Compiling the Web

Building a Just-in-Time Compiler for JavaScript

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Talk Outline

- Motivation
- Compiling Statically Typed vs Dynamically Typed Languages
- Trace Compilation and Trace Trees
- Implementation & Benchmarks
- Conclusions & Outlook

Motivation

- The Web is eating the Desktop's lunch.
  - The browser is becoming the next generation application platform.
  - GMail, Google Maps, Zimbra, Meebo
  - But also traditional "offline" applications: Google Docs, Google Spreadsheet, ...

Web Languages

- The Web uses a very different set of languages.
  - Desktop: Java, C, C++, C#, Delphi
  - Web Server: PHP, Python, Perl, Ruby, C/C++ (CGI), Java (JSP).
  - Browser: JavaScript, ActionScript (Flash), Java, C# (Silverlight), C/C++ (ActiveX).
- *Most dynamic web content is driven by dynamic languages.*

Trends

- Trends:
  - Client-side Java (slow, large footprint, fragmented) and ActiveX (security nightmare) are dying out.
  - Java seems to be holding up on the server side, but CGI is dying out (security!).
  - Microsoft is heavily investing in Silverlight, but adoption seems to be flat.

Observations

- Observations:
  - *Web programmers seem to like dynamic languages*.
  - Even evangelizing them (Silverlight!) seems to get you only so far. Despite superior tools and performance (Microsoft's C# Chess Demo) developers seem to prefer existing dynamic languages (JavaScript/PHP).
  - So what is the state of the art in JavaScript performance?

Lets travel back in time to June 17, 2008
(not even 6 month ago).

June 17, 2008

- Approximately 1.4bn (billion) Internet users [Miniwatts Marketing Group, January 2008].
- 95% of Internet users use a browser that supports JavaScript [W3Schools's web statistics, January 2008].
- *JavaScript is a purely interpreted language, no matter what browser you use.*
  - Only contenders: RHINO (JavaScript-to-JVM compiler), Tamarin (ActionScript).

August 23, 2008

- Mozilla releases the first Firefox build with a JavaScript Just-in-Time compiler (TraceMonkey).
  - Speedups in the range of 2x to 20x, depending on benchmark and application.
  - World wide press coverage, including a lot of non-technical venues (New York Times, Dallas Morning News, Der Standard).
  - *People seem to care.*

The Competition

- September 1, 2008
  - Google "slips out" Chrome.
  - Stellar on Google's own benchmarks, mixed bag on established benchmarks.
- September 18, 2008
  - Apple releases SquirrelFish Extreme (SFX).
  - Solid 1.5-2x speedup over already very fast interpreter plus RegExp JIT compiler.

October 19, 2008

- JavaScript performance has become the focal point of the new browser wars.
- Most non-Microsoft browsers will ship a JavaScript Just-in-Time compiler with the next release.
  - Even Microsoft is working on JavaScript performance. IE8 will feature a much faster JavaScript interpreter.

Key Questions

- Why did it take so long to get JIT compilation for JavaScript off the ground?
  - Java uses JIT compilation for over a decade.
  - HotSpot will turn 10 next year!
- State of the art very similar for Python, Ruby, PHP, Perl.
  - Some projects under way (PyPy, Parrot), but performance is still severely lacking.

Is compiling a dynamically typed language really that different from compiling a statically compiled language?

Compiling Dynamic Languages

- Lets take a look at machine code generation for Java:

```
int a, b, c;
...
c = a + b;
```

```
mov eax, [ebp+4] // a
add eax, [ebp+8] // b
mov [ebp+12], eax // c
```

Compiling Dynamic Languages

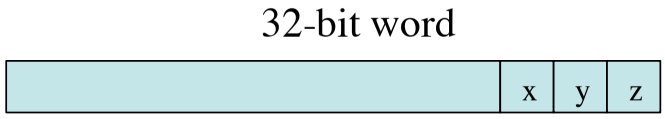
- What about JavaScript?

```
var a, b, c;
...
c = a + b;
```

```
if (isInt(a) && isInt(b) && !overflowsIfAdded(int(a), int(b)))
    c = box(int(a) + int(b));
else if (isDouble(a) && isDouble(b))
    c = box(double(a) + double(b))
else if (isString(a) && isString(b))
    c = box(concat(string(a), string(b)))
else
    c = handleReallyComplexCases(a, b); // hundreds of lines of code
```


Boxed Values

- Since all values are dynamically typed, the type has to be represented dynamically along with the value:



z = 1 31-bit integer
z = 0 object/string/boolean/double

Operators

- Almost all JavaScript operators have a different semantics based on the operand types.
  - 5-7 types, and for binary operators quite a few combinations!
- The implementation of the JSOP_ADD bytecode in SpiderMonkey consists of hundreds of bytes of machine code.
  - Compare that to 2-15 bytes for Java.

What about Objects?

- Object access in Java translates to straight forward machine code:

```
class X { public int a; };
X x = new X();
x.a = 1;
```

```
mov eax, 1
mov ebx, [ebp+4] // x
mov [ebx+offsetof(X,a)], eax
```

What about Objects?

- In JS, objects are collections of properties and use prototype-based inheritance:

```
x = { a: 1 }; // x=new Object(); x.a=1;
y = { a: 2 };
x.__proto__ = y;
print(x.a) => 1
delete(x.a);     // remove property
print(x.a) => 2 // prototype lookup
```


Prototype Chain

- For every "field" access, we have to potentially walk the entire prototype chain:

```
do {
    if (hasProperty(x, p))
        return getProperty(x, p);
    x = getPrototype(x);
} while (x != null);
```

Wait, it gets worse!

- Property names can be dynamic strings:

```
x = "y";
a[x + x] = 1;
print(a.yy) => 1
```

- In other words *offsetof* is a dynamic runtime function, not always a compile time constant.

What about Arrays?

- Arrays are almost as efficient as Objects in Java, except for an array bounds check:

```
int[] x = new int[3];
y = x[n];
mov ebx, [ebp+4] // x
mov eax, [ebp+8] // n
cmp eax, [ebx+0] // x.length
jnb @exception // if not below (unsigned)
mov eax, [ebx+eax*4+4]
```

Arrays in JavaScript

- Arrays in JavaScript look like Java, but they are really JavaScript objects (with all the quirks that come with that):

```
x = [1,2,3];
y = [4,5,6];
y.__proto__ = x;
print(y[1]) => 5; // zero-indexed
delete y[1];
print(y[1]) => 2; // not very intuitive
```


http://shaver.off.net/diary/

```
shaver@carnifex-4 5:src$ cat loop.js; Darwin_OPT.OBJ/js -j loop.js; time -p Darwin_OPT.OBJ/js -j loop.js
function main() { for (var i = 0; i < 300000000; i++) /* nothing */; }
main();
real 1.07
user 1.03
sys 0.03
shaver@carnifex-4 6:src$ cat loop.c; gcc -o loop loop.c; ./loop; time -p ./loop
int main() { int i; for (i = 0; i < 300000000; i++) /* nothing */; }
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HOW ?

Translation Unit

- Compilers for statically typed languages traditionally use methods as translation unit.
  - Some compilers perform inlining, but the smallest translation unit is still an entire method.
- We can generate efficient machine code because at every point in a method the type of a value is fixed (no matter what the control flow does).
  - In case of Java for example, if *d* is declared as double, we can allocate it into a floating-point register and all arithmetic operations are emitted using floating-point math.

Static Typing

- Consider the following Java pseudo code:

