University of Pisa
Department of Computer Science

“**Just In Time**” to understand

(An introduction to how *JIT compilers* work under the hood)

Presented by: **Gabriele Pappalardo** (a.a 2021/2022)

Why this topic?

I am really curious about computer works under the hood. My curiosity lead me to try and find out how the JIT compilers function.

- How is the code compiled during the run-time?
- How is it possible to compile code into the memory and then execute it?
- Are JIT compilers horrible monsters?(Spoiler: *maybe not* :D)

I hope these questions will be answered during the presentation.

“Great code is efficient code. But before you can write truly efficient code, you must understand how computer systems execute programs and how abstractions in programming languages map to the machine's low-level hardware.” - ***Randall Hyde*** *(Write Great Code, No Starch Press)*

Minimum Requirements

To fully understand the presentation, you will need a *bit* of knowledge about:

1. *Computer Architecture*.
2. *Operating System.*
3. *C++ language*.
4. *JVM Instruction Set*.
5. *Interpreters*.

Outline

1. Brief history of **Just In Time** compilation
2. **What** is a **JIT compiler**?
3. **Where** is it used?
4. **How** does it work? A look at HotSpot JVM
5. (“*Tiny*”) **C++ implementation** of a JIT compiler
6. Conclusions

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Origins of JIT Compilers

- The first signs of JIT compilers date back to the 1960, from the LISP's creator John McCarthy.
- Another ancestor of initial just-in-time compilers is the regular expression compiler created by Ken Thompson in 1968, which converted regexes to IBM 7094 CPU native code.
- In the ‘70 and ‘80, the calculation power of computers was unlike today’s. Whoever had an interpreted program and wanted to speed it up, a “**mixed-code**” approach was the best idea.
- Mixed-code approach was good, however maintaining pieces of program, write in native code and other pieces in interpreted code, was not an *easy* task.

Origins of JIT Compilers (cont’d)

- From a mixed-code approach, developers moved to "**throw-away**" compiling.
- Program pieces were compiled dynamically according to the necessities. When the memory was about to run out, then the compiled code would be thrown away.
- At the end of the ‘90, **Java** was born. Initially, the Java Virtual Machine was really *inefficient*.
- **Sun Microsystem** developed a Just-in-time compiler to boost Java performances.

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What is “Just in Time” compilation?

Just-in-Time compilation is a dynamic translation technique that compiles running code during the execution of a program at runtime rather than before execution.

JIT compilation is a **merge** between **ahead-of-time compilation** and **interpretation**.

Benefits and Drawbacks of a JIT compiler

As a combination of these two traditional approaches, the JIT compilation brings **advantages** and **drawbacks** of **both**.

Compilation to Native Code

Advantages

1. **Blazing fast and efficient**
2. Developers can interact directly with the underlay hardware

Disadvantages

1. **Poor portability** due to CPU architecture
2. Large program size

Just-in-Time

- Some JIT compilers need time to startup.

+ JIT compilers know a lot of information about the program during run-time

Interpretation

Advantages

1. Greater Portability
2. Small program size
3. **Knows a lot of information during run-time**

Disadvantages

1. **Really slow** because of interpreter

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Where it is used?

- Most **browsers** today, use JIT compilers to enhance performances of web pages and applications. Browser engines compile JavaScript code in native one.

- Other than browsers, programs written in Python, running on **PyPy**, "may" also gain performance boost.

Apple's SquirrelFish

Google's V8

Mozilla's SpiderMonkey

pypy

Where it is used? (cont'd)

- JIT compilation is used inside the **Linux** Kernel for network packet filtering (see **eBPF**).

- Even **Android** use JIT compilation to run its applications!

- Furthermore, in the video games **emulation** scene, JIT compilers are used to enhance the performances (basically, a console ISA is translated to the CPU host ISA).

eBPF

Android

Dolphin Emulator

They are used everywhere, even in your pockets!

