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Instructions

Familiarize yourself with the architecture and instruction set of the Tiny86 virtual machine used in the NI-GEN course. Investigate native debuggers on the Windows and UNIX platforms and their principles. Improve the debugging capabilities of Tiny86 so that they are comparable to modern native debuggers. Design a debugging interface and implement a debugger as a reference client. The debugger must support native and source level debugging, but be extensible for intermediate level debugging (such as IR).

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Master's thesis

TINY86 DEBUGGER

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First and foremost, thanks to my parents, who have always supported me and enabled me to pursue my dreams, whatever they may be.
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Declaration

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Abstract

Programmers often need to inspect the state of their programs at runtime. A special tool called a debugger exists precisely for this purpose. Despite its widespread use, very few know how exactly this tool works. This is partly because it must be supported at multiple layers, like the CPU, the operating system, and the compiler. Most of the courses that teach about these do not delve into debugging.

This thesis explores what support must be provided by the CPU and operating system to enable native-level debugging. A small debugger implementation is demonstrated on the x86-64 architecture and the Linux operating system. Focus is then shifted onto compiler support for source-level debugging.

Using this knowledge, the thesis presents a debugger for the T86 architecture and the TinyC language, both of which are used by the NI-GEN compilers course at FIT, CTU. This debugger is fully functional, making it easier for students to work with the T86. Additionally, the thesis presents a design and implementation of a novel format of debugging information that keeps the interesting concepts from real-world debuggers while being extremely simple to use on both machine and human level, which is ideally suited for its intended classroom use.

Keywords Debugging, Debugger, Debug, Debugger implementation, Compiler, LLVM, Linux, Windows, Tiny x86, Debugging support, Errors in programs

Abstrakt

Programátoři často potřebují kontrolovat stav svých programů za běhu. Právě pro tento účel byl vytvořen speciální nástroj zvaný debugger. Přestože je tento nástroj velmi rozšířen, málokdo ví, jak přesně funguje. Částečně je to proto, že musí být podporován na více úrovních, jako je procesor, operační systém a překladač. Většina kurzů, které o nich vyučují, se debugováním nezabývá.

Tato práce zkoumá, jakou podporu musí poskytovat procesor a operační systém, aby bylo možné provádět debugování na nativní úrovni. Implementace malého debuggeru je demonstrována na architektuře x86-64 a operačním systému Linux. Pozornost je poté přesunuta na podporu překladače pro debugování na úrovni zdrojového kódu.

Na základě těchto poznatků je v práci představen debugger pro architekturu T86 a jazyk TinyC, které jsou využívány v kurzu překladačů NI-GEN na FIT ČVUT. Tento debugger je plně funkční a usnadňuje studentům práci s architekturou T86. Kromě toho práce představuje návrh a implementaci nového formátu debugovacích informací, který zachovává zajímavé koncepty z reálných debuggerů a zároveň je jeho použití extrémně jednoduché na strojové i lidské úrovni, což je ideální pro jeho zamýšlené použití ve výuce.

Klíčová slova Debugování, Debugger, Překladač, Implementace debugeru, LLVM, Linux, Windows, Tiny x86, Podpora pro debugování, Chyby v programech

Chapter 1
Introduction

At the core of every computer program lies the Central Processing Unit (CPU), which is responsible for executing programs. The CPU excels at performing very primitive operations very fast. These operations, called instructions, perform simple arithmetics, move values from and to memory, and change the control flow of the program. They are encoded as a sequence of binary numbers, which are easy for the CPU to understand, but are rather incomprehensible for humans.

To help programmers better understand written programs, a text mapping was created called *assembly language*. Each instruction is assigned a text representation, as are the operands of the instruction. The control flow instructions do not have to jump to an address offset but can instead use labels. An example of a simple program in both an assembly language and a machine code can be seen in figure 1.1. If a programmer is familiar with the instruction set architecture of the processor, they can easily recognize the instructions the program is made of.

However, as computers became increasingly more powerful, so did the programs became bigger and more complex. When programming in the assembly language, the programmer must have extensive knowledge of the processor's internal workings.

To spare the programmers from this, high-level programming languages were created. These are designed to abstract from the specific machine the program will run on, allowing programmers to focus more on their tasks. As shown in figure 1.1c, even a simple program written in the C programming language [1], one of the oldest programming languages around, provides a clear understanding of the functionality. In contrast, examining the equivalent program in assembly language, as seen in figure 1.1b, requires knowledge of the specific architecture of the machine. High-level languages also introduce control flow statements, which makes the code easier to follow compared to assembly jumps [2].

But processors only understand machine code and high-level languages are far from it. Therefore, a translation of a high-level language program into a machine code program is necessary. This is a task for a *compiler*. The compiler is a program that reads source code of a high-level language and produces machine code. Compilers are highly complex software; we will discuss them in detail in chapter 2.3. For now, it is crucial to understand that the computer cannot directly run the source code of a high-level language and that it is translated into machine code. Additionally, compilers often take advantage of unique features of the architecture to make the programs faster [3].

```
01010101 01001000
10001001 11100101
10001001 01111101
11111100 10000011
01111101 11111100
00000000 01111110
00000111 10111000
00000001 00000000
00000000 00000000
11101011 00000101
10111000 00000000
00000000 00000000
00000000 01011101
11000011
```

(a) A machine code program.

```
positive:
        push    rbp
        mov     rbp, rsp
        mov     -4[rbp], edi
        cmp     -4[rbp], 0
        jle     neg
        mov     eax, 1
        jmp     pos
neg:
        mov     eax, 0
pos:
        pop     rbp
        ret
```

(b) An assembly program.

```
bool positive(int n) {
    if (n > 0) {
        return true;
    } else {
        return false;
    }
}
```

(c) A program in the C language.

Figure 1.1 An example of a program that checks if a number is positive, shown in an assembly language, in a machine code, and in the C programming language.

```c
int binary_search(int* arr, int len, int n) {
    int lo = 0;
    int hi = len;
    while (lo < hi) {
        int i = (lo + hi)/2;
        if (arr[i] < n) {
            lo = i;
        } else if (arr[i] > n) {
            hi = i;
        } else {
            return 1;
        }
    }
    return 0;
}
```

Figure 1.2 A possible implementation of the binary search algorithm written in the C programming language.

1.1 Debugging

In figure 1.2, we present a more complicated example of a program written in a high-level programming language. This is an implementation of the binary search algorithm. As an input, it receives a sorted sequence of numbers and a number n. The algorithm then checks whether the number n is in the sequence. This algorithm is widely used when searching in sorted sequence because of its $\mathcal{O}(\log_2(n))$ complexity [4].

Programs are mostly written by humans, who tend to make mistakes [5]. We are no exception, as we have also made a mistake in the binary search program. Let us try to run the program with a `[1,2,3]` sequence and search for the number 4. This number is not in the sequence, so the expected output would be 0. Instead, if we ran the program, it would run forever because of a mistake we made in the source code. Such mistakes are called *bugs*[1]. The process of finding these mistakes and correcting them is called *debugging* [6].

There are several approaches to debugging. We could try to look at the source code and find the mistake this way[2]. Here we could assume that the condition `lo < hi` never comes to be since it is the most obvious place where we could get stuck forever. Now, it would be helpful if we could see the states of `lo` and `hi` in each iteration of the cycle. We could resort to print statements, but that is not very flexible. If we changed our minds and wanted to also see the value of variable `i`, we would have to recompile the program and rerun it. The output can also quickly get overwhelming, especially in an infinite loop. A different approach is to use a debugger, which is a special tool fitted exactly for this purpose.

Debugger is able to inspect the state of another program, like the values of its variables. It is also able to control the flow of the program. They allow *breakpoints* to be set at each

[1] The term *bug* actually comes from an actual bug that got stuck in relays back when computers were made from relays. They literally had to debug the machine by taking the bug out.

[2] Do note that this approach does not scale well with bigger programs.

```
   3               int hi = len;
   4               while (lo < hi) {
   5                   int i = (lo + hi)/2;
-> 6                   if (arr[i] < n) {
   7                       lo = i;
   8                   } else if (arr[i] > n) {
   9                       hi = i;
Target 0: (a.out) stopped.
> p lo
(int) $0 = 0
> p hi
(int) $1 = 3
```

Figure 1.3 Debugging session in the LLDB [7] debugger, showing breakpoint hit report and printing variable values.

line of the source code[3]. When the program is about to execute the line of code with the breakpoint, the control is passed back to the debugger, and the user can inspect the state of the program at that line. There are also conditional breakpoints, which only trigger when some condition holds. An example of such a condition can be that the breakpoint gets activated only when `i == 3`.

Finally, debuggers also allow *stepping*. There are several kinds of steps:

- *step-in* - Executes the current statement and stops on the next one. If the current statement is a function call, it will be executed, and the program will be paused on the first statement in that function.
- *step-over* - Same as a step-in, but if the current statement is a function call, the program will be paused on the next statement after the call.
- *step-out* - Executes as much as needed to return from the current function. Stops on the next statement that should be executed after the function returns.

To illustrate the workings of the debugger, let us look back at the program in figure 1.2. We will place a breakpoint on line 6 after i is set and we will monitor how the values in variables `lo` and `hi` change. If the program is run with the debugger attached, an output similar to what is displayed in figure 1.3 will be seen. Here, it is possible to see the line on which the execution was stopped. It is also possible to print the state of variables. In each loop, we could print the value of a variable and then continue execution until another breakpoint is hit. If we continue, the execution will again be stopped on line 6. The value of `hi` will not change, which is expected. Variable `lo` will gain the following values: $0, 1, 2, 2, 2, \ldots$ It apparently gets stuck at 2. The value of variable i is computed as $i = (\text{lo} + \text{hi})/2 = (2 + 3)/2 = 2$, because division in C rounds the value down. The fix is to change the line 7 to `lo = i + 1`. With the debugger, it was simple to find out where the error came from, and we did not have to recompile the program.

We previously mentioned that processors themselves only understand machine code. Hence, the question arises as to how the debugger can know about lines, variables, and

[3] Advanced debuggers allow breakpoints to be set inside expressions. This is especially important for functional languages, as their functions often consist of one big expression.

```
->  0x100003e3c <+112>: b      0x100003e78               ; <+172>
    0x100003e40 <+116>: ldr    x8, [sp, #0x20]
    0x100003e44 <+120>: ldrsw  x9, [sp, #0xc]
    0x100003e48 <+124>: ldr    w8, [x8, x9, lsl #2]
```

Figure 1.4 Example of debugging a program in the LLDB debugger without debugging information generated by the compiler.

similar traits of the source code when the program itself is just machine code. The compiler has to lend a hand here. It embeds information about the source code, either into the executable itself or into a separate file. For example, it maps lines of source code to machine code instructions. Thanks to this mapping, the debugger knows that line x corresponds to instruction y in the machine code and can put a breakpoint there. If the compiler does not emit any information into the executable, the debugger would only work with assembly, as seen in figure 1.4. This can be very difficult for the programmer to work with compared to debugging the source code directly.

1.2 Teaching Compilers

Many schools about computer science have a compiler course, and the Faculty of Information Technology, CTU, is no exception. The course is called *Code Generators* (NI-GEN). In this course, students are tasked to build a simple compiler from a C-like language called TinyC. The target of the compiler is the Tiny x86 (T86) architecture. This architecture does not have a processor that implements it. Instead, a virtual machine, a program that reads the assembly and executes it, was created for it. The architecture is supposed to ease the code generation and let the students focus on the more interesting parts of the compiler, like register allocation or optimization, instead of the uninteresting details of real CPU architectures.

There is, however, a problem with using T86, as it has almost non-existing debugging support. So if a compiler of some student generates the code badly, which is frankly inevitable, it takes a non-trivial amount of effort to find the error. T86 has some very light debugging capability, but it is far from real debugging. Also, compiling debugging information is not taught in the NI-GEN course because there is no reason to as of now. If a debugger was provided to the students, it might be incentivizing to compile such information to ease their lives later when they need to find errors in their compilers. This way, they will also learn how and what information the compiler needs to embed for the debugger to work.

1.3 Goals of the Thesis

The primary goal is to add debugging support to the T86 and create a debugger that supports debugging both on the machine and source code levels. The debugger should be extensible enough to also work with an intermediate representation. The debugger should be similar to real-world debuggers in terms of how it works. This will require non-trivial changes in the T86 virtual machine source code. The students' compilers will also have to generate debugging information. The format of the debugging information should be

so that it is not discouraging for students to generate but also comparable to debugging information generated by real compilers.

1.4 Structure of the Thesis

1. The *Introduction* is the motivation behind the thesis and introduces basic terms with which should the reader be familiar.
2. *Debugging Techniques* describes how are debuggers implemented and what support is required on various levels (OS, processors, compilers) to make their implementation possible.
3. *Tiny x86* describes the T86 architecture and discusses some of the parts of the virtual machine, mainly its existing debugging capabilities.
4. *Implementation* focuses on extending the T86 instruction set and adding a debugging interface to the virtual machine. It also describes the implementation of the debugger and the chosen format of the debugging information.
5. *Evaluation* evaluates the performance of the debugger and its ease of use.
6. *Conclusions* summarizes the result of the thesis and speaks of possible future work.