```
double d = 0;
for (...) {
    if (cond) d = d + 0.5;
    else d = "";  // type error
}
return d + 1; // always a FP addition!
```

- *In Java, the control flow can affect values, but not types.*

Dynamic Typing

- In JavaScript, types are control-flow dependent:

```
var d = 0;
for (...) {
    if (cond) d = d + 0.5;
    else d = "";  // ok in JavaScript
}
return d + 1; // number or string "1"
```

Solutions

- Static Analysis
  - Some promising research work underway, but for non-trivial programs analysis time is seconds to minutes. User unlikely to be willing to wait that long.
- Generate generic code (similar to the corresponding interpreter implemenation).
  - Apple's Squirrelfish Extreme (SFX)
  - Google's V8 VM

Generating Generic Code

JavaScript: `for (var i = 0; i < 100; ++i) { /* do nothing */ }`

```
i = box(1)
label:
    if (isInt(i)) i = box(int(i) + 1);
    if (isDouble(i)) i = box(double(i) + 1.0);
    if (isString(i)) i = box(String2Num(string(i)) + 1.0);
    if (isBoolean(i)) i = box(Bool2Num(boolean(i)) + 1.0);
    if (isObject(i)) i = box(Object2Num(object(i)) + 1.0);
    if (isUndefined(i)) i = box(NaN);

    if (isInt(i) && (int(i) < 100)) goto label;
    if (isDouble(i) && (double(i) < 100.0)) goto label;
    if (isString(i) && (String2Num(i) < 100.0)) goto label;
    if (isBoolean(i) && (Bool2Num(i) < 100.0)) goto label;
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```

What we really want ...

JavaScript: `for (var i = 0; i < 100; ++i) { /* do nothing */ }`

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i = box(1)
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    if (isInt(i) && (int(i) < 100)) goto label;
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```


Our Approach: Traces

- A trace represents the series of instructions executed by the CPU (or VM) while running a program.
  - While traces can be constructed statically [Trace Scheduling, Fisher, 1991], most often they are recorded dynamically. [Dynamo, Bala, 1999]
  - Conditional branches become side exit points.
  - Since loops dominate the execution time of most programs, we are are only interested in loop traces.

Example Trace

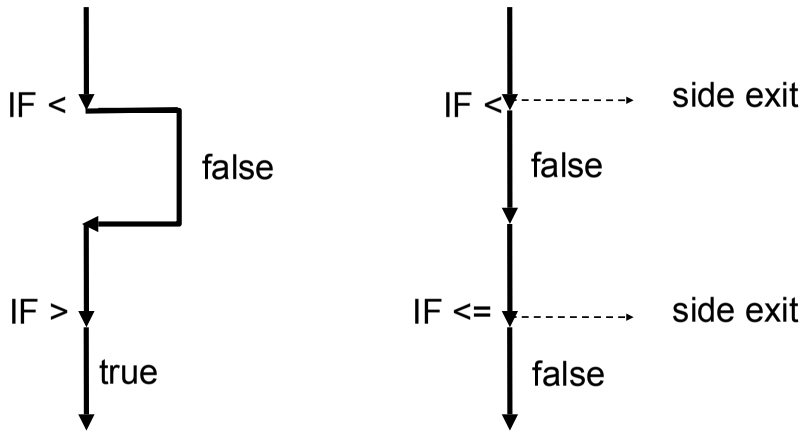
JavaScript: `for (var i = 0; i < 100; ++i) { /* do nothing */ }`

```
loop-header:
    if (int(i) >= 100)) break;
    i = box(int(i) + 1);
    goto loop-header;
```

- A trace starts at a loop header and loops back to it.
- A trace records the sequence of activities the VM executed while running the loop.
- If the VM operates on integers, we record a trace that operates on integers.

Control Flow

Conditional branches become Guard instructions.



Guard Instructions

- Traces are entered at the loop header, and execute until a guard instruction fails, in which case we return to the interpreter.
  - A trace is a speculative control-flow path.
- A trace is a linear sequence of instructions.
  - All instructions have **exactly one** predecessor instruction.
  - If the original trace conditions no longer hold, we must side-exit.

What about types?

JavaScript: `for (var i = 0; i < 100; ++i) { /* do nothing */ }`

```
loop-header:
    ensure(isInt(i));         // type guard
    ensure(int(i) < 100));    // loop condition guard

    ensure(isInt(i));         // type guard
    i = box(int(i) + 1);
    loop;                     // jump to loop header
```

- In addition to guarding the control-flow, we also have to guard the operand types if we only record a specialized instruction sequence.
- But wait ... we have a linear sequence of instructions ...

Type Stability on Trace

JavaScript: `for (var i = 0; i < 100; ++i) { /* do nothing */ }`

```
loop-header:
    ensure(isInt(i));        // type guard
    ensure(int(i) < 100));   // loop condition guard

    /* ensure(isInt(i)); */ // redundant
    i = box(int(i) + 1);
    loop;                    // jump to loop header
```

- Since traces specialize the control flow, the use of i always reads from the same definition of i.
  - The second guard is actually redundant.
- Next question: If types are stable, why box?

Unboxed Trace Code

JavaScript: `for (var i = 0; i < 100; ++i) { /* do nothing */ }`

```
loop-entry:
    ensure(isInt(i));  // check once when entering the trace
    ii = int(i);       // unbox when entering the trace
loop-header:
    ensure(ii < 100);  // loop condition guard
    ii = ii + 1;       // operate directly on unboxed value
    loop;              // jump to loop header
```

- Values are boxed only when we exit the trace (failed guard).
  - At compile-time, we store the types for each value at every side exit.

Summary: Traces

- A trace is a path through a loop in the original program.
- A trace is statically typed, but is only valid as long both control-flow and type-guards hold.
- Type-guards can often be hoisted out of the loop, producing a speculative, statically-typed equivalent representation of the original program.

