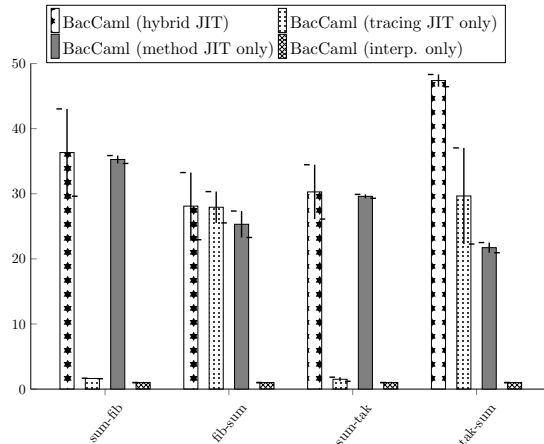


Figure 10. Results of hybrid JIT microbenchmarking. X-axis represents the name of a target program, and Y-axis represents speedup ratio relative to the interpreter-only execution. Higher is better. The error bars represent the standard deviations.

From the results, we can report that there are programs that can be run faster by the hybrid compilation strategy.

7 Related Work

Self-optimizing Abstract-syntax-tree interpreter.

Self-optimizing abstract-syntax-tree interpreter [38] also enables language developers to implement effective virtual machines. The framework and the compiler are called Truffle and Graal, respectively. The difference from our system is the basic compilation unit. Our system is based on a meta-tracing compiler, so the compilation unit is a trace. In contrast, Truffle/Graal applies partial evaluation for an AST-based interpreter of an interpreter at execution time. By profiling the runtime types and values, it can optimize a base-program and run it efficiently.

GraalSqueak. GraalSqueak [28] is a Squeak/Smalltalk VM implementation written in Truffle framework. In [27], Niephaus et al. provided an efficient way to compile a bytecode-formatted program; that is, they showed a way to apply trace-based compilation with an AST-rewriting interpreter strategy.

We extend the meta-tracing JIT compilation framework to support method-based compilation, but their approach involves creating an interpreter to enable trace-based compilation on a partial evaluation-based meta-JIT compiler framework. Their idea is to implement an interpreter with some specific hint annotations to expand the loop of an application program. Sulong has already demonstrated the same idea [32], and it was applied for implementing Squeak/Smalltalk VM.

Region-based JIT compiler. HHVM [29] is a high-performance VM for PHP and Hack programming languages. An important aspect of HHVM 2nd generation is its region-based JIT compiler. A region-based compiler [18] is not restricted to compile the entire body of methods, basic blocks, or straight-line traces; it can compile a combination of several program areas. Their compilation strategy is more flexible than our hybrid compilation strategy, because an HHVM region-based compiler can compile basic blocks, the entire body of methods, loops, and any combination of them. However, their approach is limited to a specific language system; we aim to provide some flexibility of compilation as a meta JIT compiler framework.

Lazy basic block versioning. Lazy basic block versioning [11] is a JIT compilation technique based on basic blocks. This strategy combines type specialization and code duplication to remove redundant type checking, and it can generate effective machine code. Moreover, as well as HHVM’s region-based JIT compiler, it can compile straight-line code paths and the entire method bodies by constructing basic blocks. Chevalier-Boisvert and Feely implemented lazy basic block versioning on Higgs, a research-oriented JavaScript VM⁸. Their method-based compilation is similar to ours; tracing both sides of conditional branches, not inlining functions, and not handle loops specially. The difference is that our method-based compilation is not based on basic blocks, but on traces. Moreover, our hybrid compilation can be applied not only for specific, but also for any languages.

HPS: High Performance Smalltalk. High Performance Smalltalk (HPS) is a virtual machine used in VisualWorks Smalltalk [25]. HPS achieves efficient performance by well-planned stack frame management. In HPS, the key technique for efficient implementation of contexts is mapping (closure or method) activations to stack frames in runtime. HPS has three context representations. (1) *Volatile* contexts: procedure activations which have yet to be accessed as context objects. (2) *Stable* contexts: the normal object form of procedures. (3) *Hybrid* contexts: a pair of a context object and its associated activation. By preparing extra slots for hybrid contexts in the stack frames, HPS can distinguish between hybrid and volatile contexts. This technique is similar to our stack hybridization. Stack hybridization also has the two contexts, which represent tracing and method JIT, respectively. Moreover, the stack hybridization checks the return pc by a flag in an user-defined array structure as well as HPS manages the context in a separate array object. To avoid impacting the garbage collector, the header of a hybrid context is spotted as an object including raw bits rather than object pointers. However, stack hybridization is so naive that it currently does not consider the impact of garbage collector.

⁸<https://github.com/higgsjs/Higgs>

8 Conclusion and Future Work

8.1 Conclusion

We proposed a meta-hybrid JIT compiler framework to take advantage of trace- and method-based compilation strategies as a multilingual approach. For supporting the idea, we chose a meta-tracing JIT compiler as our foundation and extended it to perform method-based compilation using tracing. By customizing the following features, we realized it: (1) trace entry/exit points, (2) conditional branches, (3) function calls, and (4) loops. We also proposed Stack Hybridization: an interpreter design to enable connecting native code generated from different strategies. The key concept of Stack Hybridization is (1) embedding two types of interpreter implementation styles into a single definition, (2) selecting an appropriate style at just-in-time compilation time, and (3) putting a flag on the stack data structure to indicate whether it is under trace- or method-based compilation.

We implemented a prototype of our meta-hybrid JIT compiler framework called BacCaml as a proof-of-concept. We created a small meta-tracing JIT compiler on the MinCaml compiler, and supported method-based compilation by extending trace-based compilation, and achieved Stack Hybridization on it.

We evaluated the basic performance of BacCaml's trace- and method-based compilers. The results showed that our trace-based compiler ran from 6.02 to 31.92x faster than interpreter-only execution in programs with straight-line control flow, but 1.44 to 2.68x faster in programs with complex control flow. Our method-based compiler ran 15.04 to 37.8x faster than interpreter-only execution in all types of programs.

We finally executed a synthetic experiment to confirm the usefulness of the hybrid strategy, and reported that there are example programs that are faster with the hybrid strategy.

8.2 Future Work

Selecting a suitable strategy dynamically. Since we focused on studying how to construct an essential mechanism of hybrid compilation and how to connect code fragments generated from different strategies, we have not investigated an approach for automatic selection of a suitable strategy. Such a mechanism is needed for applying our idea to more complex and productive programs. To realize it, we currently plan to create and combine the following profiling and analyzing techniques: (1) Profiling runtime information related to branching biases and the depth of function calls. If a target function has branching bias or deeply-function calls, we apply trace-based compilation to it. On the other hand, a target program has complex control flow; we apply method-based compilation to it. (2) Statically analysis the structure of a target program. The analyzer parses the program and examines the complexity of the target's control flow. When it has straight-line control flow, we apply trace-based compilation

for it. On the other hand, if it has complex control flow, we apply a method-based compilation on it.

Designing more fluent interpreter definition. Making hybrid-capable interpreter definition easier is also our future work. To support Stack Hybridization, the language designer has to manually insert code fragments to record/check different stack styles, which would be tedious and error-prone. This would be resolved by providing annotation functions for function call/return. Those annotation functions would also help develop further optimization techniques around dynamic checks for hybridized stacks using stub return addresses.

Realizing our idea at a production level. BacCaml is just a proof-of-concept meta-JIT compiler framework; therefore, to measure the impact of our hybrid JIT compilation on real-world applications, we will create our hybrid compilation strategy on a practical framework, such as RPython or Truffle/Graal.

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