

Trace-based Just-in-Time Type Specialization for Dynamic Languages

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Abstract

Dynamic languages such as JavaScript are more difficult to compile than statically typed ones. Since no concrete type information is available, traditional compilers need to emit generic code that can handle all possible type combinations at runtime. We present an alternative compilation technique for dynamically-typed languages that identifies frequently executed loop traces at run-time and then generates machine code on the fly that is specialized for the actual dynamic types occurring on each path through the loop. Our method provides cheap inter-procedural type specialization, and an elegant and efficient way of incrementally compiling lazily discovered alternative paths through nested loops. We have implemented a dynamic compiler for JavaScript based on our technique and we have measured speedups of 10x and more for certain benchmark programs.

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1. Introduction

Dynamic languages such as JavaScript, Python, and Ruby, are popular since they are expressive, accessible to non-experts, and make deployment as easy as distributing a source file. They are used for small scripts as well as for complex applications. JavaScript, for example, is the de facto standard for client-side web programming

and is used for the application logic of browser-based productivity applications such as Google Mail, Google Docs and Zimbra Collaboration Suite. In this domain, in order to provide a fluid user experience and enable a new generation of applications, virtual machines must provide a low startup time and high performance.

Compilers for statically typed languages rely on type information to generate efficient machine code. In a dynamically typed programming language such as JavaScript, the types of expressions may vary at runtime. This means that the compiler can no longer easily transform operations into machine instructions that operate on one specific type. Without exact type information, the compiler must emit slower generalized machine code that can deal with all potential type combinations. While compile-time static type inference might be able to gather type information to generate optimized machine code, traditional static analysis is very expensive and hence not well suited for the highly interactive environment of a web browser.

We present a trace-based compilation technique for dynamic languages that reconciles speed of compilation with excellent performance of the generated machine code. Our system uses a mixed-mode execution approach: the system starts running JavaScript in a fast-starting bytecode interpreter. As the program runs, the system identifies *hot* (frequently executed) bytecode sequences, records them, and compiles them to fast native code. We call such a sequence of instructions a *trace*.

Unlike method-based dynamic compilers, our dynamic compiler operates at the granularity of individual loops. This design choice is based on the expectation that programs spend most of their time in hot loops. Even in dynamically typed languages, we expect hot loops to be mostly *type-stable*, meaning that the types of values are invariant. (12) For example, we would expect loop counters that start as integers to remain integers for all iterations. When both of these expectations hold, a trace-based compiler can cover the program execution with a small number of type-specialized, efficiently compiled traces.

Each compiled trace covers one path through the program with one mapping of values to types. When the VM executes a compiled trace, it cannot guarantee that the same path will be followed or that the same types will occur in subsequent loop iterations.

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Hence, recording and compiling a trace *speculates* that the path and typing will be exactly as they were during recording for subsequent iterations of the loop.

Every compiled trace contains all the *guards* (checks) required to validate the speculation. If one of the guards fails (if control flow is different, or a value of a different type is generated), the trace exits. If an exit becomes hot, the VM can record a *branch trace* starting at the exit to cover the new path. In this way, the VM records a *trace tree* covering all the hot paths through the loop.

Nested loops can be difficult to optimize for tracing VMs. In a naïve implementation, inner loops would become hot first, and the VM would start tracing there. When the inner loop exits, the VM would detect that a different branch was taken. The VM would try to record a branch trace, and find that the trace reaches not the inner loop header, but the outer loop header. At this point, the VM could continue tracing until it reaches the inner loop header again, thus tracing the outer loop inside a trace tree for the inner loop. But this requires tracing a copy of the outer loop for every side exit and type combination in the inner loop. In essence, this is a form of unintended tail duplication, which can easily overflow the code cache. Alternatively, the VM could simply stop tracing, and give up on ever tracing outer loops.

We solve the nested loop problem by recording *nested trace trees*. Our system traces the inner loop exactly as the naïve version. The system stops extending the inner tree when it reaches an outer loop, but then it starts a new trace at the outer loop header. When the outer loop reaches the inner loop header, the system tries to call the trace tree for the inner loop. If the call succeeds, the VM records the call to the inner tree as part of the outer trace and finishes the outer trace as normal. In this way, our system can trace any number of loops nested to any depth without causing excessive tail duplication.