Chapter 2
Debugging Techniques

> *Debugging is twice as hard as writing the code in the first place. Therefore, if you write the code as cleverly as possible, you are, by definition, not smart enough to debug it.*
>
> Brian W. Kernighan

We need the compiler to emit debugging information to debug a program written in a high-level programming language. Without this information, we can debug the program at the assembly level. This can still be useful, for example, for reverse engineering. Furthermore, without assembly-level debugging, there is no source-level debugging since it builds upon it. This chapter describes at which level and what kind of debugging support is provided. First, we will mention what kind of mechanism the CPU itself offers. Going one step higher, we will talk about the API that various operating systems provide. Finally, we will discuss how compilers and debuggers can allow us to debug source code, although the program we debug was compiled into a machine code program.

2.1 CPU Level Support

The CPU can only execute machine code which is made of instructions. It also has several registers to help with computations. Which instructions and registers the CPU has can differ from CPU to CPU. This is specified by an *Instruction Set Architecture* (ISA) [8]. It is an abstract interface between the hardware and the lowest-level software (machine code). It contains all information needed to write a program in machine code. In general, ISA specifies the following:

- Set of machine code instructions - Specifies instructions the ISA has and what operands each instruction has.
- Register set - Which registers the ISA has[1].
- Addressing modes - Possible methods to refer to memory or register.

[1] Strictly speaking ISA does not have to use registers. It is possible to use only stack or accumulator, but most used ISAs use registers, so we will ignore those architectures.

This list is not exhaustive, but for our purposes, it suffices. For each instruction and operand, it is specified how they should be encoded into binary. CPU then *implements* some ISA. If two different CPUs implement the same ISA, then they should be able to run the same machine code program. For example, personal computers often use the x86-64 while mobile devices like smartphones or tablets use the ARM architecture [9]. The ARM architecture is also beginning to find its way into the computer space. For example, Apple Silicon is based on the ARM architecture.

The x86-64 architecture is an example of the so-called *Complex Instruction Set Architecture* (CISC). The CISC instructions often perform many actions at once, have varying lengths, and take multiple clock cycles to complete [10]. On the other hand, the ARM architecture is an example of the *Reduced Instruction Set Architecture* (RISC). The number of instructions is smaller. They are intended to be small building blocks from which complex operations may be created by using many of them. Each instruction in RISC also has the same length. Both architectures have their pros and cons, although some literature suggests that in modern days the choice of architecture is irrelevant if one is only considering performance and power consumption [11, 9]. Unless specified otherwise, the rest of this chapter will be talking about x86-64. This is because the T86 architecture, described in section 3, is loosely based on x86-64, so it is most relevant for us.

In the first chapter, we briefly mentioned that machine code programs could be written in assembly language instead. Assembly is almost a one-to-one mapping to machine code. When showing programs, we will show them in assembly so that they are readable. In figure 2.1, we present another example of a program written in the C programming language that was compiled into an assembly for the x86-64 architecture. As seen, instructions have various operands. Most often registers (`rbp, rsp, eax`), memory (`[rbp-4]`), or labels (like `L2`). Labels are not part of machine code; instead, a memory address has to be provided. This is a small part where assembly and machine code differs. For a detailed overview of the x86-64 instruction set, see [10].

Registers

The main advantage of registers is that they are much faster to access than the main memory. The x86-64 architecture has a set of general purpose registers. Some of these are

- `rax` - Accumulator for operands and results data,
- `rcx` - Counter for string and loop operations,
- `rsp` - Stack pointer,
- `rbp` - Pointer to data on the stack.

The `rsp` and `rbp` registers are used for pointing at the top of the stack, respectively to the base of the stack. Stack is a special part of program memory with LIFO semantics. It can be used to store the intermediate result, arguments to functions, return address, etc.

The instruction pointer register (`rip`) contains the address of the current instruction to be executed. Programs are executed sequentially from top to bottom, with particular instructions having the ability to change the control flow. When an instruction gets executed, the size of the instruction will be added to the value in the `rip` register. This will

```
max:
    push    rbp
    mov     rbp, rsp
    mov     QWORD PTR [rbp-24], rdi
    mov     DWORD PTR [rbp-28], esi
    mov     rax, QWORD PTR [rbp-24]
    mov     eax, DWORD PTR [rax]
    mov     DWORD PTR [rbp-4], eax
    mov     DWORD PTR [rbp-8], 1
    jmp     .L2
.L3:
    mov     eax, DWORD PTR [rbp-8]
    cdqe
    lea     rdx, [0+rax*4]
    mov     rax, QWORD PTR [rbp-24]
    add     rax, rdx
    mov     eax, DWORD PTR [rax]
    cmp     DWORD PTR [rbp-4], eax
    cmovge  eax, DWORD PTR [rbp-4]
    mov     DWORD PTR [rbp-4], eax
    add     DWORD PTR [rbp-8], 1
.L2:
    mov     eax, DWORD PTR [rbp-8]
    cmp     eax, DWORD PTR [rbp-28]
    jl      .L3
    mov     eax, DWORD PTR [rbp-4]
    pop     rbp
    ret
```

Figure 2.1 An example of an assembly program that was compiled from a program written in the C programming language using the GCC compiler.

advance the instruction pointer to the next instruction. Alternatively, if the instruction changes the control flow, the value in the instruction pointer will be changed to the instruction's destination. The register can also be changed directly.

Another interesting register is the `eflags` register. The register is made up of various flags, which can alter the CPU behavior, or the CPU itself sets them as a result of some instruction. For example, the instruction `cmp` compares its two operands, and if they are the same, the *zero* flag in the `eflags` register will be set.

2.1.1 Interrupts

An interrupt is a special request to the CPU to stop the execution of the current program and to quickly react to the reason that caused the request [12]. An example of such an event can be a keyboard press or an error in a program (division by zero). There are two main categories [10]:

- An **interrupt** is an asynchronous[2] event that is typically triggered by an Input/Output (IO) device.
- An **exception** is a synchronous event that is generated when the processor detects one or more predefined conditions when executing an instruction. These are further divided into three classes: faults, traps, and aborts.

For the rest of this thesis, we will use the word interrupt interchangeably for both interrupt and exception, although we will mainly talk about exceptions. This is to disambiguate the exceptions at a programming language level (like C++) and Microsoft structured exceptions, which are the subject of section 2.2.3. When an interrupt (or exception) happens, the processor halts the execution of a current program and switches to a specific interrupt handler. An interrupt handler is just a sequence of instructions that gets executed when the interrupt happens.

An example of an exception is the `int3` instruction. When this instruction is executed, an interrupt is generated. This instruction is specifically meant to be used as a breakpoint. In theory, we could supply code that will be responsible for handling the breakpoint as the interrupt handler. We could then set the `int3` instruction where we want the breakpoint to occur and inspect the code through the interrupt handler. However, on modern PCs, an Operating System (OS) governs the PC and consequently is responsible for setting interrupt handlers. Alas, we cannot touch the interrupt handler directly. Instead, the OS will have to provide another layer of support for debugging.

Recall the EFLAGS register mentioned in section 2.1. There is a special flag called the trap flag. When it is set, the CPU will issue an interrupt after every executed instruction. This could be useful if we wanted to inspect execution instruction by instruction.

The CPU may also contain special debug registers. The x86-64 architecture has six of them, named `dr0` to `dr7`, with `dr4` and `dr5` being synonyms for `dr6` and `dr7` on most CPUs, otherwise, they are reserved anyway and cannot be used. The CPU provides special breakpoints through these registers. Each of the first four registers contains an address of the breakpoint. The debug status register `dr6` contains debug conditions that were sampled at last debug interrupt. Lastly, the debug control register `dr7` is used to enable

[2] Meaning that the interrupt may happen when another instruction is being processed, and not at the CPU clock edge. However, The handling of the interrupt happens at the clock edge.

and disable breakpoints for each of the address registers and set breakpoint conditions. The conditions are either instruction execution on a specific address or a memory read or write. When the breakpoints are hit, for example, the address stored in `dr0` is written into, the breakpoint is enabled, and the condition is set to memory write in the `dr7` register, an interrupt is issued by the CPU and the `dr6` register contains information about which register caused the interrupt [10].

2.1.2 Superscalar CPUs

Modern CPUs do not execute instructions strictly one by one. They instead use *pipelines* and *out-of-order execution* [8, 12]. This means that they can execute several instructions at once and can execute them in non-sequential order. The observable behavior of the program has to be the same as if it was run sequentially. The CPU has to be careful about which instructions it can run in parallel and out of order. The execution of an instruction consists of several stages, which together form an *execution pipeline*. The stages can be *Fetch*, *Decode*, *Execute*, *Memory*, and *Writeback*; this may vary depending on the architecture. However, the general ideas behind it are the same. The instruction must pass all these stages to be successfully executed. To maximize efficiency, all stages are occupied by an instruction. This means that when instruction x leaves the fetch stage, it goes to the decode stage, and instruction y is put into the fetch stage.

However, when the next instruction is a conditional jump, there may be no way to be sure if the jump will be taken. CPUs deal with it in various ways and try to predict the right branch. Sometimes, however, the prediction fails, and the whole pipeline needs to be flushed. The same action must be taken when an interrupt occurs. The execution changes to the interrupt handler, and the pipeline must therefore be flushed because it contains instructions from the previous location before the control flow was switched to the handler. Also, if we hit the breakpoint, we want to make sure that instructions before it were all executed and that none were executed after. Otherwise, it would be very confusing for the user that tries to debug the program.

2.2 Operating System Support

An operating system is a layer between computer components (CPU, memory, input/output devices, etc.) and software. It is responsible for handling all the resources so programmers do not have to think about it [13, 14]. Managing resources is not only to make writing programs easier but to make sure that the programs are safe from each other. Modern operating systems allow running multiple programs at once (or at least offer the illusion that they can), and they make sure that one program cannot overwrite data or otherwise interfere with other programs. The kernel runs in the so-called *kernel space*. It has full access to the hardware of the computer, can use all instructions, can permit or mask interrupts, and so on. On the other hand, regular programs run in the *user space*, where they have limited capabilities.

However, if programs were kept in user space all the time, they would be very limited. Sometimes, they need to escape the confinement of the OS, for example, to read a file or communicate with other processes. Operating systems provide an interface through which the user space program can leverage a small part of the kernel in the form of system calls. They offer a way of requiring some service from the OS. This API is often in the form of

C and C++ functions [14]. A part of these functions is a special instruction, like `SYSCALL` on x86-64 [10], that switches the mode to kernel space.

The most used operating systems today are Microsoft Windows, Linux, and MacOS. Linux and MacOS systems are somewhat similar, but Windows is very different. To debug programs, we need to be able to read and modify the state of a running program. This is in direct conflict with the encapsulation the operating system is trying to achieve. As such, the operating system must provide an API through which we can do these operations that are needed for debugging.

2.2.1 Linux

Linux offers a special system call which is very handy for debugging. It is called `ptrace` [15] - process trace. It has the following signature: `ptrace(request, PID, void* addr, void* data)`. The request is a `PTRACE_COMMAND`, which specifies the behavior of the function (for example `PTRACE_SINGLESTEP`), process id (PID) of some process (presumably the debuggee) and two other parameters, whose meaning change depending on the `PTRACE_COMMAND` that was chosen. It allows one to observe and control the execution of another process; this process will be the debuggee. In the context of this chapter, we will sometimes use the word tracee for the debuggee, and tracer for the debugger, to be consistent with ptrace documentation.

The `ptrace` function has many commands, here are some of the most important:

- `PTRACE_PEEKTEXT, PTRACE_PEEKDATA` - Read tracee's memory.
- `PTRACE_POKETEXT, PTRACE_POKEDATA` - Write into tracee's memory.
- `PTRACE_GETREGS` - Read tracee's register values.
- `PTRACE_SETREGSET` - Modify tracee's register values.
- `PTRACE_GETSIGINFO` - Retrieve information about the signal that caused tracee to stop.
- `PTRACE_CONT` - Restart the stopped tracee process.
- `PTRACE_SINGLESTEP` - Restart the stopped tracee but stop it after executing one instruction.

Linux, however, needs some way of notifying the debugger that the tracee encountered a breakpoint or that some other event requiring debugger attention happened. To this end, *signals* are used. They serve as an abstraction on top of the CPU interrupts. Interrupts are sent by the CPU and processed by the operating system kernel. Signals are sent by the operating system kernel and received by processes. They can also be sent by a process. That, however, happens via system calls and the kernel is the one who sends the signal.

A signal is used in UNIX and Linux systems to notify a process that a particular event has occurred [14]. When a process receives a signal, it stops its execution and starts the execution of a signal handler. There are various signal types. Most signals can have a custom signal handler defined by the process. If no handler is defined, then the OS provides a default one. However, handlers for `SIGKILL` and `SIGSTOP` cannot be changed [16].

The reason for sending a signal to a process can, for example, be a CPU interrupt (like division by zero or breakpoint hit) or a system call (`kill(pid, signal)`). One such signal is the `SIGTERM`, which can be sent to a process to "ask it" to exit. The process can handle this request, for example, to save some state before exiting. It can also be entirely ignored. To prevent this, a signal `SIGKILL` can be used, which cannot be handled, ignored, or blocked.