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How a JIT compiler works

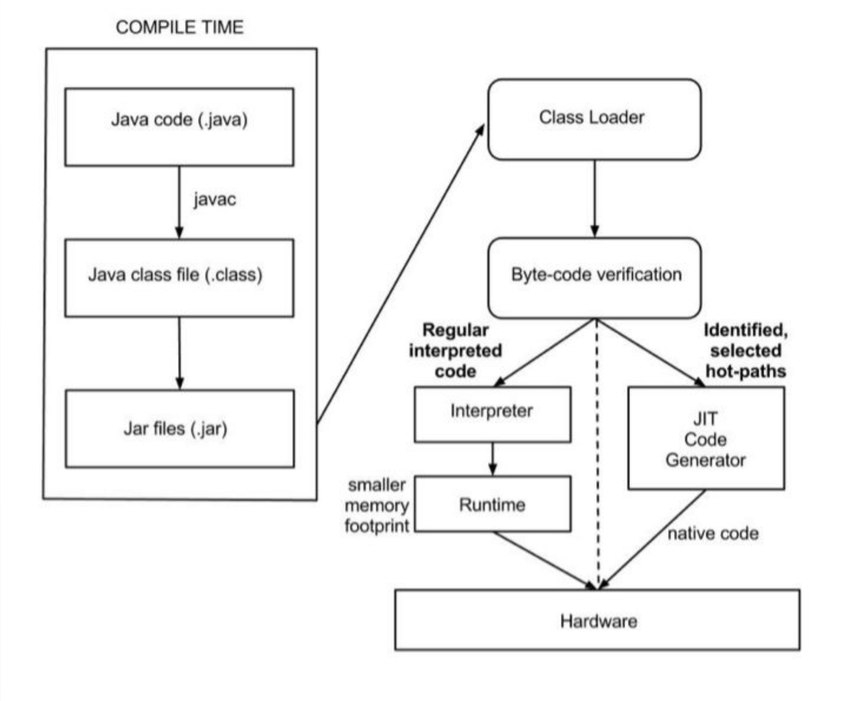
- In JIT compilation process, starting with the interpreter, some features of a static compiler are built into the system.

- A JIT compiler *will isolate some sections of the code at run-time which are accessed more often*.

- Then it will *compiles them to native code*, **aggressively** optimizing those sections in the process.

HotSpot JVM

- **HotSpot JVM** is the default interpreter of Java.
- The virtual machine is equipped with a JIT compiler.
- HotSpot practice “**trace-JIT**” compilation.
- Frequently used methods inside Java programs will be compiled in native code.
- The methods compiled in machine code are called **hot methods** 🔥.

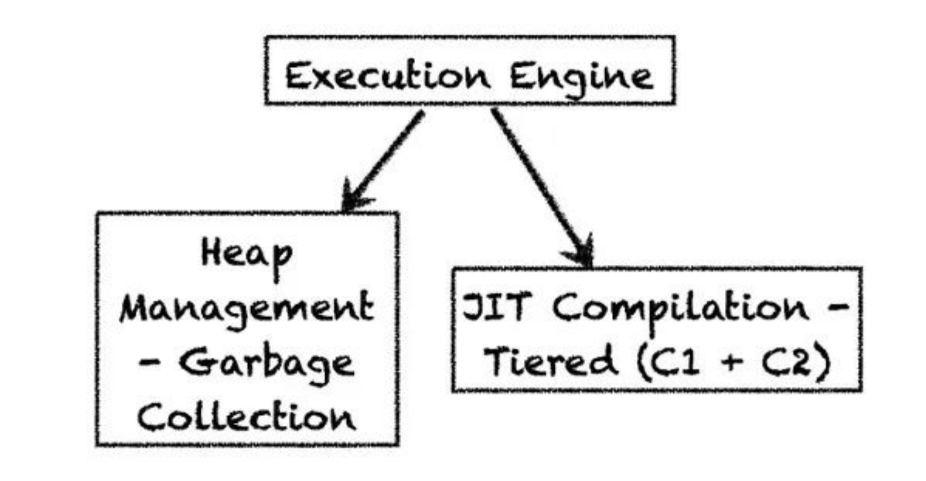


HotSpot JVM (cont'd)

HotSpot has **two main JIT compilers** that are executed according to established thresholds:

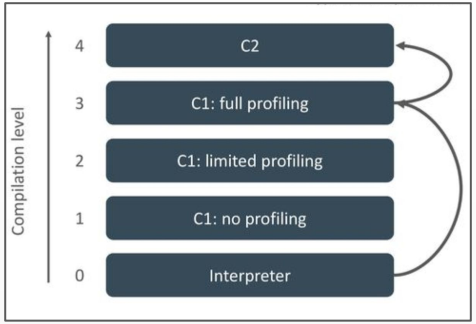
1. the **Client compiler**, or **C1**, has a low threshold (≈ 1.500 method calls), this is used to reduce startup time.

