A Comparison of API-based JIT Compiler Overhead during Run-time

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ABSTRACT

Just-in-Time compilation has allowed for significant performance gains during the run-time of applications. Two popular open-source JIT frameworks are LLVM MCJIT and OMR JitBuilder, both of which can be embedded within applications, offering interaces to define and generate native code at run-time. LLVM is a collection of modular compiler and toolchain components, while MCJIT is a framework based on these components to provide JIT compilation. Similarly, JitBuilder is a JIT framework based on the OMR compiler and runtime components. In this report we discuss the different approaches these two frameworks employ. In addition, we measure the overhead of each framework while compiling and then executing a small handful of functions. We found that while LLVM required a larger memory footprint, in certain cases it was able to generate code more quickly. Furthermore, the code LLVM generated typically offered high throughput. JitBuilder, a relatively young project compared to LLVM, does not currently expose the underlying configuration of TRJIT. Instead, it locks the compilation level to the *warm* setting, thus limiting the oppourtunities for optimizations.

CCS CONCEPTS

• **Software and its engineering → Compilers**.

KEYWORDS

compilers, just-in-time, optimization

1 INTRODUCTION

Just-in-time compilation, or JIT compilation, is a technique to improve the run-time binary translation of an application [1]. Using information collected from the running application, JIT compilers can further optimize generated code. For instance, by collecting profile information on executed code paths, JIT compilers can generate code that is optimized for hot-paths [2]. A JIT compiler might also inline entire blocks of code, or generate an inline cache to speed up the dispatch of polymorphic method calls [3].

Popular high-level language runtimes for Java make heavy use of JIT compilers, allowing their workloads, to execute much faster than if they were entirely interpreted [4]. Given that JIT compilation can add significant overhead to a workload, compilation is typically applied selectively to the code executed most frequently. Furthermore, given that compilation can be viewed as a continuum, where slow, unoptimized code is cheap to generate, and where fast, optimized code is expensive to generate, a compiler will often support multiple optimization levels [2]. A runtime with such an optimizing JIT compiler can then employ a staged compilation strategy which would allow the runtime to apply compilation and optimization according to heuristics [5].[1]

Considering JIT compilers may also need perform some of the optimizations found in a static compiler such as common subexpression elimination, loop unrolling and constant propagation [9], an application developer, or language designer interested in enhancing run-time performance by adding a JIT compiler, will have a large engineering task ahead of them. In addition, for projects targeting multiple architectures, considering JIT compilers generate native, or architecture specific code, the effort required will increase significantly. It is no surprise then, that libraries or frameworks, encapsulating proven, high-performance JIT compilers are available to software engineers today. For an engineer interested in incorporating an existing JIT framework, it is useful to consider the following questions when making their selection:

- How much larger is the application binary with the inclusion of the JIT framework?
- How is the resident state set for the application effected?
- How much processor overhead does the JIT compiler have?
- How configurable is the JIT framework?
- What is the quality of the generated JIT code and what effect does this have on throughput?
- How easy is it for the programmer to incorporate and use the JIT framework?

In this report, we will consider those questions while looking at two such JIT frameworks: LLVM MCJIT [10] and OMR JitBuilder [11]. In Sections 2, and 3 we will discuss the background of each compiler and consider the techniques they employ. In Section 3, we outline the methods we used to answer those questions. In Section 4, we will consider the results. In Section 5, we will discuss related work. In Section 6, we will look at potential future work, and finally in Section 7, we will summarize our findings.

2 BACKGROUND

In this section we will discuss the background of the two JIT compiler frameworks we are interested in: LLVM MCJIT and OMR JitBuilder. In particular, we will focus on the motivation for each

[1] An example of a staged, or tiered compilation strategy can seen with the Testarossa JIT compiler (TRJIT) in the OpenJ9 JVM [6, 7]. Here an invocation threshold must be met before the JIT compiler will compile a method. Additionally, separate thresholds can be associated with each optimization level [8]. We will discuss TRJIT in more detail when we look at JitBuilder in Section 2.2.