To begin tracing a command `PTRACE_ATTACH` may be used for an already existing process, or a `fork` followed with a child calling `PTRACE_TRACEME` and typically `execve`. When the tracee is being traced, it will stop each time a signal is delivered to it, even if it chooses to ignore said signal. The tracer will be notified that the tracee received a signal at its next call to the `waitpid` function. When the tracee is stopped, the tracer can initiate various ptrace requests listed above to inspect and change the state of the tracee [15].

In chapter 2.1.1, we mentioned that the debug instructions cause an interrupt. The Linux kernel, however, does not permit us to work with interrupt handlers. Instead, it translates those interrupts into signals. So when the tracee executes the `int3` instruction, it will receive a signal that we will catch with the `waitpid` function.

2.2.1.1 Debugger implementation

Now, we have all the necessary building blocks to build a simple debugger on the Linux operating system running on the x86-64 platform. Running a program under the debugger is simple. Figure 2.2 shows the initialization of the debugger. It uses the fork-exec idiom. The `fork` system call creates an exact copy of the process as a child except the following: process ID (PID) of the child is different. In the parent process, `fork` returns the PID of the child. In the child, 0 is returned. The child initiates the `PTRACE_TRACEME` call, which indicates that this process is to be traced by its parent. Then it calls the `execve` system call, which replaces this program with the one we want to debug. The execve causes a `SIGTRAP` signal on completion because the process is being traced [17].

The parent first issues a `waitpid` system call. This waits for the child `execve` to finish. The debugger then has a chance to debug the child immediately because it is stopped. The `while` loop can then request input from the user and act accordingly. The tracee can be continued by `PTRACE_CONT` command.

The `PTRACE_PEEKTEXT` and `PTRACE_POKETEXT` commands can be used for reading and writing into tracee's memory. This call reads or writes a word (32 or 64 bits, depending on the Linux variant) into the tracee's memory. However, if we want to write an arbitrary amount of bytes, we have to work around the word limitation. We need to write by blocks, and for the last one, we have to pad the write with already existing data if the block size does not divide the word size. Figure 2.3 shows how to read and write precisely one byte of memory at a given address, which is simpler to implement but not ideal for writing many bytes.

Registers are similar to a memory in regards to how to read them. Linux contains a predefined structure `user_regs_struct`, which maps all registers on the current architecture. The command `PTRACE_GETREGS` then fills up this structure with the values in registers. To save registers, `PTRACE_SETREGS` can be used. One has to pass the whole structure, so if we want to modify only some registers, we first need to fetch the structure, fill the registers we want with values, and then finally use `SETREGS`. An implementation can be seen in figure 2.4, the `get_register` functions maps the structure members to the

```
pid_t pid = fork();
if (pid == 0) {
    // Begin tracing
    ptrace(PTRACE_TRACEME, 0, NULL, NULL);
    // Replace the code with the intended tracee code
    execve(executable, argv, NULL);
} else {
    int w;
    waitpid(pid, &w, 0);
    while(...) {
        // Main debugger loop
    }
}
```

Figure 2.2 Linux debugger implementation - Initialization of the tracee process.

```
uint8_t read_memory(pid_t pid, uint64_t address) {
    uint64_t data = ptrace(PTRACE_PEEKDATA, pid, address, NULL);
    return (uint8_t)data;
}

void write_memory(pid_t pid, uint64_t address, uint8_t data) {
    uint64_t old = ptrace(PTRACE_PEEKDATA, pid, address, NULL);
    uint64_t new_data = (old & ~0xFF) | data;
    ptrace(PTRACE_POKEDATA, pid, address, new_data);
}
```

Figure 2.3 Reading and writing one byte to debuggee memory using ptrace.

```
void set_register(pid_t pid, const char* name, uint64_t data) {
    struct user_regs_struct regs;
    ptrace(PTRACE_GETREGS, pid, NULL, &regs);
    uint64_t* reg_data = get_register(&regs, name);
    *reg_data = data;
    ptrace(PTRACE_SETREGS, pid, NULL, &regs);
}
```

Figure 2.4 Setting debuggee register value using ptrace.

```
01 d0      add eax,edx
88 45 fd   mov [rbp-0x3],al
ff e0      jmp rax
```

```
01 d0      add eax,edx
cc 45 fd   int3
ff e0      jmp rax
```

Figure 2.5 Code with and without a breakpoint. The breakpoint is highlighted by the blue color. The red color shows invalid instruction.

register's name. Since the address of the current instruction to be executed is also stored in a register (`rsp`), we now have access to it.

Breakpoints are more interesting. Debuggers often allow to enable and disable a breakpoint, so we will distinguish between setting a breakpoint and enabling it. Setting a breakpoint just means that the debugger needs to keep track of where the breakpoint was set and if it is enabled or disabled. Enabling a breakpoint means writing into the program memory the debug instruction (we will use the x86-64 `int3` instruction with opcode `0xCC`). Figure 2.5 shows how code looks with and without enabled breakpoint. The blue color shows the new breakpoint. On line 2, the opcode changes from `0x83` to `0xCC`. Since the breakpoint is set via the `PTRACE_POKEDATA`, which only works with words, one has to pad the breakpoint opcode with already existing data. Also, the rewritten data (in this case, the `0x88`) has to be kept so that the breakpoint may later be deactivated. Abbreviated implementation can be found on 2.6.

When a breakpoint is hit, the control is passed to the debugger. At this point, the instruction pointer would point to the next instruction, which has opcode `0x7D`, not `0xFF` (the `jmp` instruction) as might be expected. This is because `int3` is an instruction with size 1. It gets executed, the instruction pointer is advanced by the size (1), and an interrupt is issued. However, after the `int3`, there were operands to the `mov` instruction (the red text in the figure). We definitely do not want to interpret them as instruction. Because of this, we need to move the instruction pointer before the breakpoint instruction. Additionally, we found out that on some architectures, advancing PC does not happen when an instruction that issues an interrupt is executed, such as the ARM `BKPT` instruction. This was later confirmed by looking at the LLDB code, as it only moves back the program counter for a few architectures [18].

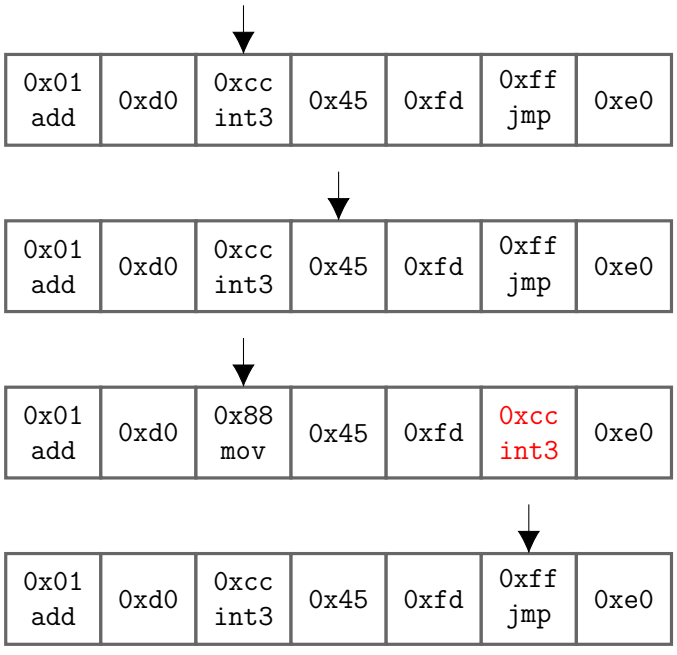
If we resumed the program after moving back, we would again hit the breakpoint, which is still set. We need to temporarily unset it, move one instruction forward and set it again. The general idea behind it can be found in figure 2.7. With breakpoints, we essentially gained the ability to single step as well.

However, putting a breakpoint on the instruction that will be executed next is more challenging than it might appear. Due to the varying sizes of instructions on CISC ar-

```
void enable(pid_t pid, struct breakpoint* bp) {
    if (bp->enabled) {
        return;
    }
    bp->backup = read_memory(pid, bp->address);
    write_memory(pid, bp->address, BP_OPCODE);
    bp->enabled = true;
}

void disable(pid_t pid, struct breakpoint* bp) {
    if (!bp->enabled) {
        return;
    }
    write_memory(pid, bp->address, bp->backup);
    bp->enabled = false;
}
```

Figure 2.6 Enabling breakpoints, abbr.



Just before hitting a breakpoint.

After software breakpoint is executed.

Move instruction pointer back, replace the `int3` instruction with the original one and set a breakpoint at the next instruction.

Resume the execution, remove the newly set breakpoint and restore the old one.

Figure 2.7 A diagram of how a continue operation might be performed. The arrow signalizes an instruction pointer.

```
void step_over_bp(pid_t pid) {
    uint64_t loc = read_register(pid, "rip");
    struct breakpoint* bp = find_bp(loc);
    if (bp == NULL || !bp->enabled) {
        return;
    }

    disable(pid, bp);
    ptrace(PTRACE_SINGLESTEP, pid, NULL, NULL);
    // Waits until debuggee finishes singlestepping
    wait_for_debuggee(pid);
    enable(pid, bp);
}
```

Figure 2.8 Stepping over an active breakpoint. The `wait_for_debuggee` is a wrapper function around the `waitpid` function.

chitectures, even determining the instruction that follows the current one in the code is challenging. RISC architectures facilitate this because all instructions have the same length. Finding the next instruction to be executed may still pose a challenge if the instruction is a conditional jump. Accurately determining where the jump will go can be an arduous task. To achieve this, some debuggers use instruction emulators. Fortunately, some architectures have built-in hardware support for single stepping, like the trap flag we mentioned in section 2.1.

The ptrace library contains a special `PTRACE_SINGLESTEP` command, which executes one instruction in the tracee before sending the `SIGTRAP` signal. The Linux kernel (as of v6.1.8) uses the previously mentioned trap flag for x86-64 [19]. The call will return an error if the architecture does not provide a hardware-supported single stepping. In lieu of the breakpoint dance mentioned earlier, the singlestep command will be used in our implementation because x86-64 supports it. Implementation is described in figure 2.8. We presume that the instruction pointer was moved when the breakpoint was hit, eliminating the need to return one byte backward. This is more reasonable anyway, since we want to show the user at which address the breakpoint hit happened. The LLDB [7] debugger uses hardware support if there is one, else it uses an instruction emulator. For instance, for the ARM architecture, LLDB uses an instruction emulator, whereas, for the x86-64, it uses the trap flag.

To perform a step-in, the `PTRACE_SINGLESTEP` command can be used. However, in the case where the current address contains an active breakpoint, the debugger would treat it as a breakpoint hit, reverting the program counter back before the breakpoint, rendering it impossible to step over. Therefore, a check for the presence of an active breakpoint must be performed prior to the execution of the single step `ptrace` call. If a breakpoint exists, the code from figure 2.8 will be used. Otherwise, the `PTRACE_SINGLESTEP` command will suffice.

Next in the line is the step out, which allows one to jump out of the current function. When a procedure is entered using the `call` instruction, the address immediately after the call instruction is put onto the stack. Upon entry into the function, the value of the `rbp` register is pushed onto the stack, and then the register is updated to reflect the current

value of the stack pointer. As a result, the return address is located at `rbp + 8`. We can set a breakpoint at that address, continue execution, wait for the debuggee to hit the breakpoint, and then disable and remove it. This has its flaws. For example, it will not work if the step out is used before the `rbp` is set or if some library completely bypasses the call instruction.

This concludes the implementation of a very basic assembly-level debugger for Linux on the x86-64 platform. The proof of concept implementation is provided as an extension to this thesis and can be found in the `linux-debugger/` folder. The implementation was partially inspired by [20] and [7]. It demonstrates the feasibility of building a very basic debugger with the `ptrace` API.

Hardware versus Software breakpoints

The presented implementation has used `software breakpoints`, which are implemented by modifications to the actual code. In section 2.1, we mentioned that the CPU also supports breakpoints. These are called *hardware breakpoints*. The difference between these two is mostly felt when conducting reverse engineering, which involves studying compiled programs in machine code because they do not have access to the source code of the programs, often in order to identify potential malicious activity. However, the programs may try to defend themselves from being debugged. Software breakpoints change the actual code, so a checksum of instruction opcodes can detect them. Hardware breakpoints, on the other hand, do not modify the code and are, therefore, more difficult to detect. Additionally, they can also be used to break on memory access, which is not possible with software breakpoints. However, only a limited amount of hardware breakpoints can be set, with only four available on the x86-64 architecture [10].

2.2.2 UNIX systems

There are other systems based on UNIX, however, the implementation is very similar to the Linux one. For example, MacOS, FreeBSD, and OpenBSD also have the `ptrace` system call. The call itself is a little different on each operating system, but it can be used to achieve the same functionality as on the Linux operating system.

2.2.3 Windows

The Microsoft Windows operating system also offers built-in support for debugging. It is provided at the Win32 API layer [21, 22]. It builds on *debug events* and *debug functions*. Unlike POSIX systems such as Linux, Windows uses a different approach for signaling abnormal conditions, such as breakpoint hits or just interrupts in general. We will explore this mechanism before getting to the debugging API.

Structured Exception Handling

Instead of signals, Windows uses *Structured Exceptions* (SEH) [23]. An exception is an event that requires the execution of code outside the normal flow of control. There are software exceptions, like throwing an exception explicitly or by the operating system, and hardware exceptions that are caused by the CPU (e.g., interrupts). SEH unifies both of these things into one, just like signals do.