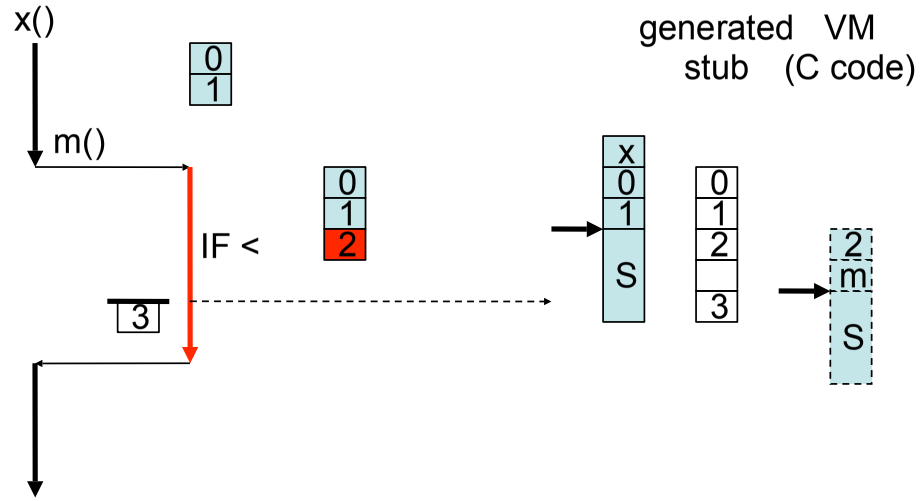
Inlining

- All instructions (potentially) affecting the control flow are replaced with guard instructions.
  - Conditional branches, switch tables, virtual method calls, etc.
- Code from invoked method is inlined into the trace. No method frames are created during trace execution, only when we side exit (if needed).

Recovery

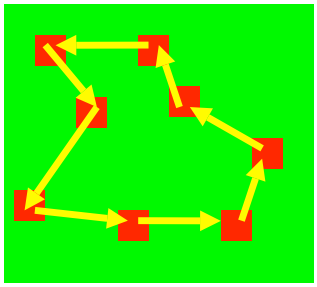
- Recovery stubs are generated for every side exit in the trace.
  - Compiler ensures that temporary values that have to be written back to the stack stay alive until the side exit.
  - Local variables modified in the trace are assumed to be live along all side exits (we can't and don't want to analyze code outside the trace).
  - Stack values and local variables are written back using the types stored by the compiler.
  - Execution returns to the interpreter, which will generate filler frames when returning from within a method call.

Deep Side Exits



Compiling Traces

SpiderMonkey



nanojit

Compiling Traces

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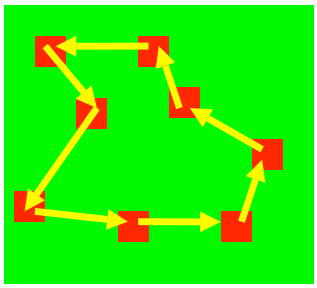
Monitor



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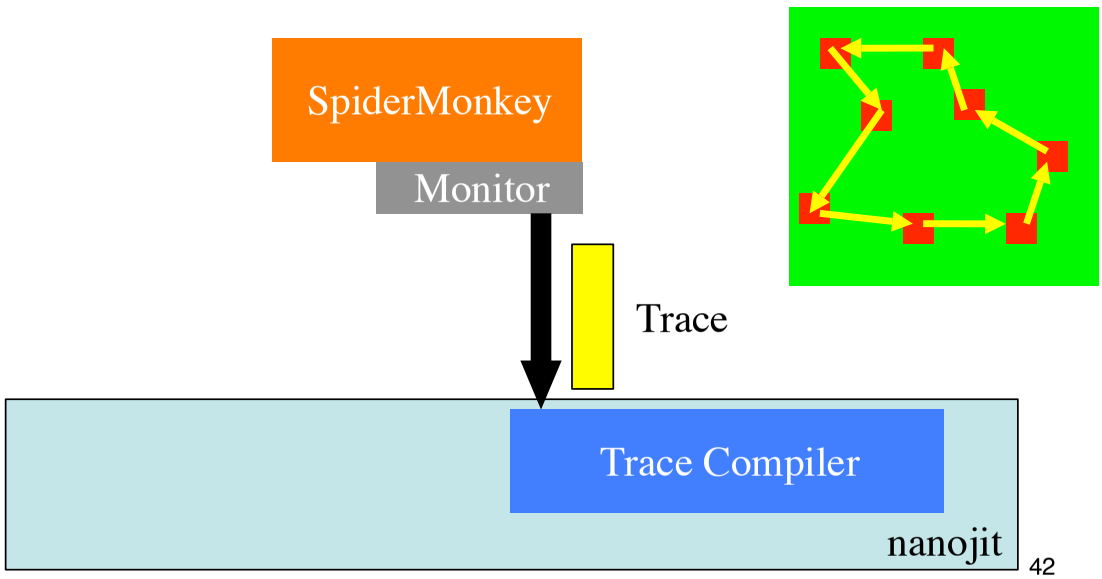

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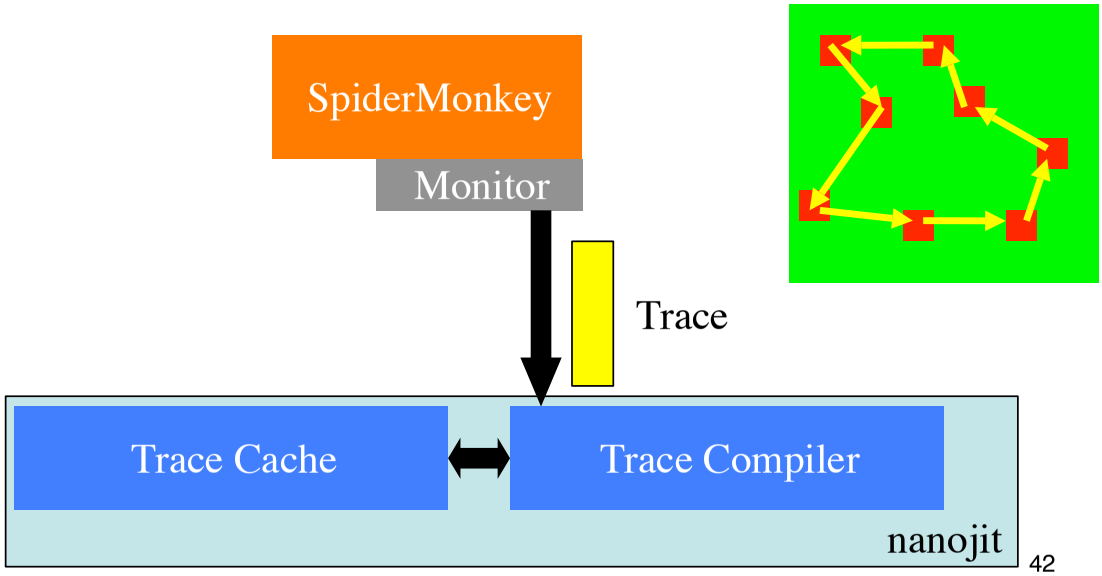