These techniques allow a VM to dynamically translate a program to nested, type-specialized trace trees. Because traces can cross function call boundaries, our techniques also achieve the effects of inlining. Because traces have no internal control-flow joins, they can be optimized in linear time by a simple compiler (10). Thus, our tracing VM efficiently performs the same kind of optimizations that would require interprocedural analysis in a static optimization setting. This makes tracing an attractive and effective tool to type specialize even complex function call-rich code.

We implemented these techniques for an existing JavaScript interpreter, SpiderMonkey. We call the resulting tracing VM *TraceMonkey*. TraceMonkey supports all the JavaScript features of SpiderMonkey, with a 2x-20x speedup for traceable programs.

This paper makes the following contributions:

- We explain an algorithm for dynamically forming trace trees to cover a program, representing nested loops as nested trace trees.
- We explain how to speculatively generate efficient type-specialized code for traces from dynamic language programs.
- We validate our tracing techniques in an implementation based on the SpiderMonkey JavaScript interpreter, achieving 2x-20x speedups on many programs.

The remainder of this paper is organized as follows. Section 3 is a general overview of trace tree based compilation we use to capture and compile frequently executed code regions. In Section 4 we describe our approach of covering nested loops using a number of individual trace trees. In Section 5 we describe our trace-compilation based speculative type specialization approach we use to generate efficient machine code from recorded bytecode traces. Our implementation of a dynamic type-specializing compiler for JavaScript is described in Section 6. Related work is discussed in Section 8. In Section 7 we evaluate our dynamic compiler based on

```

1 for (var i = 2; i < 100; ++i) {
2   if (!primes[i])
3     continue;
4   for (var k = i + i; i < 100; k += i)
5     primes[k] = false;
6 }

```

Figure 1. Sample program: sieve of Eratosthenes. `primes` is initialized to an array of 100 false values on entry to this code snippet.

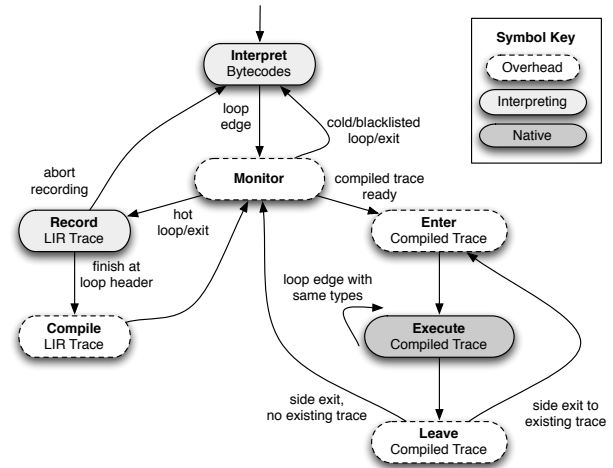


Figure 2. State machine describing the major activities of TraceMonkey and the conditions that cause transitions to a new activity. In the dark box, TM executes JS as compiled traces. In the light gray boxes, TM executes JS in the standard interpreter. White boxes are overhead. Thus, to maximize performance, we need to maximize time spent in the darkest box and minimize time spent in the white boxes. The best case is a loop where the types at the loop edge are the same as the types on entry—then TM can stay in native code until the loop is done.

a set of industry benchmarks. The paper ends with conclusions in Section 9 and an outlook on future work is presented in Section 10.

2. Overview: Example Tracing Run

This section provides an overview of our system by describing how TraceMonkey executes an example program. The example program, shown in Figure 1, computes the first 100 prime numbers with nested loops. The narrative should be read along with Figure 2, which describes the activities TraceMonkey performs and when it transitions between the loops.