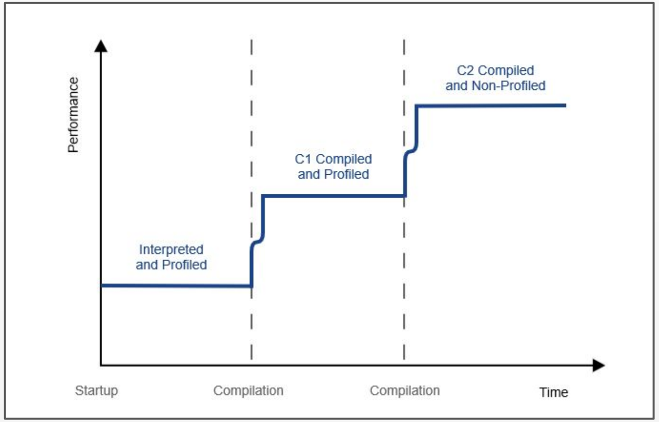
2. the **Server compiler**, or **C2**, has a bigger threshold (≈ 10.000 method calls) and it generates efficient optimized code for critical methods.



HotSpot's Tiered Compilation

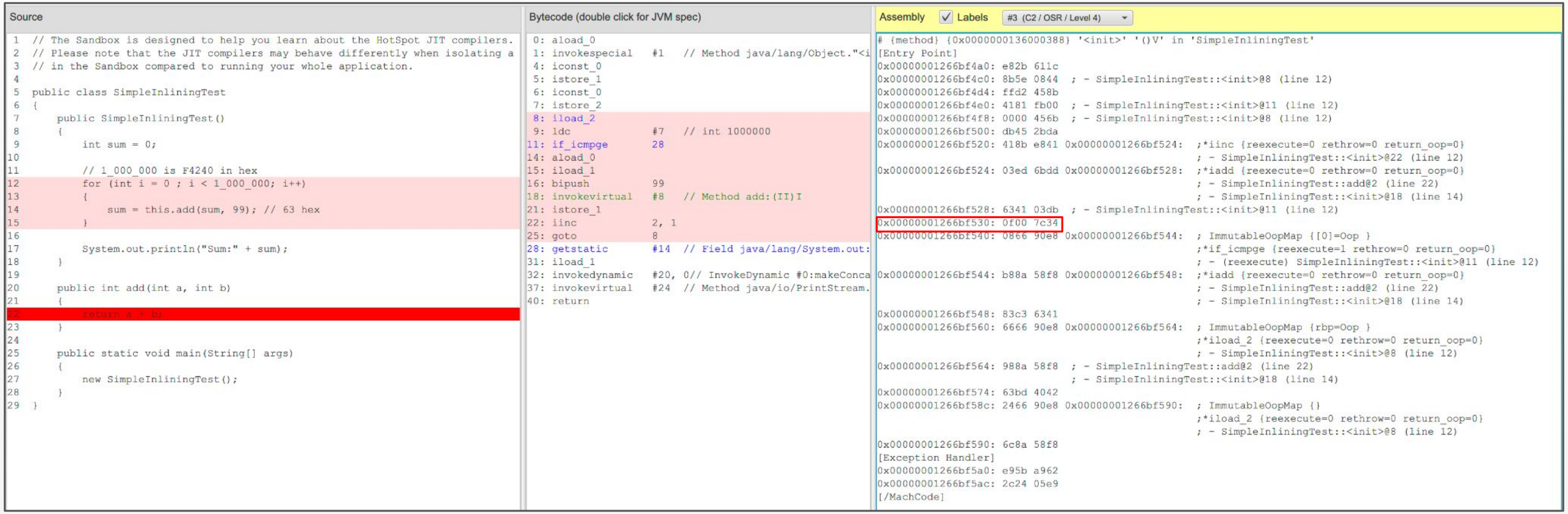
- HotSpot JVM comes with a "**tiered-compilation mode**".
- At the startup, the JVM interprets the bytecode and monitors it to get profiling information about the execution path.
- Firstly **C1**, will be executed to compile the bytecode into machine code to reach native performance.
- After collecting other informations, **C2** will re-compe all the code optimizing it.
- Finally, during the execution the **deoptimization** phase may happen.