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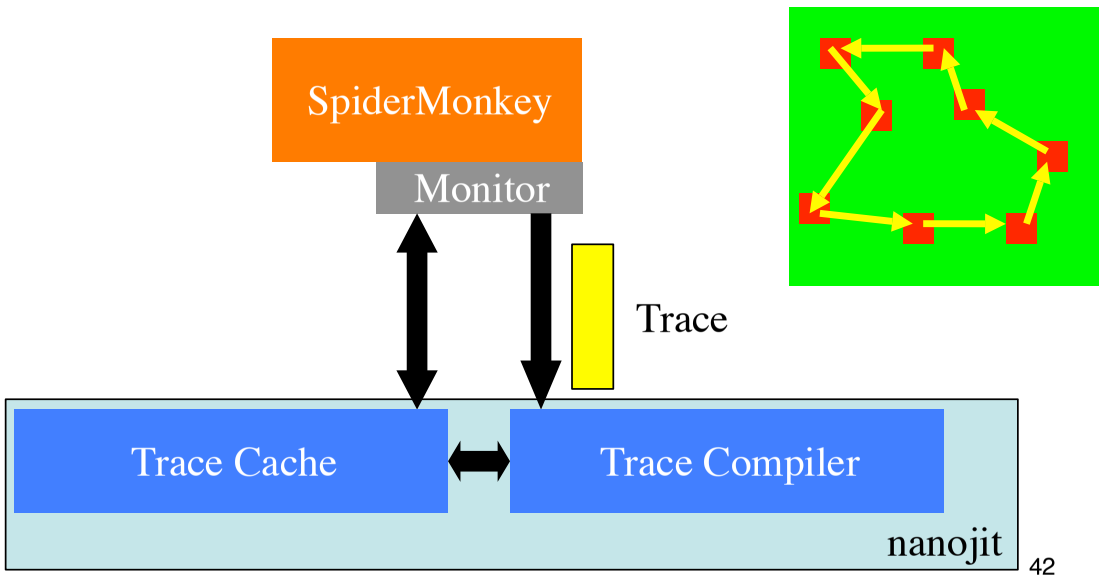
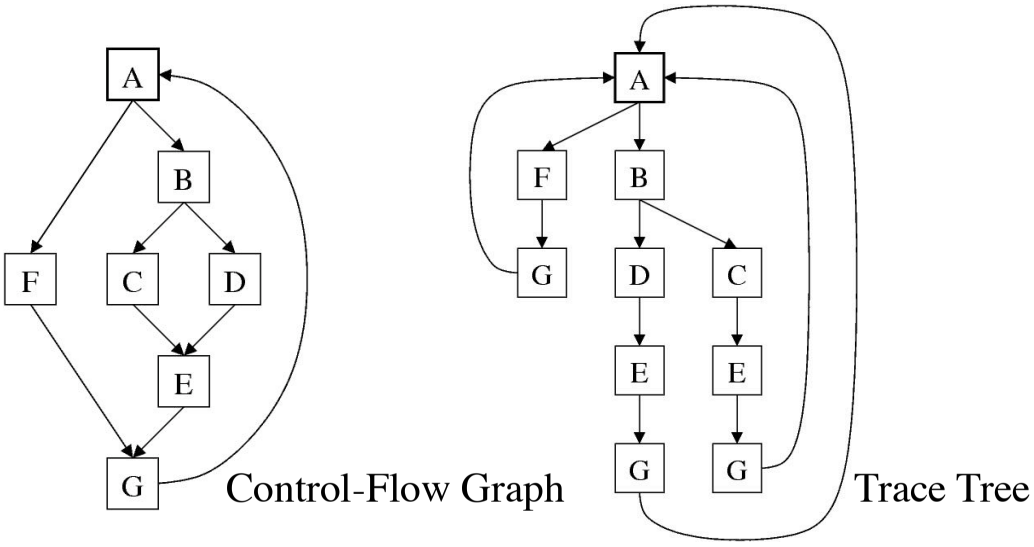
Compiling Traces



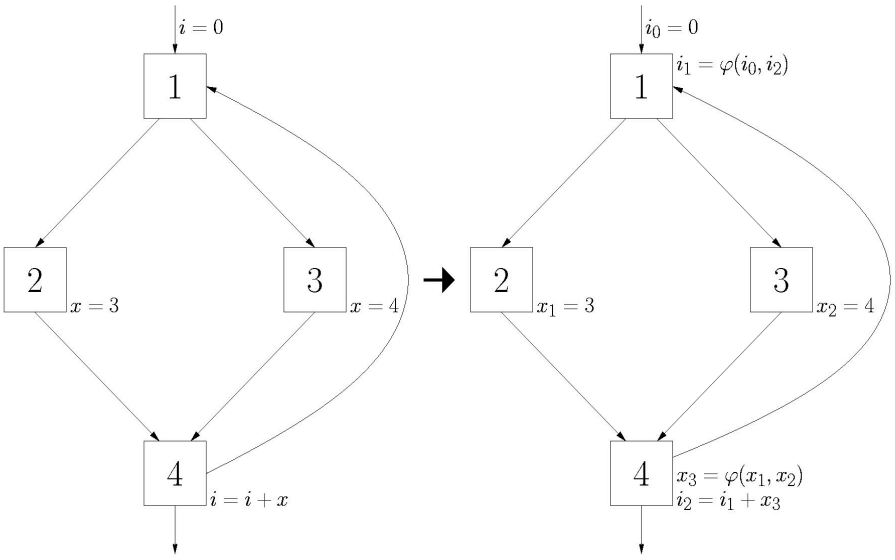
Trace Trees

- Record a new trace every time we bail out along a guard instruction.
- Stop recording when returning to the loop header or trace gets too long.
- The first trace is the *primary trace*.
- A *secondary trace* can start at any guard instruction and must also return to the loop header.

Trace Trees (2)



Tail Duplication



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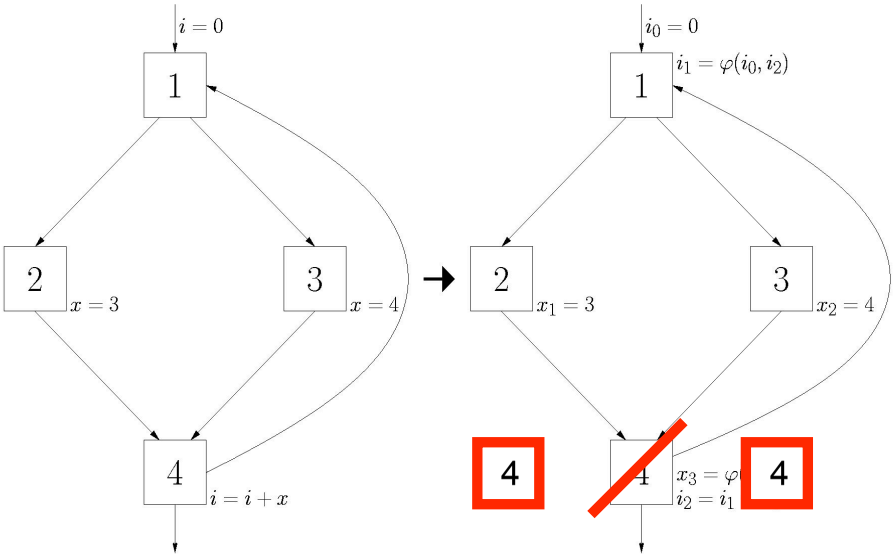