TraceMonkey always begins executing a program in the bytecode interpreter. Every loop back edge is a potential trace point. When the interpreter crosses a loop edge, TraceMonkey invokes the *trace monitor*, which may decide to record or execute a native trace. At the start of execution, there are no compiled traces yet, so the trace monitor counts the number of times each loop back edge is executed until a loop becomes *hot*, currently after 2 crossings. Note that the way our loops are compiled, the loop edge is crossed before entering the loop, so the second crossing occurs immediately after the first iteration.

Here is the sequence of events broken down by outer loop iteration:

```

v0 := ld state[748]    // load primes from the trace activation record
    st sp[0], v0      // store primes to interpreter stack
v1 := ld state[764]    // load k from the trace activation record
v2 := i2f(v1)         // convert k from int to double
    st sp[8], v1      // store k to interpreter stack
    st sp[16], 0      // store false to interpreter stack
v3 := ld v0[4]        // load class word for primes
v4 := and v3, -4      // mask out object class tag for primes
v5 := eq v4, Array    // test whether primes is an array
    xf v5             // side exit if v5 is false
v6 := js_Array_set(v0, v2, false) // call function to set array element
v7 := eq v6, 0        // test return value from call
    xt v7             // side exit if js_Array_set returns false.

```

Figure 3. LIR snippet for sample program. This is the LIR recorded for line 5 of the sample program in Figure 1. The LIR encodes the semantics in SSA form using temporary variables. The LIR also encodes all the stores that the interpreter would do to its data stack. Sometimes these stores can be optimized away as the stack locations are live only on exits to the interpreter. Finally, the LIR records guards and side exits to verify the assumptions made in this recording: that `primes` is an array and that the call to set its element succeeds.

```

mov edx, ebx(748)      // load primes from the trace activation record
mov edi(0), edx        // (*) store primes to interpreter stack
mov esi, ebx(764)      // load k from the trace activation record
mov edi(8), esi        // (*) store k to interpreter stack
mov edi(16), 0         // (*) store false to interpreter stack
mov eax, edx(4)        // (*) load object class word for primes
and eax, -4           // (*) mask out object class tag for primes
cmp eax, Array         // (*) test whether primes is an array
jne side_exit_1        // (*) side exit if primes is not an array
sub esp, 8             // bump stack for call alignment convention
push false            // push last argument for call
push esi              // push first argument for call
call js_Array_set      // call function to set array element
add esp, 8            // clean up extra stack space
mov ecx, ebx          // (*) created by register allocator
test eax, eax          // (*) test return value of js_Array_set
je side_exit_2         // (*) side exit if call failed
...
side_exit_1:
mov ecx, ebp(-4)       // restore ecx
mov esp, ebp          // restore esp
jmp epilg             // jump to ret statement

```

Figure 4. x86 snippet for sample program. This is the x86 code compiled from the LIR snippet in Figure 3. Most LIR instructions compile to a single x86 instruction. Instructions marked with (*) would be omitted by an idealized compiler that knew that none of the side exits would ever be taken. The 17 instructions generated by the compiler compare favorably with the 100+ instructions that the interpreter would execute for the same code snippet, including 4 indirect jumps.

i=2. This is the first iteration of the outer loop. The loop on lines 4-5 becomes hot on its second iteration, so TraceMonkey enters recording mode on line 4. In recording mode, TraceMonkey records the code along the trace in a low-level compiler intermediate representation we call *LIR*. The LIR trace encodes all the operations performed and the types of all operands. The LIR trace also encodes *guards*, which are checks that verify that the control flow and types are identical to those observed during trace recording. Thus, on later executions, if and only if all guards are passed, the trace has the required program semantics.

TraceMonkey stops recording when execution returns to the loop header or exits the loop. In this case, execution returns to the loop header on line 4.