When an exception is triggered, control is transferred to the system. It saves all necessary information that can later be used to continue execution from the point where the exception was thrown. It also contains information about which type of exception was thrown, if the execution can continue after handling the exception, the address where the exception occurred, and more[3]. The system then searches for an exception handler that will handle the exception. The search is performed in this order:

1. If the process is being debugged, the debugger is notified.
2. If the process is not debugged or the debugger does not handle the exception, the frame-based exception handler is to be found[4].
3. If no frame-based handler can be found, or no handler handles the exception, but the process is being debugged, then the debugger gets notified a second time.
4. The system provides a default handler, which often is the termination of the program via `ExitProcess`.

The debugger has two opportunities to handle the exception. The *first-chance* is before the exception gets to the debuggee. This is intended for exceptions for which the debugger is responsible, for example, breakpoint or single stepping. The debugger should handle these because it is responsible for them, while the debuggee is not. The second opportunity, called last-chance, is when a debuggee does not have an appropriate frame-based handler to handle the exception. If no debugger were attached, the system would have already used the default exception handler, which is often program termination. An example of an exception the debugger should not handle on first chance is `EXCEPTION_INT_DIVIDE_BY_ZERO`. It should pass it along to the debuggee. If the debuggee does not have any appropriate handler, the debugger will have a last chance to look at the program's state before it is killed [24].

Two important exception types for debugging, both of which should be handled on first-chance:

- `EXCEPTION_BREAKPOINT` - Raised when a breakpoint was encountered.
- `EXCEPTION_SINGLE_STEP` - Raised when a hardware-supported single step was completed.

Debugging Events and Functions

Now that we have explained how a breakpoint may be signaled, let us look at other tools that the Windows API gives us to allow debugger implementation. On Linux, we had a single function called `ptrace`. The behavior of this function changed based on its arguments. Windows, on the other hand, provides us with many functions, some of which are:

- `DebugActiveProcess` - Attaches the debugger to an active process.
- `DebugBreakProcess` - Causes a breakpoint exception to occur in the specified process. This passes control of the process to the debugger, if there is one.

[3]Refer to [23] for a full list.

[4]For detailed information about the handlers, see [23].

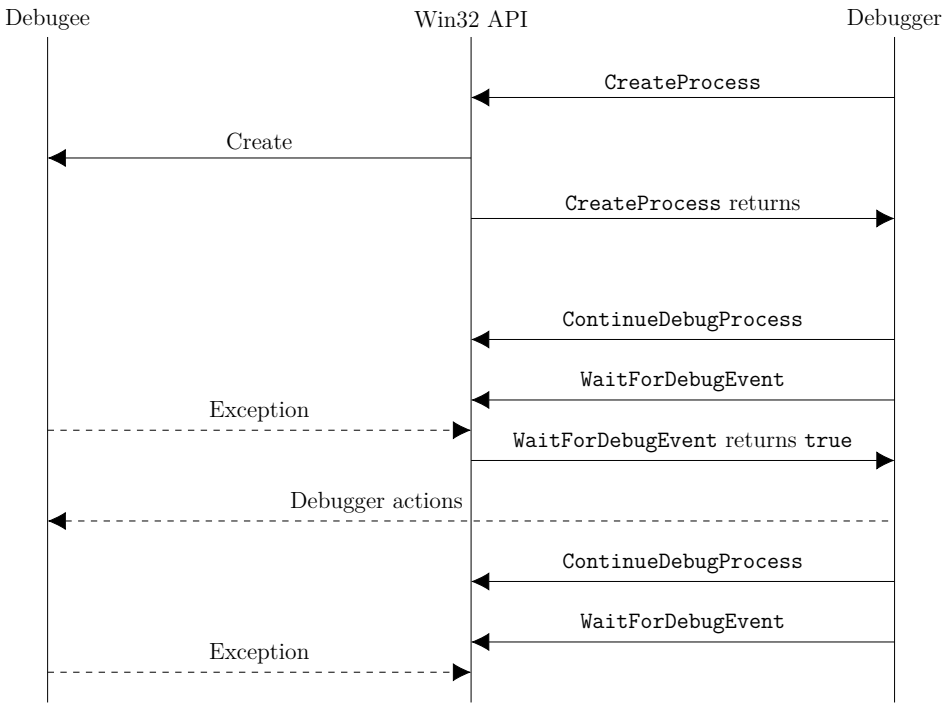


Figure 2.9 A diagram representing the communication between the debuggee, the Windows operating system, and the debugger [25].

- `WaitForDebugEvent` - Waits for new debugging events (on Linux, we used `waitpid`, which is more of a general-purpose function).
- `ContinueDebugEvent` - Continue the process execution after processing a debugging event (on Linux, we used the `PTRACE_CONT`).
- `OutputDebugString` - Sends a string from the debuggee to the debugger.
- `ReadProcessMemory` and `WriteProcessMemory` - Read and modify process virtual address space. On linux we used `PTRACE_PEEKTEXT` and `PTRACE_POKETEXT`.
- `FlushInstructionCache` - Flushes the instruction cache of the process. This should be used when modifying the process text section because the old instructions may still be cached.

The figure 2.9 depicts how a communication between the debugger, the Windows operating system, and the debuggee can look. The debugger waits for debug events via function `WaitForDebugEvent`. This function has a timeout parameter, so the debugger can also do other things while it is waiting, like GUI updates.

Debugging Events

Debugging events are various incidents in the debuggee that causes the system to notify the debugger [26]. These are stored in special `DEBUG_EVENT` structure, which is received in `WaitForDebugEvent` call initiated from the debugger. This structure contains various

```
typedef struct _DEBUG_EVENT {
  DWORD dwDebugEventCode;
  DWORD dwProcessId;
  DWORD dwThreadId;
  union {
    EXCEPTION_DEBUG_INFO      Exception;
    CREATE_THREAD_DEBUG_INFO  CreateThread;
    CREATE_PROCESS_DEBUG_INFO CreateProcessInfo;
    EXIT_THREAD_DEBUG_INFO    ExitThread;
    EXIT_PROCESS_DEBUG_INFO   ExitProcess;
    LOAD_DLL_DEBUG_INFO       LoadDll;
    UNLOAD_DLL_DEBUG_INFO     UnloadDll;
    OUTPUT_DEBUG_STRING_INFO  DebugString;
    RIP_INFO                  RipInfo;
  } u;
} DEBUG_EVENT, *LPDEBUG_EVENT;
```

Figure 2.10 A structure that contains information about a debugging event.

information about the event. The internals can be seen in figure 2.10. These events include loading and unloading a DLL, creating and exiting a process, sending debug strings via the `OutputDebugString`, and last but not least, exception occurrence. Exceptions include the `EXCEPTION_BREAKPOINT` and `EXCEPTION_SINGLESTEP` mentioned previously, which are vital to the debugger.

Tying it all together

Now we have all the necessary building blocks to create a tiny Windows debugger. The implementation itself would be very similar to the Linux one we presented in section 2.2.1. To provide at least some idea, figure 2.11 contains an abbreviated main loop of the debugger [27]. We need to handle all of the debugging events if we want the debugger to be robust. For example, thread creation should be handled so that we may trace all threads spawned by the debuggee.

2.3 Source Level Debugging

If we want to debug at the source code level, we must provide the debugger with additional information because otherwise, it can only work with the generated machine code. For instance, we somehow need to tell the debugger that the instruction at address *0xABCD* belongs to line `5` in the source code so that we may properly set a breakpoint at this line. We also need to provide information about where some variable is located so that we may display its value to the user. All this information is passed to the debugger together with the executable, whose format we will describe next.

```
void EnterDebugLoop(const LPDEBUG_EVENT DebugEv)
{
    DWORD dwContinueStatus = DBG_CONTINUE; // exception cont.
    for(;;)
    {
        WaitForDebugEvent(DebugEv, INFINITE);
        switch (DebugEv->dwDebugEventCode)
        {
            case EXCEPTION_ACCESS_VIOLATION:
                // First chance: Pass this on to the system.
                // Last chance: Display an appropriate error.
                break;

            case EXCEPTION_BREAKPOINT:
                // First chance: Display the current
                // instruction and register values.
                break;

              // Other exception types like singlestep ...
              ...
            }
            // Other debug events
            ...
       }
       ContinueDebugEvent(DebugEv->dwProcessId,
                          DebugEv->dwThreadId,
                          dwContinueStatus);
   }
}
```

Figure 2.11 An abbreviated example of a Windows Debugger loop, taken from [27].

2.3.1 Executable File Formats

ELF is one of the executable file formats. The abbreviation ELF means Executable and Linkable format. The file itself consists of sections, some of which are

- `.text` - the executable code.
- `.data` - allocated space and values of initialized static[5] variables and other objects.
- `.bss` - allocated space for uninitialized static variables.
- `.rodata` - data that do not change for the entirety of the program lifetime, like strings literals in the C language.
- various debug sections like `.debug_info`, `.debug_line` etc.

For inspecting the ELF files, commands `readelf` [28] and `objdump` [29] may be used on Linux systems. The ELF format also has a header, and all sections have their header too. This contains information like the name of the section, the size of the section, etc. The ELF format is not only used for executables but also for *relocatable* file, *executable* file, and *shared object* file [30]. The sections themselves are often protected. For example, the `.text` section can only be read and executed but cannot be written into. The `.data` section can be read and written to but cannot be executed. The ELF also contains various debug sections, so the debugging information is embedded in the executable itself.

ELF is not the only executable format. Others include the *COFF* and *PE* format, which are used by Microsoft Windows, or the *Mach-O*, which is used by the MacOS operating system. All of these formats use some kind of encoding for the debugging information. ELF and Mach-O use the DWARF encoding.

2.3.2 DWARF

DWARF [31] is a debugging information format used to describe programs written in procedural languages. It is primarily associated with the ELF file format. It aims to support all different types of information that may be needed while debugging. It also strives to encode this information in as much space efficient manner as possible [31]. This can make it somewhat complex.

There are five versions of the standard. We will mostly talk about version 2 since the others mainly add features to accommodate newer language features. The complete changelog can be found in the text describing DWARF version 5 [32]. We provide many examples of the information that DWARF encodes. For reading the DWARF information from object files, we used the `llvm-dwarfdump` [33], `objdump` [29], and `readelf` [28] tools to construct these examples. The information DWARF encodes is stored in various debug sections if used in conjunction with the ELF standard. The Mach-O format stores debugging information in a separate file. This file is still, however, split into several sections.

[5] In this context, static means that the variable exists for the entire lifetime of the program.

2.3.2.1 Line Number Information

Line number information needs to convey which line of code corresponds to an address of a machine code instruction. The DWARF standard [31] mentions that encoding this information would be possible in a matrix, with one row for each instruction. The columns of the matrix would contain

- the source file name,
- the source line number,
- the source column number,
- whether this instruction is the beginning of a source statement,
- whether this instruction is the beginning of a basic block[6].

They, however, argue that such a matrix would be very big. The matrix is therefore stripped of redundant information. For instance, an instruction whose row would be the same as the previous one is not saved into the matrix. This still was not enough. Instead of a matrix, they provide a virtual machine specification and a bytecode language that one has to interpret to reconstruct this matrix and, consequently, to get the necessary debugging information.

The virtual machine consists of following registers: `address`, `file`, `line`, `column`, `is_stmt`, `basic_block`, and `end_sequence`. The program itself begins with a prologue. This prologue contains the length of the program, version, length of the prologue, length of instructions (so that it may be better compressed), and similar pieces of information.

Then the *Standard opcodes* are provided, which are instructions for the virtual machine. These are mostly used for manipulating the registers of the machine or for creating a new row from the values in the registers and appending it to the matrix [31].

It also has several *Special opcodes*, each of which does all of the following operations:

- Add a signed integer to the `line` register.
- Multiply an unsigned integer by the smallest length of an instruction and add the result to the `address` register.
- Append a row to the matrix consisting of the current values in registers.
- Set the `basic_block` register to false.

All of these special opcodes always do these four operations. They only differ in what values they add to the `line` and `address` register [31]. Those values are calculated from the instruction opcode, which ranges from 10 to 255 in DWARF version 2. This is the most common series of operations the virtual machine must do. Encoding it into a single opcode makes the program extremely size efficient.

Observe the program in figure 2.12. A simple greeter-like program that displays the name given to it as an argument. With the `readelf` utility program, we can inspect the DWARF bytecode language describing the locations, which is shown in figure 2.13. The

[6] Basic block is a sequence of instructions that is entered only at the first instruction and exited only at the last instruction [31]. In other words, all of the instructions in the basic block are executed sequentially.

first few lines of the example are explained below. We ignore the set column operations, which are only used to make the location more precise.

- `0x41` - Jump to the beginning of the `main` function (i.e. `0x1139`).
- `0x4c` - Special opcode - Increment line by 1 and advance address by zero. Although the advance address was essentially a noop, it was still more space efficient to use special opcode because the `advance_pc` instruction DWARF offers would take up at least two bytes (the opcode and the operand), whereas the special opcode occupies only one.
- `0x4f` - Special opcode - Increment line by 2 to 3 and advance address by 15 to `0x1148`. This essentially skips the function prologue and advances to instruction `cmpl`, which represents line `if (argc < 2)` of the program.
- `0x52` - Special opcode - Increment line by 1 to 4 and advance address by 6 to `0x114e`. This is the `return 1;` line of the program.