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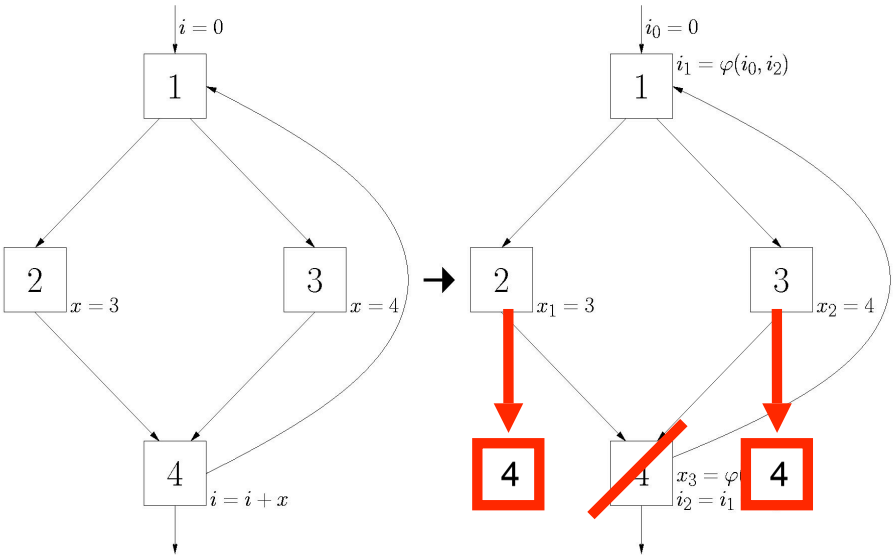

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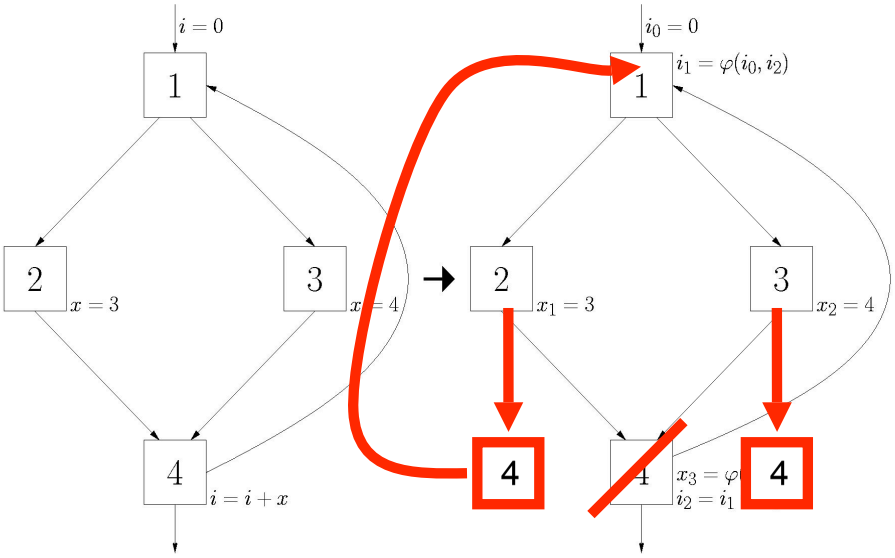

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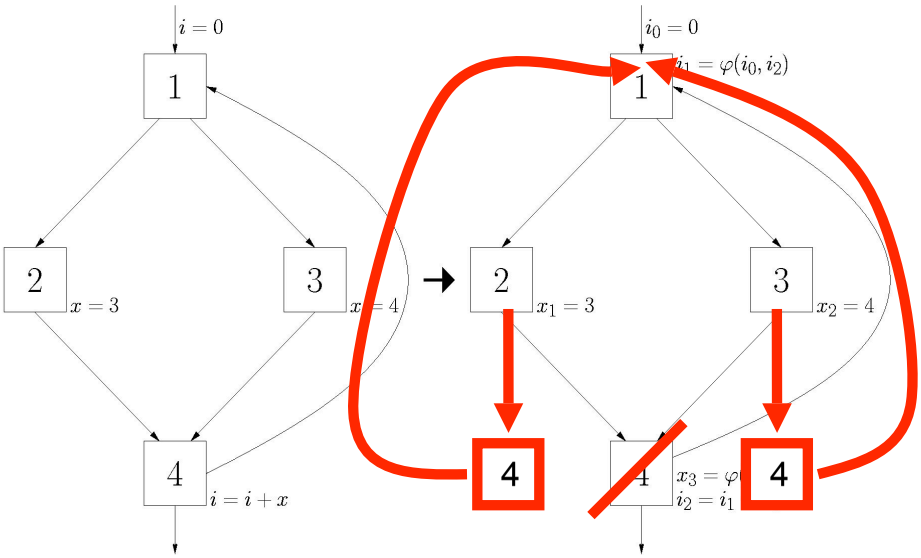

Nested Trace Trees

- Each Trace Tree represents one loop. Trees can "call" inner loop trees.

```
for (var i = 0; i < 100; ++i)
    for (var j = 0; j < 100; ++j)
        ;
```

```
tree0-ii-is-int:
    guard(ii < 100)
    call tree1-jj-is-int
    ii++
    loop
```

```
tree1-jj-is-int:
    guard(jj < 100);
    jj++
    loop
```

Note that trees are specialized with respect to the types at loop entry.

Compiling Traces

- Bottom-up code generation & register allocation.
  - No graph coloring!
- All uses are seen before the definition.
  - If no use assigned a register, definition is dead.
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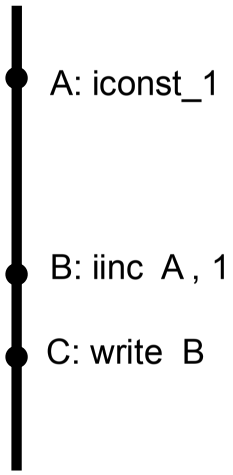

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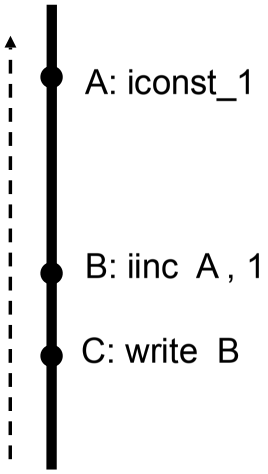

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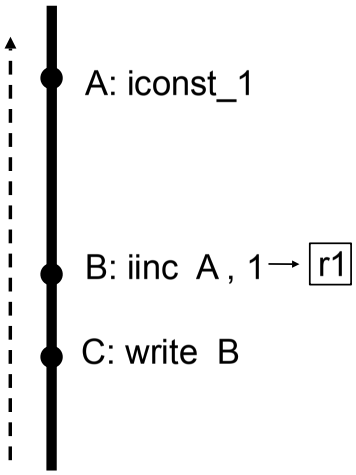

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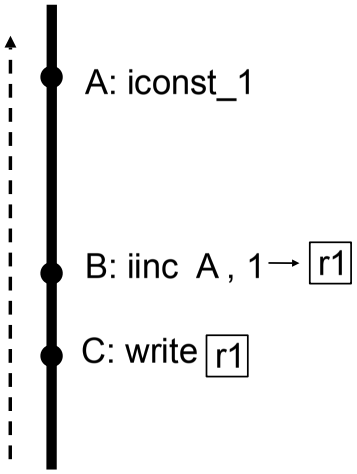