UNB FCS Directed Studies, Fall 2019, Fredericton, NB, CA
2020.

```
define i32 @mul_add(i32 %x, i32 %y, i32 %z) {
    entry:
    %tmp = mul i32 %x, %y
    %tmp2 = add i32 %tmp, %z
    ret i32 %tmp2
}
```

Listing 1: LLVM IR for a function multiplying x * y and adding z [13].

```
treetop--> istore a
           |
           imul--- isub-------+
           |                  |
           iadd               |
           |                  |
           +-----> iload b <--+
           |                  |
           +-----> iload a <--+
}
```

Listing 2: OMR IR representation for (a+b)*(a-b). Note that the iload nodes are reused [19].

framework, as well as discuss the techniques and features they provide.

2.1 LLVM

LLVM, which at one time stood for Low Level Virtual Machine, is a popular set of open-source, modular compiler and toolchain components [12]. The compiler framework was originally designed to provide analysis and transformation for an application throughout it's entire lifetime: from initial compilation and linking, through to runtime and even while the application was offline (see Figure 1). To achieve this ambitious goal, the framework utilizes a well defined, human-readable, intermediate representation called LLVM IR. The IR, which is initially generated by the front end can be packaged with the target architecture binary along with profiling instructions for later runtime compilation (JIT) as well as more aggressive offline optimizations. Several important characteristics of LLVM IR as as follows:

- The IR maintains Static Single Assignment (SSA) form with unlimited virtual registers.
- Each register is of one of four primitive types: boolean, integer, floating-point or pointer.
- Similar to RISC, memory operations are carried out in registers, and between registers and memory using Load and Store instructions.
- The IR is limited to 31 opcodes.
- The IR is organized into basic blocks which must be composed into valid control flow graphs, simplifying the work required for various optimizations.

This report will focus on LLVM's JIT component, which can be accessed through the MCJIT API. The MCJIT framework provides an API thats accepts IR, generates optimized machine code, and provides a function pointer for calling the generated code. The JIT compiler offers several levels of optimization: none, less, default, and aggressive. It should be noted that the JIT compiler by default does not perform any IR optimizations or transformations. Instead, a developer must pass the generated IR to a PassManager with specific optimizations they intend to apply. These passes can be categorized as analysis passes, or transformation passes [14]:

- Analysis Passes: collect information about IR for use later by transformations, for debugging or for visualization. A few examples are *print-callgraph*, *print-function*, and *iv-users* for printing the users of a particular induction variable. There are roughly 40 such passes available.
- Transformation Passes: These typically modify IR. Examples include *adce* for dead code elimination, *instcombine* for combining redundant instructions, or peephole optimizing, and *tailcallelim* for eliminating tail calls. There are roughly 60 such passes available.

This optimized IR will then be used by the ExecutionEngine when generating code for the target architecture. Before a function is executed by the ExecutionEngine, it first checks if the ObjectCache contains a copy. If the function could not be found, the compiler will generate code and store it in the ObjectCache before execution [15]. It is worth noting that an newer JIT API, called ORCJIT, is also part of the LLVM project. ORCJIT, or On-Request-Compilation JIT, is intended to compliment the MCJIT API – which compiles eagerly, by adding support for lazy, and concurrent compilations [16].

2.2 JitBuilder

JitBuilder is the embeddable framework for interacting with the Eclipse OMR JIT compiler Testarossa [11]. Eclipse OMR is an open-source collection of components for building language runtime environments. Some of OMR's components include a garbage collection framework, a thread library, cross-platform port support, virtual machine building blocks, and a JIT compiler [6, 17]. Much of the infrastructure driving Eclipse OpenJ9, a popular, open-source Java Virtual Machine, links to OMR components.