JITWatch

It is possible to monitor the HotSpot JIT compilers. **JITWatch** is a tool for understanding the behaviour of the Java HotSpot Just-In-Time (JIT) compilers during execution of a Java program.



So, why don't use an AOT compiler instead?

Well… That is a good question!

Java developers introduced an experimental AOT compiler in **JDK 9** (see JEP 295: Ahead-of-Time Compilation)

But…

JEP 295: Ahead-of-Time Compilation

Owner	Vladimir Kozlov
Type	Feature
Scope	Implementation
Status	Closed / Delivered
Release	9
Component	hotspot / compiler
Discussion	hotspot dash compiler dash dev at openjdk dot java dot net
Effort	M
Duration	M
Reviewed by	John Rose, Mikael Vidstedt
Endorsed by	John Rose
Created	2016/09/15 01:20
Updated	2018/10/05 22:52
Issue	8166089

Summary

Compile Java classes to native code prior to launching the virtual machine.

Goals

- Improve the start-up time of both small and large Java applications, with at most a limited impact on peak performance.
- Change the end user's work flow as little as possible.

Non-Goals

It is not necessary to provide an explicit, exposed library-like mechanism for saving and loading compiled code.

Motivation

JIT compilers are fast, but Java programs can become so large that it takes a long time for the JIT to warm up completely. Infrequently-used Java methods might never be compiled at all, potentially incurring a performance penalty due to repeated interpreted invocations.

So, why don't use an AOT compiler instead? (cont'd)

… since developers saw a little use of this compiler, and, seeing as the amount of work to maintain it was **pretty huge***, they decided to **remove it**! (see https://openjdk.java.net/jeps/410)

(*) Just think all the CPU architectures out of here: x86_64, ARM, MIPS, *RISC-V*, *PowerPC* (☠️) and so many others...

JEP 410: Remove the Experimental AOT and JIT Compiler

Owner	Vladimir Kozlov
Type	Feature
Scope	JDK
Status	Closed / Delivered
Release	17
Component	hotspot / compiler
Discussion	hotspot dash compiler dash dev at openjdk dot java dot net
Effort	S
Duration	S
Reviewed by	Mikael Vidstedt
Created	2021/03/10 02:59
Updated	2021/08/05 02:44
Issue	8263327

Summary

Remove the experimental Java-based ahead-of-time (AOT) and just-in-time (JIT) compiler. This compiler has seen little use since its introduction and the effort required to maintain it is significant. Retain the experimental Java-level JVM compiler interface (JVMCI) so that developers can continue to use externally-built versions of the compiler for JIT compilation.

Motivation

Ahead-of-time compilation (the `jaotc` tool) was incorporated into JDK 9 as an experimental feature via JEP 295. The `jaotc` tool uses the Graal compiler, which is itself written in Java, for AOT compilation.

The Graal compiler was made available as an experimental JIT compiler in JDK 10 via JEP 317.

We have seen little use of these experimental features since they were introduced, and the effort required to maintain and enhance them is significant. These features were not included in the JDK 16 builds published by Oracle, and no one complained.

and no one complained.

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Disclaimer!

The next slides will show C++ and Assembly code.

The code implements an interpreter which evaluates a small (a really small one) subset of JVM instructions, specifically, the ones about integer operations. Of course the code is only used for didactic purposes; real JIT compilers are much **more complex** (and **surely more efficient, more memory-safe**) than this one, so be aware for it!