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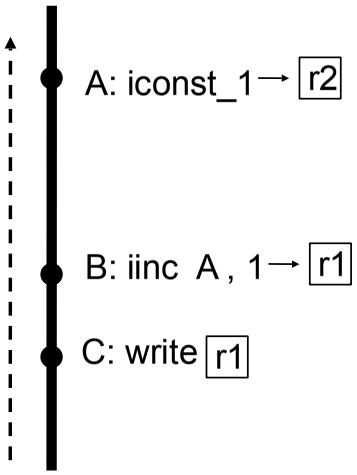

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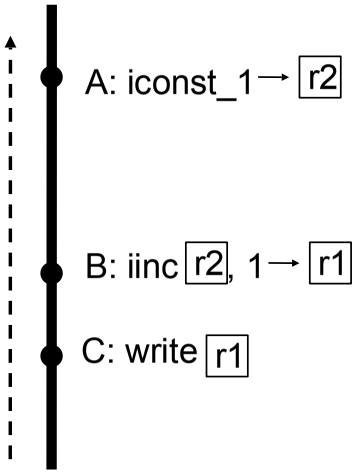

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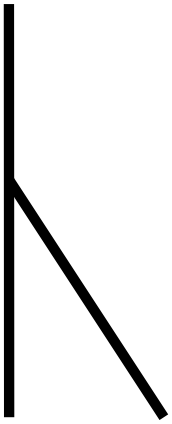

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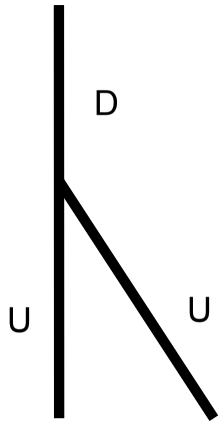

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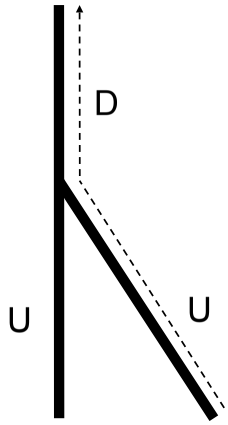

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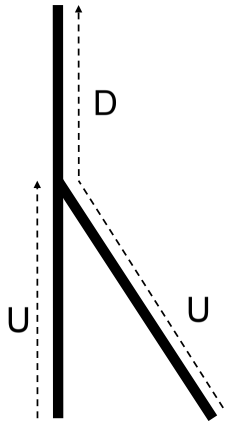

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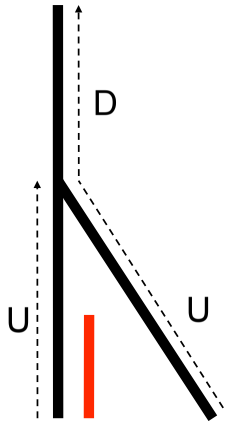

register no longer reserved

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Trace Ordering

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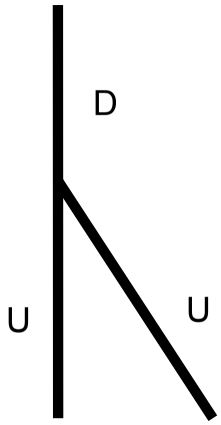

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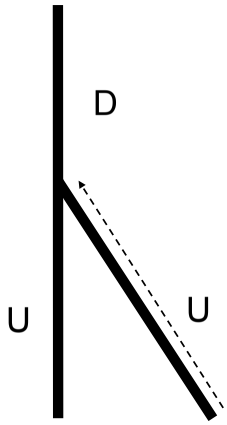

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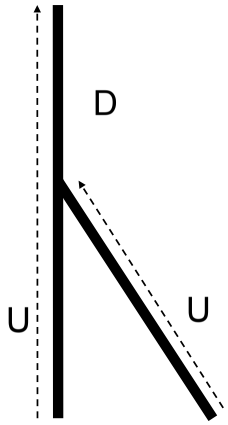


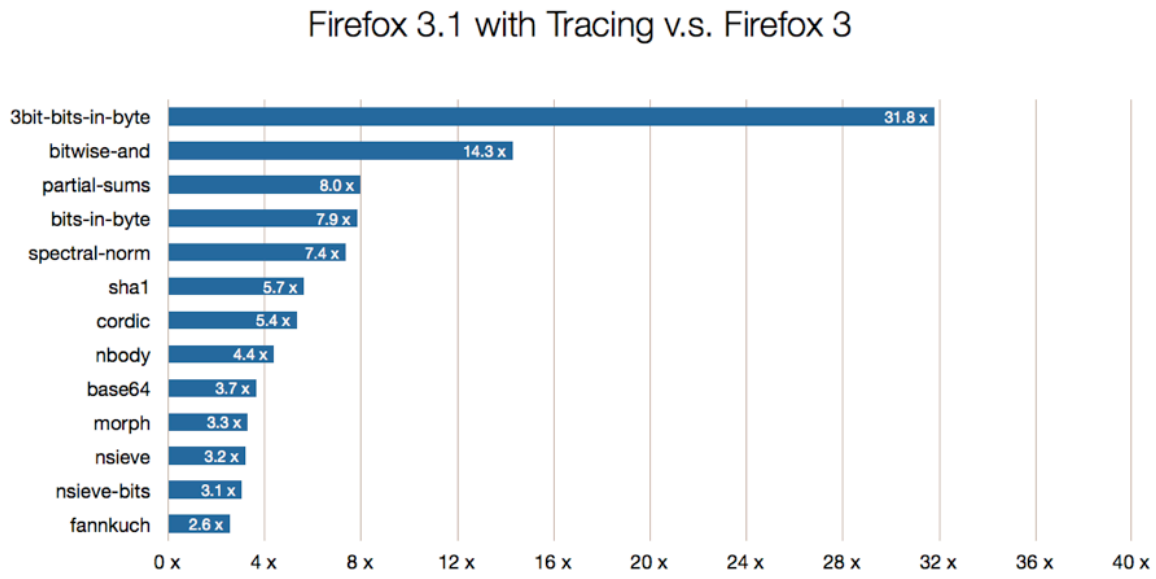
Benchmarketing

- JavaScript performance has only become the focal point of the "new browser war" fairly recently.
  - One somewhat established benchmark from Apple (SunSpider).
    - Some people think its not a very good abstraction of what matters on the web.
  - Some people prefer to bring their own benchmarks (V8 benchmark suite for example).