Through JitBuilder's API, users generate IR upon which optimizations are applied and from which native code is generated [18]. Based on basic-blocks, the IR is arranged into directed acyclic graphic (DAG) structures called trees, composed of nodes which each contain an opcode. OMR IR has several hundred opcodes, where typically with each type operation has a code for each data type: integer, pointer, double, float, vector, etc...[2] The children of these opcode nodes are in turn operands. Trees with side-effects, which cannot be reordered, belong to a list of elements called treetops [19]. Existing nodes can be reused within a given tree, making optimizations such as common subexpression elimination relatively simple (see Listing 2). Though Testarossa supports several levels of optimization ranging from *cold*, with roughly 20 optimizations applied, all the way to *scorching*, where as many as 170 optimizations are applied, as of writing, JitBuilder is locked at the *Warm* optimization level [20, 21].

3 QUESTIONS AND METHODS

To answer the questions we outlined in the introduction, we wrote three simple programs for each of LLVM MCJIT, JitBuilder, and a

[2] This can be contrasted with LLVM's roughly 31 opcodes, where the data type code is instead embedded within the instruction.

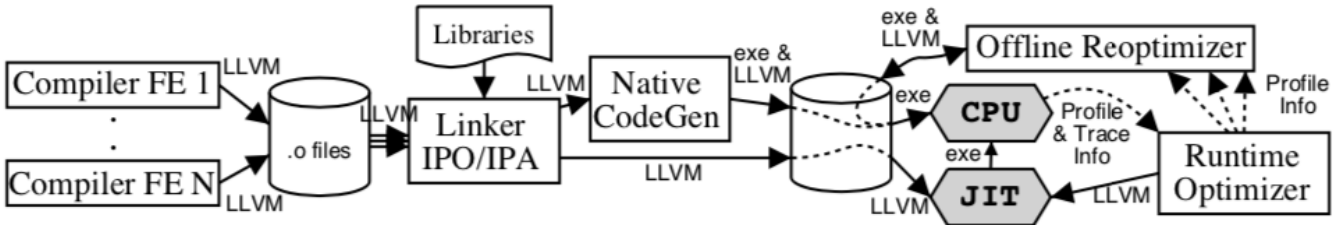

Figure 1: The LLVM Compiler Framework Architecture [12].

```
bool
IncrementMethod::buildIL()
{
  Return(
    Add(
        Load("value"),
        ConstInt32(1)));
  return true;
}
```

Listing 3: Generating JitBuilder IR for the increment program.

straight forward native implementation without a JIT framework. The programs are as follows:

- increment - Calls a single function that adds one to an integer argument.
- recursive-fib - Calls a recursive fibonacci function for *fib(20)*.
- iterative-fib - Calls an iterative fibonacci function for *fib(20)*.

For the JIT implementations, the functions were created using the provided API's, then native code was generated and later used for the actual function call. We built and benchmarked the programs on an x86-64 Linux workstation running Ubuntu 19.04 with 32GB of RAM and an Intel i7-8700 (6-core, 12 thread) processor. Both LLVM, and OMR were built from source from their respective Github repositories [22, 23]. All the source code for this project can be found online through Github[24].

4 RESULTS

4.1 Compilation Time

The first question we looked at was how long each framework took to compile a function 25 times. This time includes running the program from start to finish and thus includes the setup and teardown time of the JIT.