All the JVM instructions can be found here:
https://docs.oracle.com/javase/specs/jvms/se7/html/jvms-6.html

Under the hood: Code (1)

```cpp
int main(int argc, char** argv) {

    auto env = std::map<int, int>{{VAR_X, 3}};

    auto squareFun = std::vector<std::string> {
        "iload_0",
        "iload_0",
        "imul",
        "ireturn"
    };

    auto jit_compiler = JITCompiler{env};
    auto jvm_interpreter = JVMInterpreter{env};

    ASTNode* tree = JVMParser::parse_from_bytecode(squareFun);
    JITFunction fun = jit_compiler.compile_jvm_function(tree);

    jit_compiler.dump_assembly();

    std::cout << "Interpreted:\t" << jvm_interpreter.interpret(tree) << "\n";
    std::cout << "Compiled:\t\t" << fun();

    return 0;
}
```

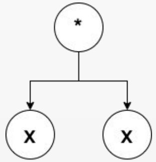
```java
public class Main {

  public static int square(int x) {
    return x * x;
  }

}
```

The code shown above is a Java function used to compute the square of a number. The compiled JVM bytecode version can be obtained using the `javap` utility.

Under the hood: Code (2)

```cpp
int main(int argc, char** argv) {

    auto env = std::map<int, int>{{VAR_X, 3}};

    auto squareFun = std::vector<std::string> {
        "iload_0",
        "iload_0",
        "imul",
        "ireturn"
    };

    auto jit_compiler = JITCompiler{env};
    auto jvm_interpreter = JVMInterpreter{env};

    ASTNode* tree = JVMParser::parse_from_bytecode(squareFun);
    JITFunction fun = jit_compiler.compile_jvm_function(tree);

    jit_compiler.dump_assembly();

    std::cout << "Interpreted:\t" << jvm_interpreter.interpret(tree) << "\n";
    std::cout << "Compiled:\t\t" << fun();

    return 0;
}
```

The **`JVMParser`** class transform the bytecode into an **Abstract Syntax Tree** (like the one shown below). This code representation is useful for both interpretation and compilation of this example.



This is the Abstract Syntax Tree representing the JVM bytecode. The leafs refers to function parameters, while the root node is a multiplicative operation between x and x.

Under the hood: Compiler's Core

Compiler's core.
Here is where the *magic* happens.

Next slides will *explain* the **three labelled blocks.**

```
typedef int(*JITFunction)();

JITFunction compile_jvm_function(ASTNode* tree) {

        assembly.clear();

        auto memory = static_cast<uint8_t*>(mmap(nullptr, 1024,
                                                PROT_READ | PROT_WRITE | PROT_EXEC,
                                                MAP_PRIVATE | MAP_ANONYMOUS ,-1, 0));
                                                                                          1
        if (memory == MAP_FAILED) {
            throw std::runtime_error{"Cannot allocate memory for the compiled function!"};
        }

        // push rbp
        assembly.push_back(0x55);
        // mov rbp, rsp
        assembly.push_back(0x48); assembly.push_back(0x89); assembly.push_back(0xe5);

        // Compile the AST to assembly code
        aux_compile(tree);
                                                                                          2
        // pop rbp
        assembly.push_back(0x5d);
        // ret
        assembly.push_back(0xc3);

        // Copy instructions inside the function
        for (std::size_t i = 0; i < assembly.size(); i++) memory[i] = assembly[i];

        return reinterpret_cast<JITFunction>(memory);                                     3
    }
```

Under the hood: Compiler's Core (1)

The first piece of the body asks to the operating system to reserve 1KB of memory inside the **heap** using **`mmap`** *syscall*. In this area of memory we are going to write our compiled function.

We cannot use the standard **`malloc`** function because we have to set some flags about the allocated memory.

These flags allow us to tell to the OS the desired memory protections. Specifically, we want that our memory can be **readable**, **writable** (risky flag) and, the most important one, **executable**.

Most of **browser exploits** are due to how JIT compilers use this memory! The attacker could write inside the memory arbitrary code! For more information see: JIT Spraying.

```
auto memory = static_cast<uint8_t*>(mmap(nullptr, 1024,
                                         PROT_READ | PROT_WRITE | PROT_EXEC,
                                         MAP_PRIVATE | MAP_ANONYMOUS ,-1, 0));

if (memory == MAP_FAILED) {
    throw std::runtime_error{"Cannot allocate memory for the compiled function!"};
}
```

Under the hood: Compiler's Core (2)

The second body piece writes the **assembly code** into a vector of bytes (`uin8_t`).