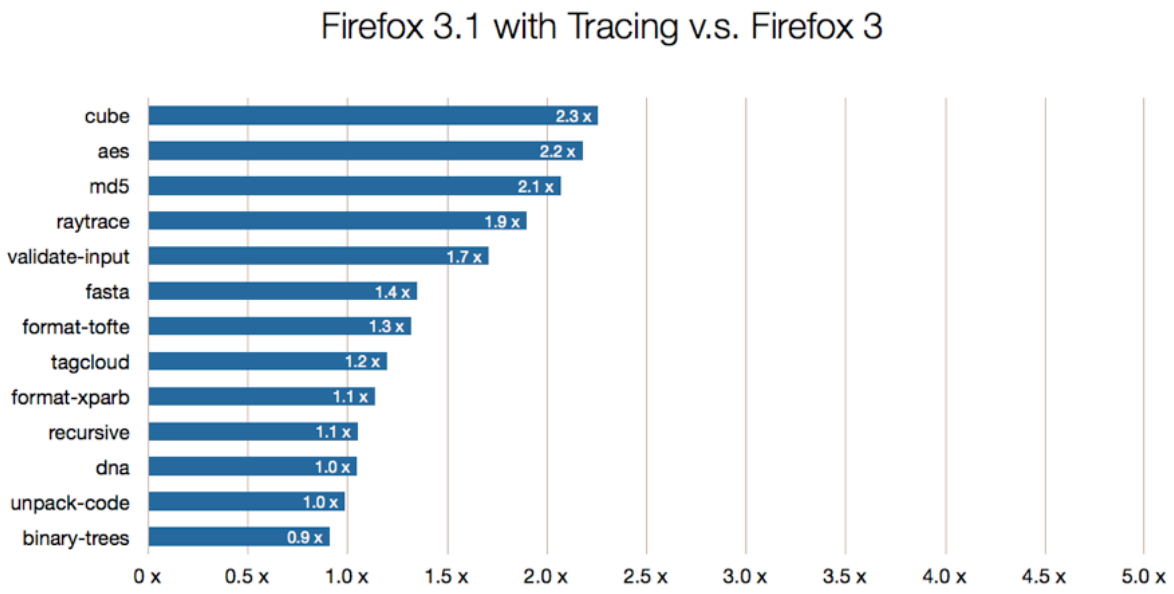
Benchmarks

- Highly volatile environment. Yesterday's numbers might be out of date today.
- The graphs I am about to show are meant to demonstrate the potential of trace-based compilation.
  - The numbers of SFX and V8 are for illustration purposes only ...

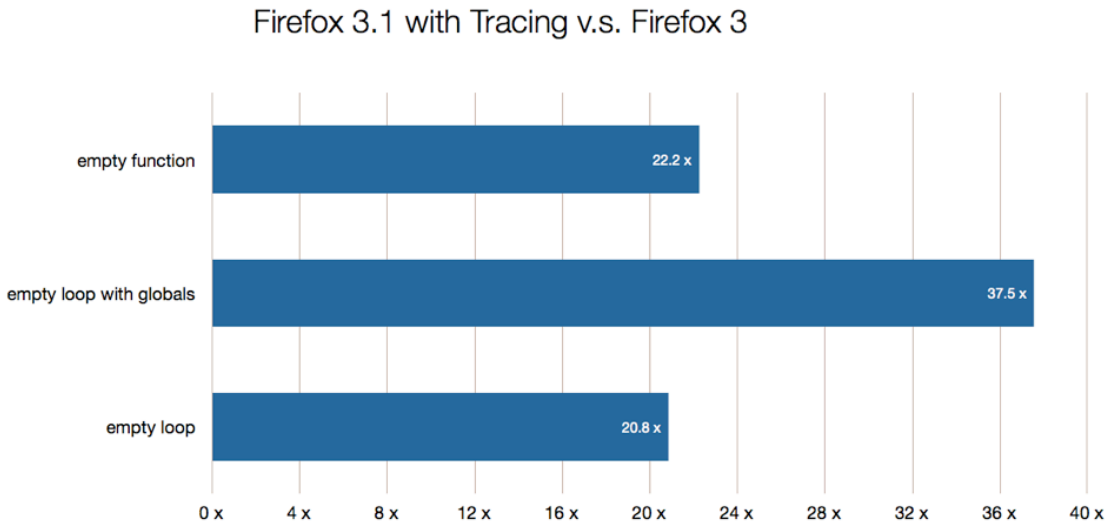
TraceMonkey vs Interpreter



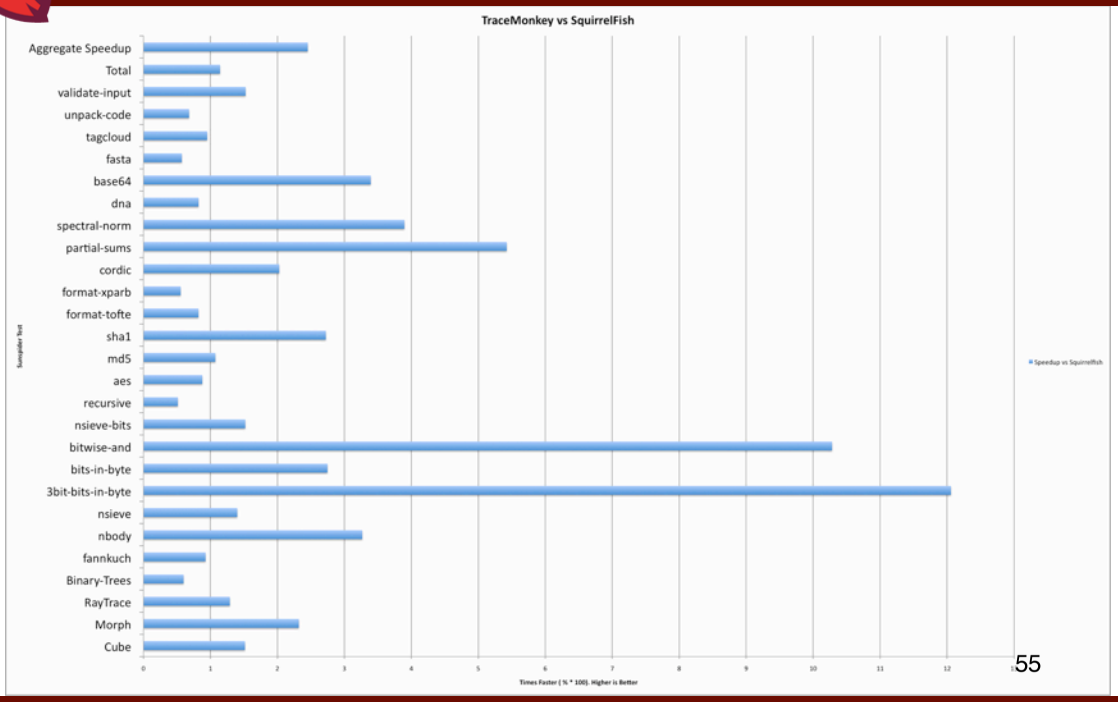
TraceMonkey vs Interpreter (2)