Remember that each of the special opcodes also creates a line in the matrix. As said, this is extremely space efficient. DWARF stores this encoded information in the `.debug_line` section.

2.3.2.2 Debugging Information Entry

The *Debugging Information Entries*, or just entries, are the building blocks of debugging information in DWARF. Each entry has a tag and a series of attributes. The tag specifies the class to which an entry belongs, like `DW_TAG_subprogram`, which is used for functions, or `DW_TAG_variable`, which is used for variables. A complete list can be found in [31]. Those entries can be found in the `.debug_info` section [31].

The attributes themselves then convey some property of the entry, like the name and the type of a variable or starting and ending address of a function. The entries form a tree-like structure. Each entry is owned by one parent (excluding the top entry) and can own multiple entries. These relations somewhat mimic the relations of the program structures. For instance, a variable is owned by a function in which it was defined. There are also other relations among the entries, not only ownership. With those relations in place, the relation is a graph, not just a tree.

An example of DWARF entries can be seen in figure 2.14. The `DW_TAG_pointer_type` is simple. Its attributes are only the size of the type and which type it points to. This is encoded as an address to another entry. The type it points to is another entry. It only contains information that its a const type, and again has a link to another entry. Finally, the entry at `0x6b` has a base type. It contains the size of the type, name, and encoding.

We also have the `DW_TAG_SUBPROGRAM`, which represents a function. It has many attributes, like name, a path to the file where it was declared, on which line and column it is located, at which machine code address the function begins and ends, and so on. This entry also owns some other entries (indicated by indentation). Here, the children are the parameters and variables of the function. Important information about variables is where they are stored so that we may look up their value. We can also see that the variable `name` has an attribute type, which points to the entry at address `0x8f`, which is the entry we were talking about previously when examining types.

```c
#include <stdio.h>
int main(int argc, char* argv[]) {
    if (argc < 2)
        return 1;
    const char* name = argv[1];
    printf("Hello, %s!\n", name);
    return 0;
}
```

```
0000000000001139 <main>:
    1139:   55                      push   %rbp
    113a:   48 89 e5                mov    %rsp,%rbp
    113d:   48 83 ec 20             sub    $0x20,%rsp
    1141:   89 7d ec                mov    %edi,-0x14(%rbp)
    1144:   48 89 75 e0             mov    %rsi,-0x20(%rbp)
    1148:   83 7d ec 00             cmpl   $0x1,-0x14(%rbp)
    114c:   7f 07                   jg     1155 <main+0x1c>
    114e:   b8 01 00 00 00          mov    $0x1,%eax
    1153:   eb 2c                   jmp    1181 <main+0x48>
    1155:   48 8b 45 e0             mov    -0x20(%rbp),%rax
    1159:   48 8b 40 08             mov    0x8(%rax),%rax
    115d:   48 89 45 f8             mov    %rax,-0x8(%rbp)
    1161:   48 8b 45 f8             mov    -0x8(%rbp),%rax
    1165:   48 89 c6                mov    %rax,%rsi
    1168:   48 8d 05 95 0e 00 00    lea    0xe95(%rip),%rax
    116f:   48 89 c7                mov    %rax,%rdi
    1172:   b8 00 00 00 00          mov    $0x0,%eax
    1177:   e8 b4 fe ff ff          call   1030 <printf@plt>
    117c:   b8 00 00 00 00          mov    \$0x0,%eax
    1181:   c9                      leave
    1182:   c3                      ret
```

Figure 2.12 A program in the C programming language and the same program compiled into x86-64 assembly via the GCC compiler.

```
0x3f: Set column to 34
0x41: Extended opcode 2: set Address to 0x1139
0x4c: Special opcode 6: advance Address by 0 to 0x1139 and Line by 1 to 2
0x4d: Set column to 8
0x4f: Special opcode 216: advance Address by 15 to 0x1148 and Line by 1 to 3
0x50: Set column to 16
0x52: Special opcode 90: advance Address by 6 to 0x114e and Line by 1 to 4
0x53: Set column to 17
0x55: Special opcode 104: advance Address by 7 to 0x1155 and Line by 1 to 5
0x56: Set column to 5
0x58: Special opcode 174: advance Address by 12 to 0x1161 and Line by 1 to 6
0x59: Set column to 12
0x5b: Advance PC by constant 17 to 0x1172
0x5c: Special opcode 146: advance Address by 10 to 0x117c and Line by 1 to 7
0x5d: Set column to 1
0x5f: Special opcode 76: advance Address by 5 to 0x1181 and Line by 1 to 8
0x60: Advance PC by 2 to 0x1183
0x62: Extended opcode 1: End of Sequence
```

Figure 2.13 A DWARF description of mapping source lines to addresses for the program in figure 2.12.

2.3.2.3 Locations of Variables

Locations are one of the most complicated types of debugging information in the DWARF standard. Like with line mapping, described in section 2.3.2.1, a virtual machine is needed to decode this information. Variables are generally stored in one place. This can be a memory, register, or stack. Sometimes, however, the location of an object can change throughout its lifetime, it may not be present at all since it was optimized away, it can be split into several locations, or it might be a reference to some other object. The fact that an object changes location throughout its lifetime seldom happens [34], but DWARF is nevertheless prepared for it [31].

Contrary to the virtual machine described in the line encoding section, which was register-based, this one is stack-based. This means that most operations take their operands from the stack and push the result back onto the stack. More about stack-based virtual machines can be discovered in [35]. DWARF calls those instructions *expressions* [31]. The last value on the top of the stack after the VM runs is considered to be the resulting value (this can be an address of an object, the value of an array bound, the length of a dynamic string, and so on) [31].

For example, in the figure 2.12, there is the `DW_OP_fbreg -24`, this pushes value at offset -24 by the register specified by a descriptor in `DW_AT_frame_base`, which often is a base pointer to the stack. Since there are no more expressions, the computed value on the top of the stack is the resulting location of the variable that the debugger will get to use.

There are many types of expressions, like arithmetic operations, stack manipulation, control flow operations, and last but not least, the specifications of the location. We have already provided the example with the base pointer to the stack, let us look at some more examples, mostly taken from [31]:

- `DW_OP_reg3` - The value is in register 3.

```
0x6b: DW_TAG_base_type
        DW_AT_byte_size (0x01)
        DW_AT_encoding (DW_ATE_signed_char)
        DW_AT_name ("char")

0x72: DW_TAG_const_type
        DW_AT_type (0x0000006b "char")

0x8f: DW_TAG_pointer_type
        DW_AT_byte_size (8)
        DW_AT_type (0x00000072 "const char")

DW_TAG_subprogram
  DW_AT_external    (true)
  DW_AT_name        ("main")
  DW_AT_decl_file   ("/home/gregofi1/tmp/main.c")
  DW_AT_decl_line   (2)
  DW_AT_decl_column (0x05)
  DW_AT_prototyped  (true)
  DW_AT_type        (0x00000058 "int")
  DW_AT_low_pc      (0x0000000000001139)
  DW_AT_high_pc     (0x0000000000001183)
  DW_AT_frame_base  (DW_OP_call_frame_cfa)
  DW_AT_call_all_tail_calls (true)
  DW_AT_sibling     (0x000000e0)

    DW_TAG_formal_parameter
      DW_AT_name        ("argc")
      DW_AT_decl_file   ("/home/gregofi1/tmp/main.c")
      DW_AT_decl_line   (2)
      DW_AT_decl_column (0x0e)
      DW_AT_type        (0x00000058 "int")
      DW_AT_location    (DW_OP_fbreg -36)

    DW_TAG_formal_parameter
      DW_AT_name        ("argv")
      ...

    DW_TAG_variable
      DW_AT_name        ("name")
      DW_AT_decl_file   ("/home/gregofi1/tmp/main.c")
      DW_AT_decl_line   (5)
      DW_AT_decl_column (0x11)
      DW_AT_type        (0x0000008f "const char *")
      DW_AT_location    (DW_OP_fbreg -24)
```

Figure 2.14 A part of DWARF debugging information entries for the program in figure 2.12. The indentation of the entries shows a hierarchy.

- `DW_OP_addr 0xABCD` - The value of a static variable is at address `0xABCD`.
- `DW_OP_bregx 54 3; DW_OP_deref` - Adds 54 to value in register 3. This should yield an address. The value at the location to which the yielded address points is then pushed onto the stack. This can be used for recording information about references and pointers.
- `DW_OP_reg3; DW_OP_dup; DW_OP_add` - Fetches value from register 3 and pushes it onto the stack. This value is then copied and the copy is pushed onto the stack. Finally, it pops two values from the stack, adds them together, and pushes them back onto the stack[7].

With this computational power, we can save any information we need. There are many more expressions, all of which can be found in [31]. An example of an interpreter for this can be found in the LLDB source code [36].

2.3.2.4 Call frames

Debuggers often need to know through which function calls the executed program went to arrive at a certain state [31]. For each function call, there is a *stack frame* saved on the stack. A Stack frame is a part of the stack memory that contains information relevant to the function invocation. An example of a stack frame can be seen in figure 2.15.

Return address (8B)	BP backup (8B)	Potential backup of other registers	Allocated space for variables

Figure 2.15 Basic stack layout after function prologue, disproportional.

Stack frames mostly consist of the following:

- Return address - This contains the location from which the program was called so that after the function finishes, it may properly return to that location. This fact was also used in our step-out implementation described in section 2.2.1.
- Base pointer backup - Backup of the value in the base pointer, which was set by the previous function. This register needs to be preserved between calls, which is why a backup is made. Other registers might need to be saved for the same reason.
- Allocated space for variables - A space for local variables.

Stack frames are described in more detail in [3], where they are called activation records. We also provide an example of how a function prologue and epilogue look in figure 2.16, so that one may get a better feel about how such a stack frame comes to fruition.

Debuggers need to do a so-called stack unwinding. Unwinding essentially means going to a state where the previous stack frame is the most recent. This needs to be done several times to get the whole chain of function calls which led to the current state of the program. We can get the last stack frame by looking at the current value of the base pointer. But to get to the penultimate one is not as easy. We need to know exactly where

[7] Artificial example just to show the power of the language.

```
0000000000001183 <foo>:
0x1183: push   rbp          ; Save old stack frame pointer
0x1184: mov    rbp, rsp
0x1187: sub    rsp, 0x18    ; Allocate space on the stack
        <body ...>
0x11b1: leave                ; deallocate and restore regs
0x11b2: ret
```

Figure 2.16 A prologue and epilogue of a function, shown in assembly.

was the backup of the base pointer stored so that we may simulate the unwinds [31]. We might also need the values of other registers at various points throughout the program.

DWARF proposes a table. In each row, there is an address of a location in the program, a location of a stack frame, and values of other registers for that location. However, such a table would be very large, so DWARF again uses a virtual machine for the construction of the table, since many columns in one row would have the same values in the following rows [31]. The location of a stack frame can be described either by a register and a signed offset which are added together, or a DWARF expression may be used (the ones used to describe variable locations).

Figure 2.17 contains an example of the encoding of this information and also the decoded values for the program in figure 2.16. The `advance_location` adds a new row to the matrix, with the only thing changing from the previous row being the location value. The `def_cfa_offset` specifies that the CFA (current stack frame) is at the provided offset from the same register it was offseted in the previous row. We can see that in the example on line 2, the offset changes from 8 to 16, but the register stays the same. This is apparent in the decoded information where on the address `0x1184`, the `CFA` changed from `RSP + 8` to `RSP + 16`. This happened because the `push rbp` advanced the stack pointer by eight bytes.

On the contrary, the `def_cfa_register` changes the register but keeps the offset. This happens when the instruction `mov rbp, rsp` is executed. From that point, the stack frame is at sixteen byte offset from the base pointer. This holds until the epilogue, where the old stack pointer is restored. In the example in the decoded information, many more registers are missing. This is because their value did not change across the function, so there was no need to save information about them.

DWARF offers more instructions for manipulation, for a complete overview and another example consult [31]. With this information, DWARF can describe a way to simulate a stack unwinding without touching the state of the debuggee.

2.3.2.5 Other Debugging Information

The DWARF standard has information about compilation units since object files may be derived from multiple compilations units [31]. It also has information about subroutines and inlined subroutines, lexical blocks, try-and-catch blocks, and many other constructs. These are not special in any way. We have seen a small example in figure 2.14. They mainly store the beginning and end and some other information. They also contain various information about macros so that the debugger can work with the original code before the macro expansion.

```
... FDE cie=00000000 pc=00001183...000011b3
DW_CFA_advance_loc: 1
DW_CFA_def_cfa_offset: +16
DW_CFA_offset: RBP -16
DW_CFA_advance_loc: 3
DW_CFA_def_cfa_register: RBP
DW_CFA_advance_loc: 43
DW_CFA_def_cfa: RSP +8

0x1183: CFA=RSP+8: RIP=[CFA-8]
0x1184: CFA=RSP+16: RBP=[CFA-16], RIP=[CFA-8]
0x1187: CFA=RBP+16: RBP=[CFA-16], RIP=[CFA-8]
0x11b2: CFA=RSP+8: RBP=[CFA-16], RIP=[CFA-8]
```

Figure 2.17 A DWARF stack frame information about the program in 2.16. Top part contains the encoded program for virtual machine, bottom part contains the decoded table from interpreting the program. Abbreviated.