After recording is finished, TraceMonkey compiles the trace to native code using the recorded type information for optimization. The result is a native code fragment that can be entered if the

interpreter PC and the types of values match those observed when trace recording was started. The first trace in our example, T_{45} , covers lines 4 and 5. This trace can be entered if the PC is at line 4, `i` and `k` are integers, and `primes` is an object. After compiling T_{45} , TraceMonkey returns to the interpreter and loops back to line 1.

i=3. Now the loop header at line 1 has become hot, so TraceMonkey starts recording. When recording reaches line 4, TraceMonkey observes that it has reached an inner loop header that already has a compiled trace, so TraceMonkey attempts to nest the inner loop inside the current trace. The first step is to call the inner trace as a subroutine. This executes the loop on line 4 to completion and then returns to the recorder. TraceMonkey verifies that the call was successful and then records the call to the inner trace as part of the current trace. Recording continues until execution reaches line 1, and at which point TraceMonkey finishes and compiles a trace for the outer loop, T_{16} .

i=4. On this iteration, TraceMonkey calls T_{16} . Because $i=4$, the `if` statement on line 2 is taken. This branch was not taken in the original trace, so this causes T_{16} to fail a guard and take a side exit. The exit is not yet hot, so TraceMonkey returns to the interpreter, which executes the `continue` statement.

i=5. TraceMonkey calls T_{16} , which in turn calls the nested trace T_{45} . T_{16} loops back to its own header, starting the next iteration without ever returning to the monitor.

i=6. On this iteration, the side exit on line 2 is taken again. This time, the side exit becomes hot, so a trace $T_{23,1}$ is recorded that covers line 3 and returns to the loop header. Thus, the end of $T_{23,1}$ jumps directly to the start of T_{16} . The side exit is patched so that on future iterations, it jumps directly to $T_{23,1}$.

At this point, TraceMonkey has compiled enough traces to cover the entire nested loop structure, so the rest of the program runs entirely as native code.

3. Trace Trees

In this section, we describe traces, trace trees, and how they are formed at run time. Although our techniques apply to any dynamic language interpreter, we will describe them assuming a bytecode interpreter to keep the exposition simple.

3.1 Traces

A *trace* is simply a program path, which may cross function call boundaries. TraceMonkey focuses on *loop traces*, that originate at a loop edge and represent a single iteration through the associated loop.

Similar to an extended basic block, a trace is only entered at the top, but may have many exits. In contrast to an extended basic block, a trace can contain join nodes. Since a trace always only follows one single path through the original program, however, join nodes are not recognizable as such in a trace and have a single predecessor node like regular nodes.

A *typed trace* is a trace annotated with a type for every variable (including temporaries) on the trace. A typed trace also has an entry *type map* giving the required types for variables used on the trace before they are defined. For example, a trace could have a type map (x : `int`, b : `boolean`), meaning that the trace may be entered only if the value of the variable x is of type `int` and the value of b is of type `boolean`. The entry type map is much like the signature of a function.

In this paper, we only discuss typed loop traces, and we will refer to them simply as “traces”. The key property of typed loop traces is that they can be compiled to efficient machine code using the same techniques used for typed languages.

In TraceMonkey, traces are recorded in trace-flavored SSA LIR (low-level intermediate representation). In trace-flavored SSA (or TSSA), phi nodes appear only at the entry point, which is reached both on entry and via loop edges. The important LIR primitives are constant values, memory loads and stores (by address and offset), integer operators, floating-point operators, function calls, and conditional exits. Type conversions, such as integer to double, are represented by function calls. This makes the LIR used by TraceMonkey independent of the concrete type system and type conversion rules of the source language. The LIR operations are generic enough that the backend compiler is language independent. Figure 3 shows an example LIR trace.

Bytecode interpreters typically represent values in a various complex data structures (e.g., hash tables) in a boxed format (i.e., with attached type tag bits). Since a trace is intended to represent efficient code that eliminates all that complexity, our traces operate on unboxed values in simple variables and arrays as much as possible.

A trace records all its intermediate values in a small activation record area. To make variable accesses fast on trace, the trace also imports local and global variables by unboxing them and copying them to its activation record. Thus, the trace can read and write these variables with simple loads and stores from a native activation recording, independently of the boxing mechanism used by the interpreter. When the trace exits, the VM boxes the values from this native storage location and copies them back to the interpreter structures.

For every control-flow branch in the source program, the recorder generates conditional exit LIR instructions. These instructions exit from the trace if required control flow is different from what it was at trace recording, ensuring that the trace instructions are run only if they are supposed to. We call these instructions *guard instructions*.