The first and the latter parts are standard **x86_64** instructions used to create a new stack frame for the function's execution.
(Since my computer uses an *Intel i7*, I wrote x86_64 instructions, on **ARM**/**RISC-V** processor the code will not work).

The middle part, where the **`aux_compile`** function is invoked, uses the AST showed before to produce assembly instructions according to the tree structure.

Finally, copy the compiled assembly instructions contained inside the **`assembly`** vector into the new allocated memory pointed by the **`memory`** pointer.

```
std::vector<std::uint_8t> assembly;
```

```
// push rbp
assembly.push_back(0x55);
// mov rbp, rsp
assembly.push_back(0x48); assembly.push_back(0x89); assembly.push_back(0xe5);

// Compile the AST to assembly code
aux_compile(tree);

// pop rbp
assembly.push_back(0x5d);
// ret
assembly.push_back(0xc3);

// Copy instructions inside the function
for (std::size_t i = 0; i < assembly.size(); i++) memory[i] = assembly[i];
```

Under the hood: Compiler’s Core (3)

The last body piece casts the pointer to `uint8_t` to a function pointer!

The function pointer has a definition like this one: `int(*JITFunction)()`

The cast is the real deal we were looking for. Basically, this operation will allow the program to call the compiled function during the run-time, resulting in the function execution.

Since our example compiles and computes only integer numbers the function will return an integer.

```
return reinterpret_cast<JITFunction>(memory);
```

Under the hood: Inspecting Call (1)

```
call     compile_jvm_function()
mov      qword ptr [rbp - 8], rax
call     qword ptr [rbp - 8]
```

```cpp
int main(int argc, char** argv) {

    auto env = std::map<int, int>{{VAR_X, 3}};

    auto squareFun = std::vector<std::string> {
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    ASTNode* tree = JVMParser::parse_from_bytecode(squareFun);
    JITFunction fun = jit_compiler.compile_jvm_function(tree);

    jit_compiler.dump_assembly();

    std::cout << "Interpreted:\t" << jvm_interpreter.interpret(tree) << "\n";
    std::cout << "Compiled:\t\t" << fun();

    return 0;
}
```

1. After the compilation, the `fun` variable contains a pointer to the allocated function.

Under the hood: Inspecting Call (2)

```
call    compile_jvm_function()
mov     qword ptr [rbp - 8], rax
call    qword ptr [rbp - 8]
```

```
19        std::cout << "Compiled:\t\t" << fun();
```

2. When the CPU will execute the `call` instruction, the Program Counter will be updated with the value saved inside the stack. This memory address points to the allocated memory of previously compiled function.

Instruction	Description
`call` *Label*	Push return address and jump to label
`call` **Operand*	Push return address and jump to specified location

Under the hood: Output

Once the function is compiled inside the program's memory we can invoke it! This is the result:

```
Compiled code: 55 48 89 e5 c7 45 fc 03 00 00 00 c7 45 f8 03 00 00 00 8b 45 fc 0f af 45 f8 89 45 f8 5d c3
Interpreted:    9
Compiled:       9
Process finished with exit code 0
```