It also contains many type entries. Those are split into different categories. We present some of the most common:

- Base types - Provided by the language, like `int`, `char`.
- Modifier types - Modifies some existing type, like type qualifiers from C (`const`, `volatile` and `mutable`), or pointers.
- Array types - A sequential storage space containing objects of the same type. Multidimensional arrays are considered a special type. An interesting attribute that a multidimensional array has is ordering - either column-wise or row-wise. This is not relevant to C, since it has no notion of a multidimensional array.
- Structure, Union, and Class types - User-defined types that pack together several different types. Information is provided about the members, especially the bit offset at which they reside in the structure and in which order they were declared. In addition, the size of the type is specified - if it can be determined at compile time (In C, it cannot be determined for forward declarations). For C++, information about inheritance, like deriving, accessibility, and if the inheritance is virtual, is provided.
- Enumeration type.
- Subroutine type - Used for types of functions in C. However, for the functions themselves, their type is specified as return type. Types of their parameters are specified in the parameters themselves since they are DIEs and are children of the function. We showed this in figure 2.14. This subroutine type is, for example, used if one creates a pointer to a function. Then the type of that is a pointer to the subroutine type. An abbreviated example can be seen on 2.18.

We have described the most interesting parts of the DWARF standard. But all this information must be created by a compiler so that the program may be debugged at the source level. In the next section, we will briefly explore compilers and how they handle debugging information.

```
0x138:   DW_TAG_subroutine_type
            DW_AT_type  (0x00000131 "int")
            DW_AT_sibling   (0x14c)

0x141:     DW_TAG_formal_parameter
              DW_AT_type    (0x131 "int")

0x146:     DW_TAG_formal_parameter
              DW_AT_type    (0x14c "double")

0x153:   DW_TAG_pointer_type
            DW_AT_byte_size (8)
            DW_AT_type  (0x138 "int (int, double)")

0x124:   DW_TAG_variable
            DW_AT_name  ("xx")
            DW_AT_type  (0x153 "int (*)(int, double)")
            ...
```

Figure 2.18 Example of a subroutine type and a pointer to function type in DWARF, abbreviated.

2.4 Compilers

A compiler is a program that transforms the source code into some other form, most often into machine code or assembly. Compilers are very complicated pieces of software. Often, they are made of several parts, the general structure can be seen in figure 2.19. We will briefly explore these stages.

It all starts with the *lexical analysis*, which groups separate symbols into groups called tokens. For example the code

```
foo = bar(1 + 2);
```

might be translated into tokens like this

```
<id:"foo"> <assignment-operator> <id:"bar">
<left-bracket> <int-number:1> <plus-operator>
<int-number:2> <right-bracket> <semicolon>
```

The *Syntactic analysis* then works with these tokens and transforms them into some other representation. This is most often an abstract syntax tree (abbr. AST, figure 2.20). It also checks that the source code complies with the language's grammar. With AST, we already lose the locations of the language constructs in the source code, so for debugging information to work, it needs to be kept in the AST together with the nodes.

The *Semantic analysis* then checks that the program is semantically consistent. For example, that used variable has been declared before. Additionally, it gathers type information and saves it for later use during the IR generation [3].

After that, intermediate code generation comes into play. It converts the AST into some other representation, most commonly called IR, which means intermediate representation. IR should be closer to the machine code to be easily translated but is still machine independent. It also should retain some high-level properties that make it easier

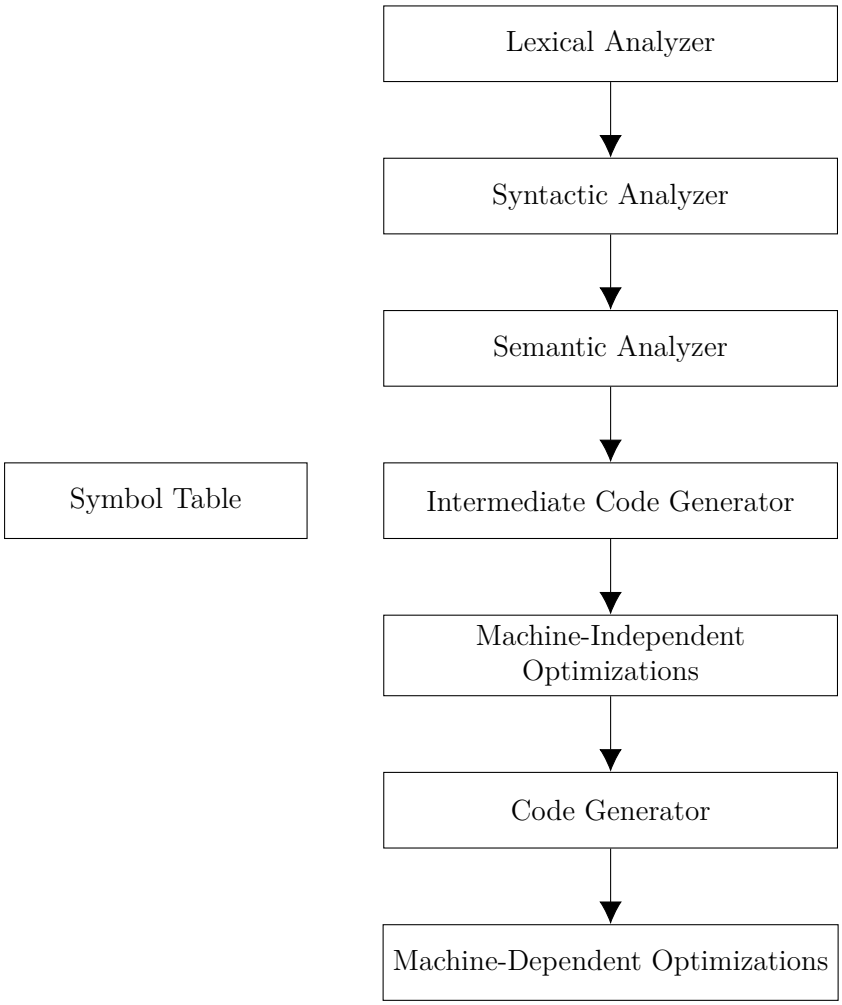


Figure 2.19 Simplified structure of a compiler [3].

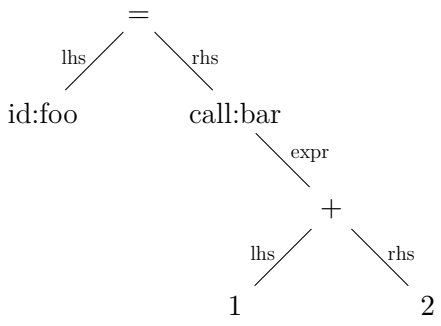


Figure 2.20 Simplified example of an abstract syntax tree.

```
define dso_local i32 @_Z6squarei(i32 %0) {
  %2 = alloca i32, align 4
  store i32 %0, i32* %2, align 4
  %3 = load i32, i32* %2, align 4
  %4 = load i32, i32* %2, align 4
  %5 = mul nsw i32 %3, %4
  ret i32 %5
}
```

Figure 2.21 Simplified example of LLVM IR, showing a function that calculates a square of two numbers.

to work with, like types and functions, but should be language-independent. There are many types of IR. One of the most popular compilers, LLVM, uses single static assignment (SSA) and satisfies all of the above [37]. An example of LLVM IR can be found in figure 2.21. Compilers perform most optimizations on this intermediate representation.

Finally, IR is translated directly to the target machine code or possibly assembly. This stage is called *code generation*. Even though IR can seem very similar to assembly, there are still some things to take care of. For example, SSA IR does not have registers. It uses an unlimited number of variables. Other architectures might have some other traits that differentiate them from the IR, and they all have to be accounted for when generating code.

2.4.1 Modular Design

The main advantage of using an IR is that there is a common ground for every language. Imagine we write a compiler for the C language. We need to write all five parts from figure 2.19. If we later decided that we also wanted to create a compiler for Haskell, we just need to write everything up to the IR translation. Once we can translate Haskell into the IR, we can reuse the previous part of the compiler to compile to machine code. This also works the other way around. If we compile IR to the machine code that works with the x86-64 architecture and we want to compile to ARM, we need to create the code generation part for the ARM architecture. There is no need to write the whole compiler. Also, most optimizations are done on the IR level, saving a lot of development time. The parts of the compiler which are dependent on the source language are called **frontend** (Syntax, Semantic, and IR translation), and the parts that are dependent on the target are called **backend** (Code generation).

This is widely used in practice. The LLVM [37] project is a compiler backend. It uses its own IR (as was mentioned in figure 2.21). It can compile this IR into many targets, including x86-64, ARM, and Spark. The *Clang* project is a compiler frontend for C, C++, and Objective-C languages. It translates these languages to the LLVM IR. Other frontends for LLVM also include *ghc*, which is a Haskell compiler, or *rustc*, which is a Rust compiler. With LLVM, creating a new programming language comes down to just writing the front end.

2.4.2 Preserving Debugging Information

With IR translation, some of the information from the AST is stripped away. The IR must encode how some of the properties of the AST map onto the IR. We will give a glimpse of how LLVM IR handles this.

Since the LLVM IR is transformed into many existing architectures and many very different existing programming languages are compiled into it, LLVM debug information does not put any restrictions on the flavor of the programming language. A high priority of the LLVM debugging information (LDI) is to make it interact well with optimizations [38]. The LDI guarantees the following:

1. LDI always provides information to accurately **read** the source-level state of the program regardless of which LLVM optimizations have been run [38]. Emphasis has been put on the word read, because it is not always possible to, for example, change the value of a variable because it might have been completely optimized away.

2. LDI does not prevent optimizations from happening.

3. LLVM optimizations may be upgraded to be aware of debugging information. This is sometimes necessary, especially if the optimizations are aggressive [38]. LLVM provides a guide for developers of optimization passes specifying how to handle certain situations [39]. For example, an accurate stack trace is desired even though inlining or tail call optimization was applied [38].

4. The LDI is optimized with the rest of the program (e.g., unused information is removed).

If one compiles the code with optimizations and with debugging information, the same optimizations must be applied that would be applied if no debugging information was generated (running `clang -O3 -g` and `clang -O3` must result in the same optimizations applied). The code must also be debuggable with optimizations enabled and provide correct information. For example, suppose a variable is completely optimized out. In that case, the debugger may present the message `optimized out`, which reduces the amount of debugging information available to the developer. However, the information is still correct and not misleading. Displaying an invalid value must not happen, even with optimizations [38].

In figure 2.22, we provide an example of LLVM IR with debugging information. It is encoded in the form of metadata, starting with an exclamation mark. LLVM IR also contains intrinsic functions to record debug information pertaining to variables. The function from the example `llvm.dbg.declare` receives the address of the variable, the description of the variable, and its location in the form of a complex expression. Complex expressions are similar to the DWARF expressions used for locations described in section 2.3.2.3. There is also the `llvm.dbg.address`, which has the same role but can be used multiple times for one variable. This is primarily used after optimizations to describe how a variable's address changes throughout the program.

The debugging information in the figure is otherwise mostly self-explanatory. The variables and locations also have their scope included because LLVM IR does not have any notion of scoping. Finally, LLVM provides *consumers*, which are able to transform the LLVM IR debugging information into some other format, like DWARF.

There are some more nuances that need to be dealt with, especially considering operations like instruction scheduling and register selection. This is beyond the scope of this thesis and is described in [38].

2.5 Existing Debuggers

In this section, we will focus on existing debugger implementations and what each brings to the table. We will not be discussing every feature of said debuggers since even some of the manuals are longer than this thesis[8], but point out the ones that were interesting to this thesis. Each debugger discussed here implements, at the very least, breakpoints, single-stepping, reading and writing into program memory and registers.

2.5.1 LLDB

The LLDB [7] debugger is part of the LLVM tools collection [37]. We will describe it more thoroughly than the other ones, mainly because it is a modern piece of software compared to the GDB debugger, and we are most familiar with it. Supported languages for debugging are the C, Objective-C, and C++ languages (LLVM tools support mainly those three languages) on desktop and iOS devices. It works closely with the Clang compiler, which is also part of LLVM, and the LLVM disassembler. Thanks to this, it stays very up-to-date with current C++ standards. The source code is kept modular with a plug-in architecture. It is both a source and instruction-level debugger.

LLDB offers a C++ API through which one can interact with the debugger. For instance, the command line application through which one can utilize the debugger uses this API. The API also offers a bridging interface for Python. Thanks to this, one can use LLDB not only as a debugger but also, for example, as a library to disassemble machine code [7].

LLDB provides a command line interface (CLI) through which one can use the debugger directly. The CLI provides a variety of commands that one can use. Some examples include

- `process launch` - Starts the debuggee.
- `process attach --pid 123` - Attaches to the process with PID 123.
- `thread step-in` - Source level single step in currently selected thread.
- `thread step-inst` - Instruction level single step in currently selected thread.
- `thread until 12` - Run until line 12 is hit or the current function returns in currently selected thread.
- `breakpoint set --name foo` - Set breakpoint on all functions named `foo`.
- `breakpoint enable 1` - Enable breakpoint 1.
- `watchpoint set variable x` - Watch a variable `x` for any writes.