In Table 1 we see that for the increment task JitBuilder's compiled the function 61.5% faster than MCJIT. For the other two tasks, we see that MCJIT was able to compile the functions more quickly than JitBuilder (recursive-fib compiled 16.5% faster, and iterative-fib compiled 40.1% faster). Looking at the JitBuilder code to generate the function (see Listing **??**), we see a much smaller function body compared to the function used to generate IR for LLVM (see Listing 4). There is no clear reason why this disparity exists. One idea is JitBuilder has a lower base overhead than LLVM, but the work required to generate code for more complex IR favours LLVM.

```
static Function *CreateIncrementFunction(
                  Module *M,
                  LLVMContext &c) {
  FunctionType *f = FunctionType::get(Type::getInt32Ty(c),
                      {Type::getInt32Ty(c)},
                      false);

  Function *incrementF = Function::Create(f,
                      Function::ExternalLinkage,
                      "increment",
                      M);

  BasicBlock *BB = BasicBlock::Create(c,
                      "EntryBlock",
                      incrementF);

  Value *One = ConstantInt::get(Type::getInt32Ty(c), 1);

  Argument *ArgX = &*incrementF->arg_begin();
  ArgX->setName("AnArg");

  Value *Sum = BinaryOperator::CreateAdd(ArgX,
                                  One,
                                  "addresult",
                                  BB);

  ReturnInst::Create(c, Sum, BB);
  return incrementF;
}
}
```

Listing 4: Generating MCJIT IR for the increment program.

4.2 Execution Time

Once compilation has completed we turn to measuring how much CPU time is spent actually executing the function. To measure this we compiled the function once and then executed the compiled function 1000 times. For each program, the process was repeated 20 times (see Table 2). Aside from the increment program, which favoured JitBuilder, both the recursive and iterative fib functions executed more quickly with LLVM generated code (0.53% faster for recursive, and 0.37% faster for iterative). Compiling the test programs GCC 5.3 with an optimization level of O3 resulted in extremely low execution times for the native increment program as our function calls were optimized away. It is worth noting that the code generated by the LLVM recursive-fib outperformed the native optimized code. Given two of our programs performed more quickly with MCJIT than with JitBuilder, it could be interesting to examine the disassembly of the generated code.[3]

4.3 Binary File Size

Looking at the size of the generated files (see Table 3), the linked LLVM MCJIT programs are roughly six times larger in size than the

[3]We used GDB to print instructions starting at the function pointer address. The disassembly is using Intel style.

Program	LLVM MCJIT			Eclipse OMR JitBuilder		
	mean (ns)	median	std. dev.	mean (ns)	median	std. dev.
increment	1,378,060	1,387,338	39,774	533,581	531,840	4911
recursive-fib	1,548,316	1,547,491	3925	1,854,393	1,850,322	21,754
iterative-fib	2,509,502	2,519,808	60,429	4,192,213	4,191,730	10,419

Table 1: Results of compiling each function 25 times with each JIT framework.

Program	LLVM MCJIT			Eclipse OMR JitBuilder			Native (C++)		
	mean (ns)	median	std. dev.	mean (ns)	median	std. dev.	mean (ns)	median	std. dev.
increment	1,463,310	1,463,032	1660	537,657	537,517	3544	0.876	0.875	0.002
recursive-fib	13,674,832	13,664,199	26,548	28,707,381	28,699,013	29,480	16,016,325	15,996,370	60,459
iterative-fib	2,657,528	2,668,792	83,388	4,227,967	4,190,232	102,744	0.876	0.875	0.003

Table 2: Results of JIT compiling each function and executing the generated code 1000 times.

```
(gdb) x/24i $1
  0x7ffff7fcd000 <fib>:        push   rbp
  0x7ffff7fcd001 <fib+1>:      push   r14
  0x7ffff7fcd003 <fib+3>:      push   rbx
  0x7ffff7fcd004 <fib+4>:      cmp    edi,0x2
  0x7ffff7fcd007 <fib+7>:      jg     0x7ffff7fcd013 <fib+19>
  0x7ffff7fcd009 <fib+9>:      mov    eax,0x1
  0x7ffff7fcd00e <fib+14>:     pop    rbx
  0x7ffff7fcd00f <fib+15>:     pop    r14
  0x7ffff7fcd011 <fib+17>:     pop    rbp
  0x7ffff7fcd012 <fib+18>:     ret
  0x7ffff7fcd013 <fib+19>:     mov    ebx,edi
  0x7ffff7fcd015 <fib+21>:     lea    edi,[rbx-0x1]
  0x7ffff7fcd018 <fib+24>:     movabs r14,0x7ffff7fcd000
  0x7ffff7fcd022 <fib+34>:     call   r14
  0x7ffff7fcd025 <fib+37>:     mov    ebp,eax
  0x7ffff7fcd027 <fib+39>:     add    ebx,0xfffffffe
  0x7ffff7fcd02a <fib+42>:     mov    edi,ebx
  0x7ffff7fcd02c <fib+44>:     call   r14
  0x7ffff7fcd02f <fib+47>:     add    eax,ebp
  0x7ffff7fcd031 <fib+49>:     pop    rbx
  0x7ffff7fcd032 <fib+50>:     pop    r14
  0x7ffff7fcd034 <fib+52>:     pop    rbp
  0x7ffff7fcd035 <fib+53>:     ret
```