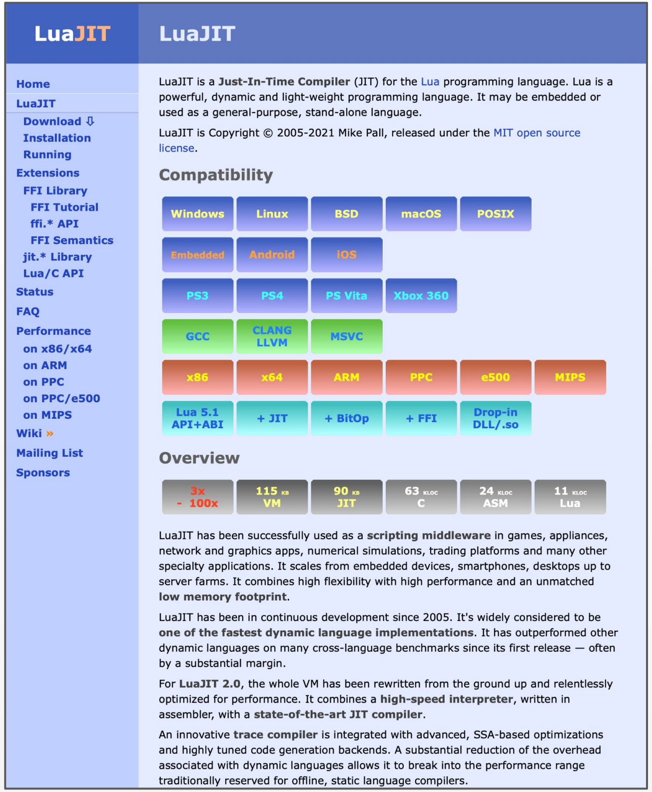
Console Output

Compiled code in x86_64

```
 0: 55                      push   rbp
 1: 48 89 e5                mov    rbp, rsp
 4: c7 45 fc 03 00 00 00    mov    dword ptr [rbp - 4], 3
 b: c7 45 f8 03 00 00 00    mov    dword ptr [rbp - 8], 3
12: 8b 45 fc                mov    eax, dword ptr [rbp - 4]
15: 0f af 45 f8             imul   eax, dword ptr [rbp - 8]
19: 89 45 f8                mov    dword ptr [rbp - 8], eax
1c: 5d                      pop    rbp
1d: c3                      ret
```

A Real JIT Compiler

- If you would like to see how a **real JIT** compiler is implemented, see **LuaJIT**.
- The compiler works for the **Lua** programming language and it is used in a lot of applications.
- For more details, see the **“LuaJIT Project”** at https://luajit.org.



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Conclusions

We saw what JIT compilers are, *how they are built* (conceptually speaking) and *where they are used*. There is a lot of content that wasn't shown in slides, I will leave some resources and references I used for this presentation.

Resources

- A brief history of Just In Time by *John Aycock*
- JIT through the ages by *Neeraja Ramanan*
- The Java HotSpot VM by Tobias Hartmann (https://ethz.ch/content/dam/ethz/special-interest/infk/inst-cs/lst-dam/documents/Education/Classes/Spring2018/210_Compiler_Design/Slides/2018-Compiler-Design-Guest-Talk.pdf)
- Understanding Java JIT Compilation with JIT Watch (https://www.oracle.com/technical-resources/articles/java/architect-evans-pt1.html)
- How the JIT compiler boosts Java performance in OpenJDK (https://developers.redhat.com/articles/2021/06/23/how-jit-compiler-boosts-java-performance-openjdk)
- JVM JIT-compiler overview (http://cr.openjdk.java.net/~vlivanov/talks/2015_JIT_Overview.pdf)
- Just in Time Compilation Explained (https://www.freecodecamp.org/news/just-in-time-compilation-explained/)
- What the JIT!? Anatomy of the OpenJDK HotSpot JVM (https://www.infoq.com/articles/OpenJDK-HotSpot-What-the-JIT/)
- Deep Dive Into the New Java JIT Compiler - Graal (https://www.baeldung.com/graal-java-jit-compiler)
- How to write a JIT Compiler (https://github.com/spencertipping/jit-tutorial)
- Adventures in JIT compilation: https://eli.thegreenplace.net/2017/adventures-in-jit-compilation-part-1-an-interpreter/
- Writing a minimal x86-64 JIT compiler in C++ (https://solarianprogrammer.com/2018/01/10/writing-minimal-x86-64-jit-compiler-cpp/)
- Just-in-time compilation (https://en.wikipedia.org/wiki/Just-in-time_compilation)
- How JIT Compilers are implemented and Fast: Pypy, LuaJIT, Graal and more (https://carolchen.me/blog/technical/jits-impls/)
- A deep introduction to JIT compilers: JITs are not very Just-in-time (https://carolchen.me/blog/technical/jits-intro/)
- OpenJDK Wiki (https://wiki.openjdk.java.net/display/HotSpot/Compiler)

Thanks

I hope you enjoyed these topics and found them interesting.

I would like to thank professor **Andrea Corradini** for the opportunity he gave to me for this presentation. Furthermore, I would like to thank my colleagues and my friends for their support and feedback.