All commands are of the following structure:

[8] Most notably the GDB manual [40].

```
define dso_local i32 @main() #0 !dbg !10 {
  %1 = alloca i32, align 4
  %2 = alloca i32, align 4
  %3 = alloca i32, align 4
  store i32 0, ptr %1, align 4
  call void @llvm.dbg.declare(metadata ptr %2,
        metadata !15, metadata !DIExpression()), !dbg !16
  store i32 2, ptr %2, align 4, !dbg !16
  call void @llvm.dbg.declare(metadata ptr %3,
        metadata !17, metadata !DIExpression()), !dbg !19
  store i32 1, ptr %3, align 4, !dbg !19
  %4 = load i32, ptr %2, align 4, !dbg !20
  %5 = load i32, ptr %3, align 4, !dbg !21
  %6 = add nsw i32 %4, %5, !dbg !22
  ret i32 %6, !dbg !23
}

declare void @llvm.dbg.declare(metadata, metadata, metadata) #1

!0 = distinct !DICompileUnit(language: DW_LANG_C99,
        file: !1, producer: "clang version 15.0.7",
        isOptimized: false, runtimeVersion: 0,
        emissionKind: FullDebug, splitDebugInlining: false,
        nameTableKind: None)
!1 = !DIFile(filename: "main.c", directory: "/home/gregofi1/dev",
        checksumkind: CSK_MD5,
        checksum: "408b866a5672c0f12dbc2c9bf3baaa58")
!2 = !{i32 7, !"Dwarf Version", i32 5}
!3 = !{i32 2, !"Debug Info Version", i32 3}
!10 = distinct !DISubprogram(name: "main", scope: !1,
        file: !1, line: 1, type: !11,
        scopeLine: 1, spFlags: DISPFlagDefinition,
        unit: !0, retainedNodes: !14)
!11 = !DISubroutineType(types: !12)
!13 = !DIBasicType(name: "int", size: 32, encoding: DW_ATE_signed)
!15 = !DILocalVariable(name: "x", scope: !10, file: !1, line: 2, type: !13)
!16 = !DILocation(line: 2, column: 9, scope: !10)
!17 = !DILocalVariable(name: "y", scope: !18, file: !1, line: 4, type: !13)
!18 = distinct !DILexicalBlock(scope: !10, file: !1, line: 3, column: 5)
!19 = !DILocation(line: 4, column: 13, scope: !18)
!20 = !DILocation(line: 5, column: 16, scope: !18)
!21 = !DILocation(line: 5, column: 20, scope: !18)
!22 = !DILocation(line: 5, column: 18, scope: !18)
!23 = !DILocation(line: 5, column: 9, scope: !18)
```

Figure 2.22 An example of LLVM IR with debugging information. The lines beginning with exclamation mark are metadatas.

```
<noun> <verb> [-options [option-value]] [argument [argument...]]
```

Some of the commands have shorter forms, like `step` for `thread step-in`. Using an unambiguous prefix works as well, like `br s -M foo` for `breakpoint set --name foo`.

The debugger also has an expression parser. While debugging, one can write an expression, and the debugger interprets that expression and prints the result back. An example of usage can be to look at some value in an `std::map` structure, which can be achieved by using the `frame variable map_var["Value"]` command. The debugger uses Clang, the C++ compiler, for parsing expressions. This can be used in conjunction with backticks in commands. For example, the `register write rax` `` `loc` `` command will write the value of variable `loc` into the register `rax`.

2.5.2 GDB

The GNU Project Debugger (GDB) [40] is a source and instruction-level debugger. It is very similar to the LLDB debugger. It, however, supports more languages, like C, C++, D, Fortran, Go, Objective-C, Pascal, Rust, and some others. GDB is written in C/C++. Like LLDB, it offers a CLI application and also has an API for Python. It is one of the oldest debugging software and, from our experience, the most reliable one on the Linux systems.

An interesting feature GDB offers is *reverse debugging*. This allows us to go back in the execution flow. For example, the command *reverse-next* returns to the previous line. A command to record executed instructions must be explicitly invoked. GDB then sets the state of the program depending on the record. It still is not fully supported, and from our limited testing, cannot handle even some basic statements, like the usage of `printf` function in a program written in the C language.

2.5.3 IDA Free

The primary role of IDA is to be an interactive disassembler, but it also offers some instruction-level debugging capabilities. It is a tool that is mainly used for reverse engineering. An example of interactivity is that it is possible to rename a location like `[RBP + 4]` to `counter` to make the assembly more readable. It can also follow references (like jumps or calls), create a control flow graph from the assembly, and much more. We show an example of an iterative factorial function disassembled via IDA in figure 2.23. In the figure, the variable locations were renamed to represent their semantic meaning. This has to be done by hand. IDA itself can sometimes know that a variable is stored in some location but it does not know its semantic meaning. IDA is an invaluable asset in reverse engineer's toolkit for static analysis.

2.5.4 Microsoft Visual Studio Debugger

Microsoft Visual Studio is an Integrated Development Environment. It packs together many tools that help develop programs for the Windows Operating System. It mainly supports the C# and C++ languages. It also has a built-in debugger. It is both a source and assembly-level debugger.

In figure 2.24, we show an example of how the GUI looks. On the left side, we can see the program's source code. The red points are the breakpoints. The arrow signalizes the

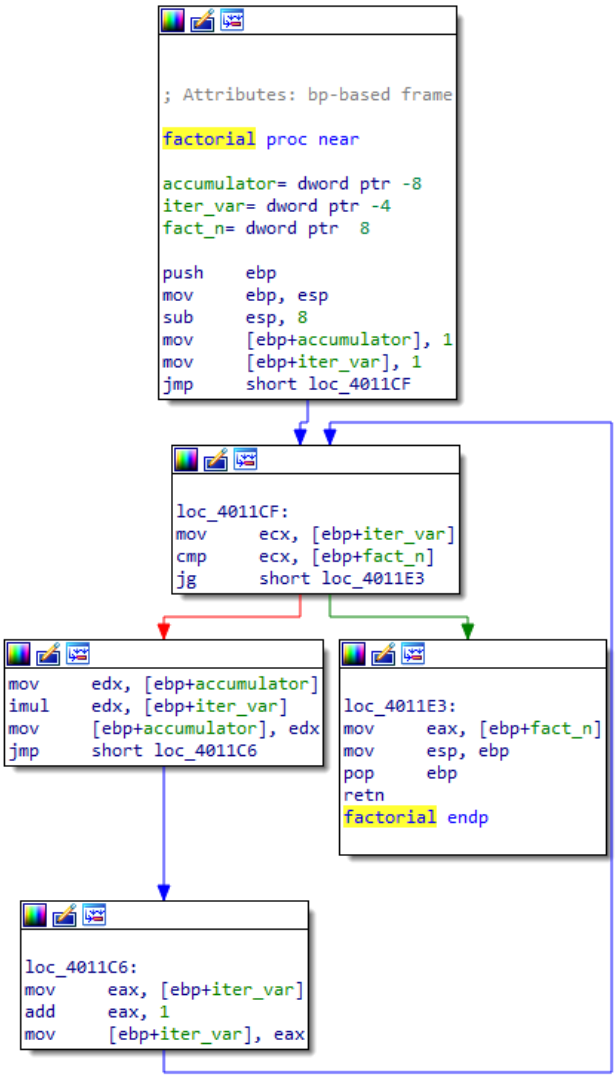


Figure 2.23 An example of a factorial program disassembled with IDA.

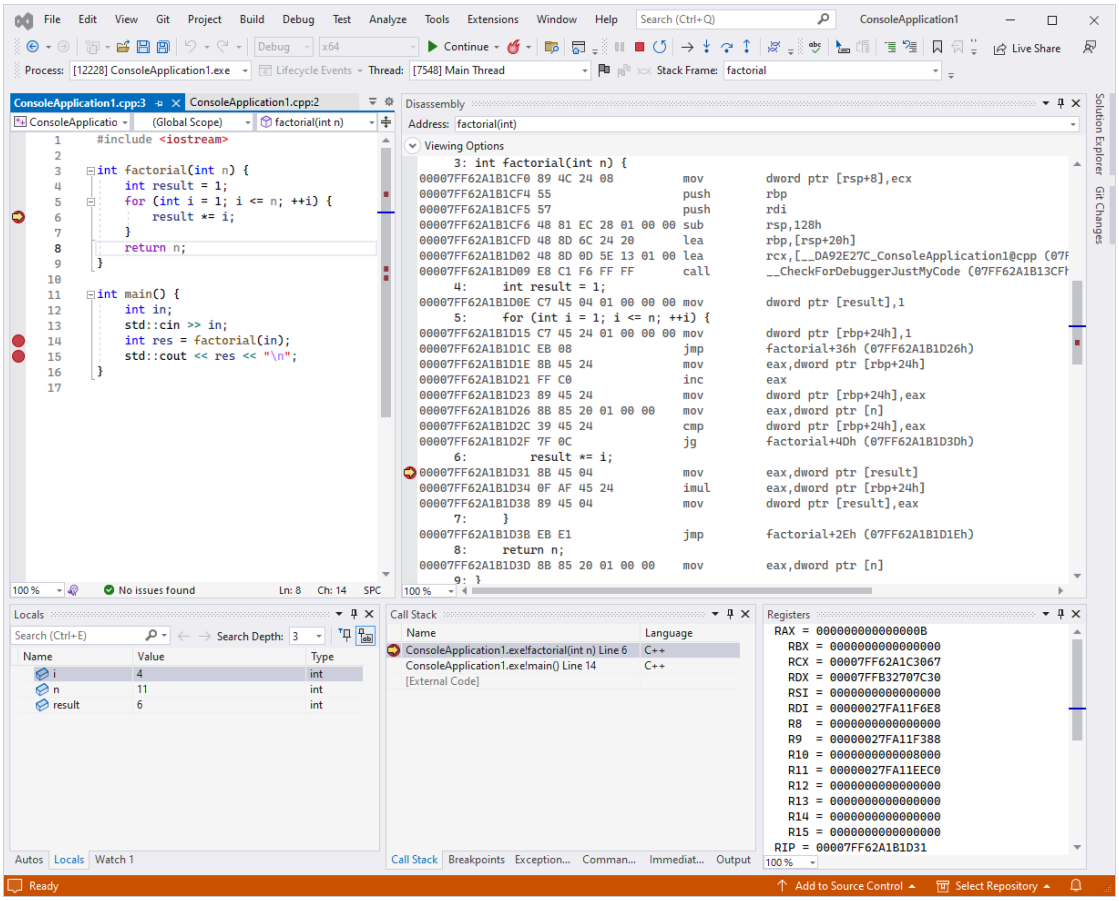


Figure 2.24 An example of debugging factorial program with MSVC debugger.

current point in the execution. On the right side, we can see the corresponding assembly. The assembly contains the lines from the source code to make the mapping between them more apparent. The value and type of every variable in the scope are displayed on the bottom left. A call stack is shown in the middle, currently only having main and factorial calls and locations from where those calls happened. On the right side, values in registers can be seen. This is only a basic overview of the features, as there are many more [41].

Chapter 3
Tiny x86

At the FIT CTU, in the NI-GEN course, students have to write a compiler. The Tiny x86 (T86) architecture was created to make code generation easier. This allows the students to focus on more interesting parts of compiler design, such as optimizations. To be able to execute programs written using this architecture, a virtual machine was created. This was all done as a part of a master's thesis made by Ivo Strejc [42]. This chapter explores said architecture and the virtual machine. It also delves into the existing debugging capabilities of said virtual machine.

3.1 The T86 Instruction Set Architecture

The primary goal of the T86 architecture is to be an educational one. The Virtual Machine made for the ISA allows configuring the number of registers, the RAM size, or the length of each instruction. This allows the students to develop their compilers incrementally.

The T86 uses a Harvard architecture, meaning the data and instructions are physically separated. Memory is addressable by 64-bit blocks, not by 8-bit blocks, as is the custom in modern computers. It shares some of the registers we saw on x86-64: the program counter (IP), the stack pointer (SP), the base pointer (BP), and the flags register. The intended roles for these registers are the same as on x86-64 architecture. It also has other general-purpose registers. As previously said, the amount of these is configurable. The registers stores 64-bit values. It also has float registers, which can store 64-bit float values. These are separated from the standard registers, similarly to x86-64.

The addressing modes, or what kind of operands instructions can have, include immediate values, registers, and memory accesses. They can also be combined in various ways, like `[R0 + R1 * 2]`, or `[R0 + 10 + R1 * 2]`. The addressing modes are, however, not arbitrary, `[R0 + R1 + R2]` is not a correct addressing mode for any instruction in the T86 architecture. The allowed addressing modes also change for each instruction. For example, the `MOV` instruction allows a vast range of addressing modes, while the `PUSH` instruction only allows a register and an immediate number. For a full list, refer to [42]. The instructions that are taken over from x86-64 often have more restrictive addressing modes than in x86-64. For example, the `add` instruction can take a memory offset as a destination operand in x86-64, but in T86, it can only take registers.