Most of our traces represent loops and end with the special `loop` LIR instruction. This is just an unconditional branch to the top of the trace. Such traces return only via guards.

Now, we describe the key optimizations that are performed as part of recording LIR. All of these optimizations reduce complex dynamic language constructs to simple typed constructs by specializing for the current trace. Each optimization requires guard instructions to verify their assumptions about the state and exit the trace if necessary.

Type specialization.

All LIR primitives apply to operands of specific types. Thus, LIR traces are necessarily type-specialized, and a compiler can easily produce a translation that requires no type dispatches. A typical bytecode interpreter carries tag bits along with each value, and to perform any operation, must check the tag bits, dynamically dispatch, mask out the tag bits to recover the untagged value, perform the operation, and then reapply tags. LIR omits everything except the operation itself.

A potential problem is that some operations can produce values of unpredictable types. For example, reading a property from an object could yield a value of any type, not necessarily the type observed during recording. The recorder emits guard instructions that conditionally exit if the operation yields a value of a different type from that seen during recording. These guard instructions guarantee that as long as execution is on trace, the types of values match those of the typed trace. When the VM observes a side exit along such a type guard, a new typed trace is recorded originating at the side exit location, capturing the new type of the operation in question.

Representation specialization: objects. In JavaScript, name lookup semantics are complex and potentially expensive because they include features like object inheritance and `eval`. To evaluate an object property read expression like `o.x`, the interpreter must search the property map of `o` and all of its prototypes and parents. Property maps can be implemented with different data structures (e.g., per-object hash tables or shared hash tables), so the search process also must dispatch on the representation of each object found during search. TraceMonkey can simply observe the result of the search process and record the simplest possible LIR to access the property value. For example, the search might find the value of `o.x` in the prototype of `o`, which uses a shared hash-table representation that places `x` in slot 2 of a property vector. Then the recorded can generate LIR that reads `o.x` with just two or three loads: one to get the prototype, possibly one to get the property value vector, and one more to get slot 2 from the vector. This is a vast simplification and speedup compared to the original interpreter code. Inheritance relationships and object representations can change during execution, so the simplified code requires guard instructions that ensure the object representation is the same. In TraceMonkey, objects’ rep-

representations are assigned an integer key called the *object shape*. Thus, the guard is a simple equality check on the object shape.

Representation specialization: numbers. JavaScript has no integer type, only a Number type that is the set of 64-bit IEEE-754 floating-point numbers (“doubles”). But many JavaScript operators, in particular array accesses and bitwise operators, really operate on integers, so they first convert the number to an integer, and then convert any integer result back to a double.¹ Clearly, a JavaScript VM that wants to be fast must find a way to operate on integers directly and avoid these conversions.

In TraceMonkey, we support two representations for numbers: integers and doubles. The interpreter uses integer representations as much as it can, switching for results that can only be represented as doubles. When a trace is started, some values may be imported and represented as integers. Some operations on integers require guards. For example, adding two integers can produce a value too large for the integer representation.

Function inlining. LIR traces can cross function boundaries in either direction, achieving function inlining. Move instructions need to be recorded for function entry and exit to copy arguments in and return values out. These move statements are then optimized away by the compiler using copy propagation. In order to be able to return to the interpreter, the trace must also generate LIR to record that a call frame has been entered and exited. The frame entry and exit LIR saves just enough information to allow the interpreter call stack to be restored later and is much simpler than the interpreter’s standard call code. If the function being entered is not constant (which in JavaScript includes any call by function name), the recorder must also emit LIR to guard that the function is the same.

Guards and side exits. Each optimization described above requires one or more guards to verify the assumptions made in doing the optimization. A guard is just a group of LIR instructions that performs a test and conditional exit. The exit branches to a *side exit*, a small off-trace piece of LIR that returns a pointer to a structure that describes the reason for the exit along with the interpreter PC at the exit point and any other data needed to restore the interpreter’s state structures.