Listing 5: LLVM MCJIT recursive-fib disassembly (Optimization level 3)

```
(gdb) x/32i $1
  0x7ffff6a81034: sub    rsp,0x18
  0x7ffff6a81038: mov    QWORD PTR [rsp+0x10],rbx
  0x7ffff6a8103d: cmp    edi,0x2
  0x7ffff6a81040: jl     0x7ffff6a8106d
  0x7ffff6a81042: mov    rbx,rdi
  0x7ffff6a81045: lea    edi,[rbx-0x2]
  0x7ffff6a81048: call   0x7ffff6a81034
  0x7ffff6a8104d: mov    rdi,rbx
  0x7ffff6a81050: mov    rbx,rax
  0x7ffff6a81053: sub    edi,0x1
  0x7ffff6a81056: call   0x7ffff6a81034
  0x7ffff6a8105b: xchg   rbx,rax
  0x7ffff6a8105e: mov    rcx,rbx
  0x7ffff6a81061: add    eax,ecx
  0x7ffff6a81063: mov    rbx,QWORD PTR [rsp+0x10]
  0x7ffff6a81068: add    rsp,0x18
  0x7ffff6a8106c: ret
  0x7ffff6a8106d: mov    rax,rdi
  0x7ffff6a81070: mov    rbx,QWORD PTR [rsp+0x10]
  0x7ffff6a81075: add    rsp,0x18
  0x7ffff6a81079: ret
```

Listing 6: JitBuilder recursive-fib disassembly (Optimization level *Warm*)

```
(gdb) x/2i $1
  0x7ffff7fcd000 <increment>:          lea    eax,[rdi+0x1]
  0x7ffff7fcd003 <increment+3>:        ret
```

Listing 7: llvm increment disassembly (Optimization level 3)

```
(gdb) x/10i 0x7ffff6a81034
  0x7ffff6a81034:      mov    rax,rdi
  0x7ffff6a81037:      add    eax,0x1
  0x7ffff6a8103a:      ret
```

Listing 8: jitbuilder increment disassembly (Optimization level *Warm*)

JitBuilder programs. Note that the JIT frameworks were compiled without debug symbols. Part of the explanation for this is may have to do with over-linking the LLVM programs. While there are over 167 possible linkable modules when using LLVM, I found the minimal set required to use MCJIT was just 8 : *core, executionengine, interpreter, passes, mc, mcjit, support, nativecodegen.*

4.4 Resident State Set

The resident state (RSS) set is amount of data loaded into RAM during execution at any one time. To measure the maximum RSS, we used the `time` utility (`/usr/bin/time -v`) to collect this. Looking at the results in Table 4, we see that LLVM consistently had the largest RSS. The memory overhead required by LLVM is roughly 4.5 times larger than JitBuilder's requirement. Looking at the number of times inactive pages were reclaimed during execution (minor page faults), we see that LLVM had roughly 4 times the number of inactive pages collected.

4.5 Developer Experience

One additional aspect to overhead worth considering is the usability of the frameworks from a developer's perspective. Under this banner, we looked at two items: ease of use, and how configurable the frameworks were.