Microbenchmarks

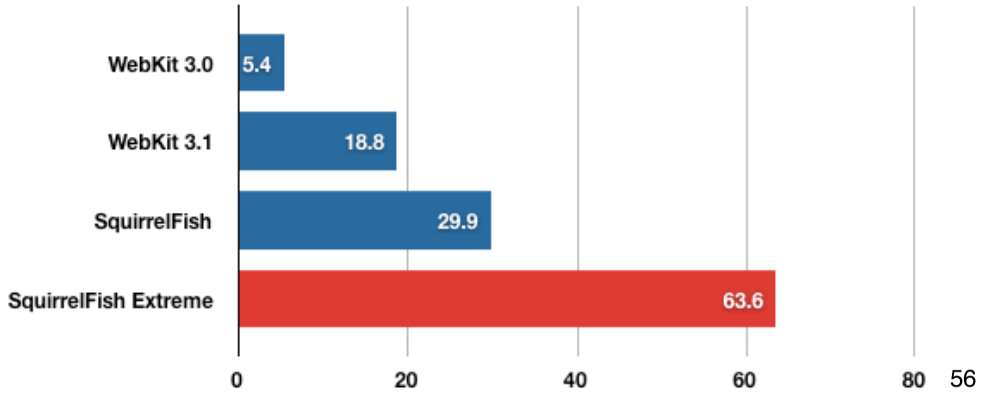


TraceMonkey vs SF



SF vs SFX

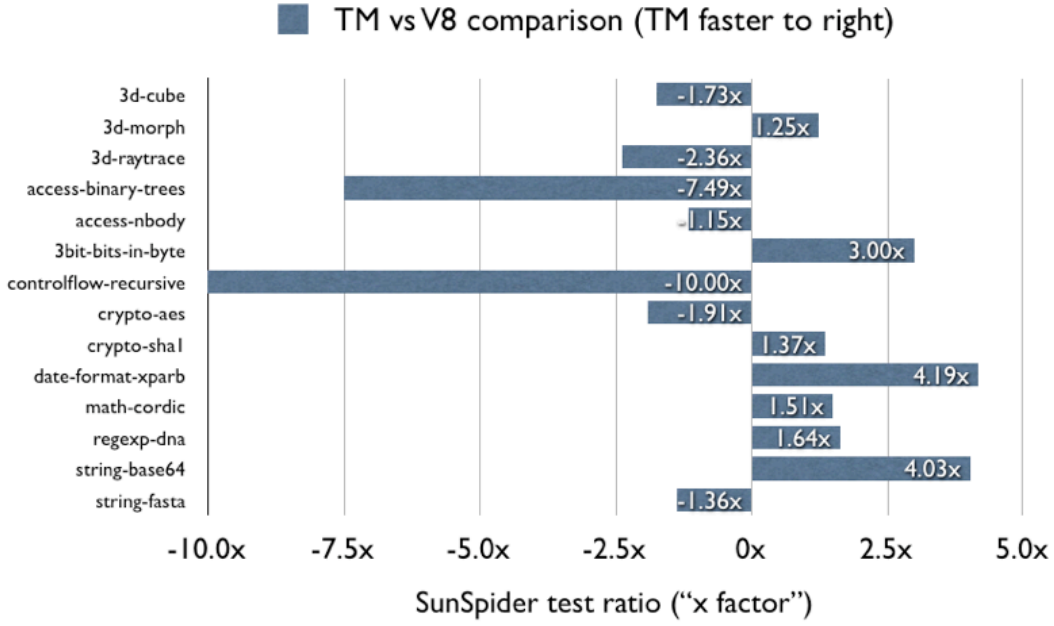
- SFX is about 2x faster than SF (including a 5x RegExp speedup which is not JS related.)



TM vs SF vs SFX

- SFX is up to 2x faster than SF's fast interpreter.
  - Highly efficient generic code generation (all types supported for every operation).
  - SFX's performance is likely the best you can do without specialization.
  - We achieve up to 12x speedup over SF using specialization. More potential for raw performance.

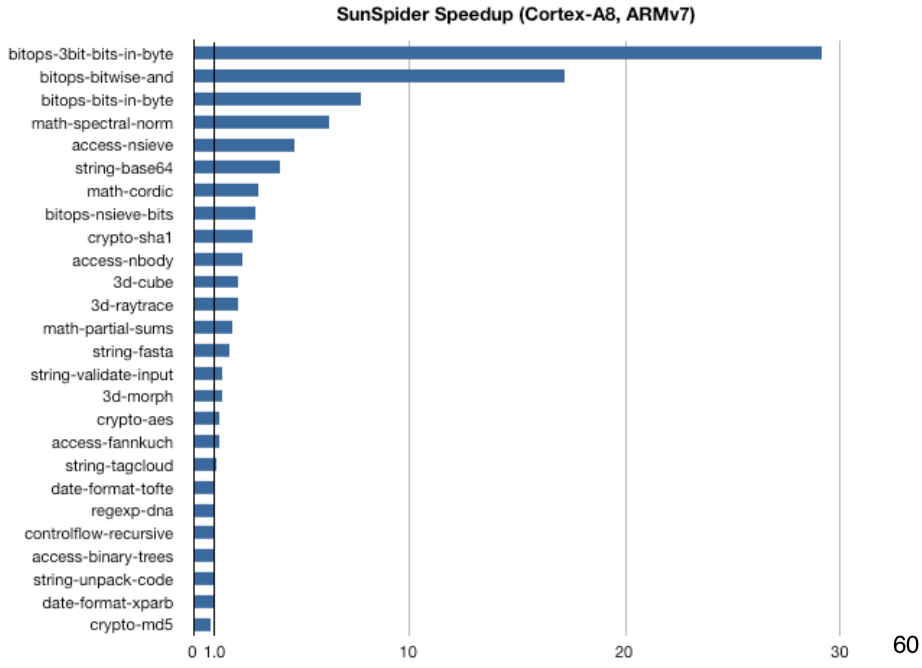
TraceMonkey vs V8



TM vs V8

- V8 is a brand-new, advanced JS engine.
  - Similar to SpiderMonkey's Property Cache, V8 uses inline caching to speed up property access ("Hidden Classes" in the V8 world).
  - However, all code is still generic. No type specialization. No inlining.
  - We are up to 4x faster on some benchmarks.
    - We don't trace recursion at all at the moment. Losing very badly there.

What about Mobile?



Mobile Devices

- Mobile devices are more constraint than Desktop system with respect to memory and CPU speed.
  - Specialized code means often much smaller machine code fragments.
  - Traces can be compiled very rapidly (compilation time often only a few micro seconds).

Conclusions

- A trace represents a path through a loop in the original program and is type-stable even for dynamically typed languages.
- Multiple paths through loops can be represented using trees of traces, and nested loops using nested trees of traces.
- Compiled trace code can in some cases compete with statically typed language code.

Conclusions (2)

- Trace Trees offer significantly higher peak performance than emitting method-based generic code.
  - The devil is in the details: tail duplication, code explosion.
- Very difficult to do comparative benchmarks at this point.
  - A lot more systematic research is needed. Remember, JS compilation is 6 month old!

Future Work

- Improve baseline performance of SpiderMonkey.
  - The performance of V8/SFX should be our baseline. Use traces to speed up suitable kernels.
- More aggressively avoid and compensate for tail duplication.
- Collaborate with other interested parties to produce a meaningful benchmark suite.

Questions?

Footnote: The speaker is looking for a tenure-track position in North America.