Aborts. Some constructs are difficult to record in LIR traces. For example, `eval` or calls to external functions can change the program state in unpredictable ways, making it difficult for the tracer to know the current type map in order to continue tracing. A tracing implementation can also have any number of other limitations, e.g., a small-memory device may limit the length of traces. When any situation occurs that prevents the implementation from continuing trace recording, the implementation *aborts* trace recording and returns to the trace monitor.

3.2 Trace Trees

Especially simple loops, namely those where control flow, value types, value representations, and inlined functions are all invariant, can be represented by a single trace. But most loops have at least some variation, and so the program will take side exits from the main trace. When a side exit becomes hot, TraceMonkey starts a new *branch trace* from that point and patches the side exit to jump directly to that trace. In this way, a single trace expands on demand to a single-entry, multiple-exit *trace tree*.

This section explains how trace trees are formed during execution. The goal is to form trace trees during execution that cover all the hot paths of the program.

Starting a tree. Tree trees always start at loop headers, because they are a natural place to look for hot paths. In TraceMonkey, loop headers are easy to detect—the bytecode compiler ensures that a bytecode is a loop header iff it is the target of a backward branch. TraceMonkey starts a tree when a given loop header has been executed a certain number of times (2 in the current implementation). Starting a tree just means starting recording a trace for the current point and type map and marking the trace as the root of a tree. Each tree is associated with a loop header and type map, so there may be several trees for a given loop header.

Closing the loop. Trace recording can end in several ways.

Ideally, the trace reaches the loop header where it started with the same type map as on entry. This is called a *type-stable* loop iteration. In this case, the end of the trace can jump right to the beginning, as all the value representations are exactly as needed to enter the trace. The jump can even skip the usual code that would copy out the state at the end of the trace and copy it back in to the trace activation record to enter a trace.

In certain cases the trace might reach the loop header with a different type map. This scenario is sometime observed for the first iteration of a loop. Some variables inside the loop might initially be *undefined*, before they are set to a concrete type during the first loop iteration. When recording such an iteration, the recorder cannot link the trace back to its own loop header since it is *type-unstable*. Instead, the iteration is terminated with a side exit that will always fail and return to the interpreter. At the same time a new trace is recorded with the new type map. Every time an additional type-unstable trace is added to a region, its exit type map is compared to the entry map of all existing traces in case they complement each other. With this approach we are able to cover type-unstable loop iterations as long they eventually form a stable equilibrium.

Finally, the trace might exit the loop before reaching the loop header, for example because execution reaches a `break` or `return` statement. In this case, the VM simply ends the trace with an exit to the trace monitor.

As mentioned previously, we may speculatively chose to represent certain Number-typed values as integers on trace. We do so when we observe that Number-typed variables contain an integer value at trace entry. If during trace recording the variable is unexpectedly assigned a non-integer value, we have to widen the type of the variable to a double. As a result, the recorded trace becomes inherently type-unstable since it starts with an integer value but ends with a double value. This represents a mis-speculation, since at trace entry we specialized the Number-typed value to an integer, assuming that at the loop edge we would again find an integer value in the variable, allowing us to close the loop. To avoid future speculative failures involving this variable, and to obtain a type-stable trace we note the fact that the variable in question as been observed to sometimes hold non-integer values in an advisory data structure which we call the “oracle”.

When compiling loops, we consult the oracle before specializing values to integers. Speculation towards integers is performed only if no adverse information is known to the oracle about that particular variable. Whenever we accidentally compile a loop that is type-unstable due to mis-speculation of a Number-typed variable, we immediately trigger the recording of a new trace, which based on the now updated oracle information will start with a double value and thus become type stable.

Extending a tree. Side exits lead to different paths through the loop, or paths with different types or representations. Thus, to completely cover the loop, the VM must record traces starting at all side exits. These traces are recorded much like root traces: there is a counter for each side exit, and when the counter reaches a hotness threshold, recording starts. Recording stops exactly as for the root trace, using the loop header of the root trace as the target to reach.

¹ Arrays are actually worse than this: if the index value is a number, it must be converted from a double to a string for the property access operator, and then to an integer internally to the array implementation.