4.5.1 Usability. While ease of use is not likely to be the highest priority when considering which JIT framework to select, research has shown that improved API usability can positively impact developer

Program	LLVM MCJIT	Eclipse OMR JitBuilder	Native (C++)
increment	60,640,216	10,148,608	16,616
recursive-fib	60,671,176	10,149,272	16,600
iterative-fib	60,652,728	10,149,184	16,600

Table 3: Total size in bytes of linked binary test programs.

	LLVM MCJIT		Eclipse OMR JitBuilder		Native (C++)	
Program	max RSS (kb)	minor page faults	max RSS (kb)	minor page faults	max RSS (kb)	minor page faults
increment	43,544	1478	9416	344	1548	65
recursive-fib	45,472	1545	9768	384	1532	63
iterative-fib	44,452	1520	10,044	423	1684	66

Table 4: Maximum resident state set (RSS) in kilobytes during execution of a single compilation and execution of the generated function. Note that Native had no run-time compilation phase. A minor page fault occurs when the OS reclaims inactive pages during execution. Page size was 4096 bytes.

productivity [25], while improving code quality and reducing errors. Overall we found that JitBuilder took less time to integrate, and provided a more intuitive API for generating IR. When considering usability we took note of the following items:

- Both of the frameworks provide public Github repositories [26, 27].
- The instructions for building the frameworks were readily available and simple to follow.
- Linking LLVM took considerable effort as it was unclear which of the 167 objects were required to use MCJIT. After some trial and error, we discovered LLVM provides a utility, `llvmconfig`, which simplifies this task by generating header and linking arguments for G++ based on a list of objects[4]
- JitBuilder on the other hand required was simple to integrate, requiring only a single header file and single module to link: `jitbuilder`. On the other hand, LLVM required us to include 20 header files in our programs.
- We found that writing the IR generators in our test programs took less time with JitBuilder than with LLVM. The most challenging task was writing iterative-fib for LLVM, as this required us to grasp the underlying IR requirements which included: an induction value, a Phi node, several basic blocks for before, during and after the loop, condition values, as well as allocation and store pointers.[5].
- The in memory objects generated by LLVM MCJIT can contain debug symbols (DWARF format) allowing debugging to take place in GDB 7.0 and higher [28].

4.5.2 Configuration. While the API of LLVM MCJIT may have an overabundance of controls, it does provide an high level of configuration compared to JitBuilder, including which optimization and analysis passes to run, control over the memory structure of the generated code, control over the object cache, and what level of optimization to generate the code at. As mentioned, JitBuilder on the other hand is currently locked at the *Warm* optimization level, limiting the number of optimizations performed on the IR.

[4]Example commands for building the programs can be found `makefiles` in the accompanying source code [24] under `src/<framework>/`.
[5]Source code for the LLVM iterative-fibonacci program can be found in the CreateFibFunction within `src/llvm/iterative-fib/fib.cpp`

4.6 Considerations

Considering the JIT compiler behind JitBuilder was designed specifically for dynamic runtime compilation, it makes sense that it has a lighter footprint than MCJIT, which shares it's codebase with the static compiler for LLVM Unlike LLVM's IR, which is meant for life-long usage, the design of OMR's IR does not have ahead of time, or offline goals in mind, thus possibly simplifying the work required whenever IR interactions are made in JitBuilder.

5 RELATED WORK

- LLVM IR -> JitBuilder

6 FUTURE WORK

Future Work

7 SUMMARY

8 ACKNOWLEDGEMENTS

This research was conducted within the Centre for Advanced Studies—Atlantic, Faculty of Computer Science, University of New Brunswick. The authors are grateful for the colleagues and facilities of CAS Atlantic in supporting our research. The authors would like to acknowledge the funding support provided by the Atlantic Canada Opportunities Agency (ACOA) through the Atlantic Innovation Fund (AIF) program. Furthermore, we would also like to thank the New Brunswick Innovation Foundation for contributing to this project.

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