Other than that, the ISA is mainly a subset of the x86-64 most used instructions,

```
MOV  R0, 1
MOV  R1, 50
ADD  R0, R1
MUL  R0, 5
HALT
```

Figure 3.1 A small example of a program in the T86 architecture.

many of which we have already seen in various examples throughout the thesis. Interesting exceptions are the IO instructions - `PUTCHAR` and `GETCHAR`, which allow for very primitive input and output handling. Also, a `DBG` and `BREAK` instructions are defined. These are used for debugging, but in a very different way than we have seen in previous sections. We will touch upon them when discussing the virtual machine implementation since they are very much tied to it. A small sample of a T86 program can be seen in figure 3.1.

3.2 T86 Virtual Machine

The primary objective of the virtual machine is to replicate the CPU as accurately as possible without prioritizing execution speed. For instance, the virtual machine simulates the out-of-order technique briefly described in section 2.1.2. The purpose of the virtual machine is to allow the students to gain a deeper understanding of the effects of pipeline stalls and similar events on program speed. The virtual machine is able to generate statistics that provide information about these factors and how much they influenced the speed of the generated program.

The virtual machine (VM) is implemented in C++, using the newer standards up to C++17. The VM offers only a single interface, and that is the `ProgramBuilder`. This is a class through which one may construct a program for the T86 VM. An example of how to use this class is in figure 3.2. Currently, there is no other way for users to run programs in the VM. This means that the students are tied to the C++ language, or use some bindings if they want to use another language.

The `Cpu` class is the backbone of the interpreter. It is responsible for running the program. It has a `halted` function, which returns true if the `Cpu` executed a `HALT` instruction. The `tick` performs one tick of the CPU. This does not mean that one instruction gets executed. The `Cpu` simulates a superscalar CPU, so one tick is one move in the pipeline. The `while` loop in the figure 3.2 shows to run a T86 program via the `Cpu` class.

3.2.0.1 Debug Instructions

The VM offers some limited debugging capabilities. It has the `DBG` and `BRK` instructions. The `DBG` instruction takes as an operand a function. The function has the following signature: `void fun(Cpu&)`. This function then gets executed when the instruction is hit. This can prove helpful in inspecting the internal state of the CPU. In figure 3.3, we show a possible usage of this instruction. The `BRK` instruction works similarly. It, however, has no operand. Instead, a function must be provided before execution to the CPU itself. `BRK` then always runs this function when hit.

Such debugging capabilities can be helpful but quickly prove insufficient. For example,

```
ProgramBuilder pb;
pb.add(MOV{Reg(0), 50);
pb.add(PUTCHAR{Reg(0)});
pb.add(HALT{});
auto program = pb.program();
Cpu cpu;
cpu.start(std::move(program));
while (!cpu.halted()) {
    cpu.tick();
}
```

Figure 3.2 Simple example of how to create and run a simple program using the T86 virtual machine.

```
pb.add(DBG{[](Cpu& cpu) {
    if (cpu.getRegister(Reg{0}) == 0) {
        std::cerr << "Register 0 is set to zero!\n";
    }
});
```

Figure 3.3 Adding a `DBG` instruction into the T86 program using the `ProgramBuilder`.

when a step-by-step inspection is sought, a debug instruction must be placed at every second line of the program. Also, interactivity is not present. However, this function can accept input, so one could create a robust enough to handle register and memory writing. An idea of how this could be done is illustrated in 3.4 via the `BRK` instruction.

This still leaves much to be desired. Not to mention placing the debug instruction can prove very bothersome.

```
cpu.connectBreakHandler([](Cpu& cpu) {
    char command;
    std::cin >> command;
    if (command == 'c') return; // continue
    else if (command == 'r') { // Read register
        int num;
        std::cin >> num;
        int regval = cpu.getRegister(num);
        std::cerr << std::format("Register {} = {}\n",
                                 num, regval);
    } else if (command == 'w') { // Write register
        int num;
        int val;
        std::cin >> num >> val;
        cpu.setRegister(Reg{num}, Reg{val});
    }
    ... // Other commands
});
```

Figure 3.4 Small debugger implementation using T86 `BRK` instruction, abbreviated.

Chapter 4
Implementation

In this chapter, we describe how we went about the implementation of the debugger and reason about the design choices we made. Also, we describe which parts of the virtual machine were modified or added to allow the implementation of the debugger.

4.1 T86 ISA Extensions

In chapter 3.2, we showed how to build a program for the T86 VM with the existing builder interface. To allow the usage of other programming languages, we have created an ELF-like format for the T86 executables. The format is a text one, making it easy to use. An example of a program in said format is shown in figure 4.1. It is very similar to the assembly we have shown in previous sections. Thanks to this, students can implement their compiler in any programming language they want and emit the T86 program in this format as a text file. An unfortunate side effect is that we can no longer use the `DBG` instruction. However, the debugger we will later present will be much more powerful than the said instruction.

As can be apparent from the example, we also use sections. The `.text` section is the only mandatory one. It contains the instructions that will be executed. Another one is the `.data` section. Here, either raw numbers or strings can be written. The contents of this section are then loaded by the VM and stored into the memory, beginning at memory cell 0 and upwards. There are also debug sections, which we will present when discussing debugging information.

We will also add two new instructions. First is the `PUTNUM` instruction, which prints the numerical value in the register and a newline. This is intended as a very primitive debug instruction and to ease the automated testing of the compiler. The only other way of output was to print a char which was represented by the ASCII value. With this instruction, students can bootstrap and test the basic implementation of their compiler more easily.

Another one is the `BKPT` instruction. This instruction is similar to the `INT3` instruction from x86-64 or the `BKPT` instruction from ARM. It is a software breakpoint. The virtual machine has no support for interrupts, which are needed for debugging to work. This will be the focus of the next section.

```
.data
"Hello, World!\n"

.text
0   MOV [BP - 1], 0
1   JMP 8
2   MOV R0, [BP - 1]
3   MOV R1, [R0]
4   PUTCHAR R1
5   MOV R0, [BP - 1]
6   ADD R0, 1
7   MOV [BP - 1], R0
8   MOV R0, [BP - 1]
9   CMP R0, 13
10  JLE 2
11  HALT
```

Figure 4.1 Example of an T86 program which prints "Hello, World!".

4.2 T86 Debugging Support

We could bake the debugger into the virtual machine itself, which would likely be the simplest way to implement it. However, the goal of the debugger is not only to ease the code generation part but to be a learning point so that students might grasp how a real debugger works[1]. Because of this, we aim to simulate the real-world debuggers as closely as possible. The compilers may also have more targets in the future, not just the T86 VM. If we made the debugger part of the T86 VM, we could not use it for a possible new virtual machine. In conclusion, the virtual machine and the debugger will be two entirely different programs and, as such, two completely different processes.

In the debugger implementation for Linux, the subject of section 2.2.1, we described how an operating system's kernel allows the debugger's implementation via a specific API. There is no operating system between the virtual machine and the program. Still, we will strive to make the API similar to the ptrace API. The debugger and the VM will have to communicate together somehow.

Both the VM and the debugger use an abstract class representing an interface that provides two methods, `Send` and `Receive`. The implementation of this interface then handles the concrete way of communication. The debugger and VM do not care about it; they merely use these two methods. There are currently two implementations of this interface. One is using network communication through sockets. This way, the debugger may attach to an existing process, even on an entirely different computer. It, however, has a disadvantage. The messages sent are often short and we need to send a lot of them. This proved too slow, even with few messages being sent. The second implementation is via threads. The debugger runs the VM in another thread, and they communicate via shared queues. This is much faster and allows the debugger to run the process by himself, making it easier to use and behave like real-world debuggers.

The format of the communication is a text one, merely because of the ease of use as opposed to binary format. It is also clearer to see what is happening. The commands

[1] The VM followed the same philosophy.

that the debugging API of the virtual machine offers are

- `PEEKREG x` - Return values of all normal registers.
- `POKEREG x y` - Set the value in register `x` to `y`.
- `PEEKFLOATREG` - Return values of all float registers.
- `POKEFLOATREG x y` - Set the value in float register `x` to `y`.
- `PEEKDEBUGREG` - Return values in all debug registers.
- `POKEDEBUGREG x y` - Set the value in debug register `x` to `y`.
- `PEEKDATA x cnt` - Return values in memory at addresses `x` to `x` + `cnt` − 1.
- `POKEDATA x y` - Write a value `y` into memory at address `x`.
- `PEEKTEXT x cnt` - Return instructions from `x` to `x` + `cnt` − 1.
- `POKETEXT x ins` - Rewrite the instruction at address `x` with the newly supplied instruction.
- `CONTINUE` - Continue the execution.
- `TERMINATE` - Stop the execution, terminating the virtual machine.
- `REASON` - Return the reason why the program stopped.
- `SINGLESTEP` - Do a native level single step.
- `TEXTSIZE` - Return the size of the program.

An example of how those commands can be used for communication between the virtual machine and the debugger is shown in figure 4.2. The interface is similar to basic ptrace commands. If the command should not return anything, the VM sends back an `OK` message. We separate the memory and instruction writing because T86 uses Harvard architecture, whereas Linux does not separate text and data address spaces [15], so the two requests were equivalent there. The API is made to be simple on purpose. Anything more complex should be handled in the debugger itself.

The `Cpu` class, which we have described in section 3.2, has no support for interrupts. The `halted` method is kind of similar to interrupts but only allows for signaling the `HALT` instruction execution. We need more than that.

We added another manager-like class called `OS`. This class will take care of running the program via the `Cpu` class. We also added an *interrupt* capability to the `Cpu`. To check if and which interrupt happened, the `Cpu` now provides a function similar to the `halted` function. The OS calls the `tick` method periodically, and after every tick, it checks if a halt or interrupt occurred. If it did, then it passes it to some handler. When an interrupt happens, unrolling must be done to display proper values in registers and memory. This was described in section 2.1.2. The unrolling mechanism was fortunately already implemented by the T86 VM author. It was used for the `DBG` and `BRK` instructions, and we can use the same mechanisms for our addition of interrupts.

The `BKPT` instruction we added is used for software breakpoints. Executing this instruction causes an interrupt `3` to occur. It is also possible to set a special flag that causes

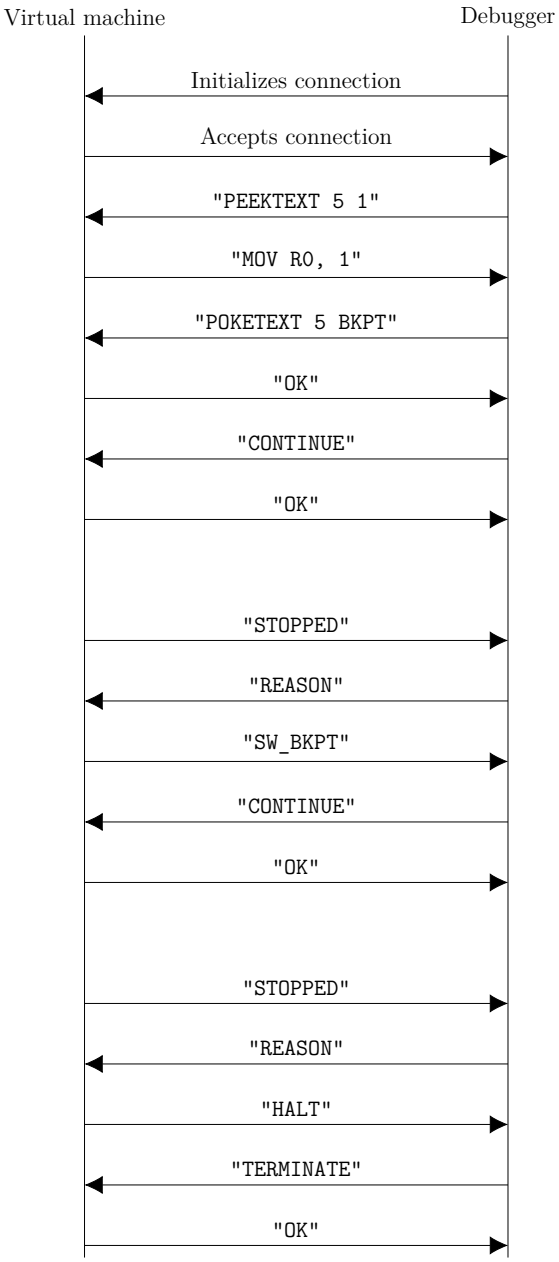


Figure 4.2 A sequence diagram for the communication between the virtual machine and the debugger. If the label is enclosed in quotes, it is the actual text message that is being sent.

the `Cpu` to send the interrupt `1` after every executed instruction. When an interrupt that is caused by some debugging features happens, the `OS` calls a method in the `Debug` class. This class is also a new addition and is responsible for communication with the debugger. It uses the text protocol we mentioned previously.

We also added debug registers. These are a special type of registers designed for triggering breaks on memory access. There are a total of five debug registers, with the first four containing the memory cell addresses. The fifth register, called the control register, contains information about the debug registers. The first four bits of this register indicate the state of each of the first four registers. If the bit is set to one, then the register is active. If a register is active and the program writes to a memory cell with the same address as is stored in the register, an interrupt `2` is generated. Furthermore, the control register's bits from 8 to 11 reveal which register caused the interrupt. For instance, if bit 10 is set to 1, the third register is responsible for the interrupt, and the address stored in that register is the one that was written into.

4.3 Native Debugger

The implementation was done in the C++ language. It uses newer standards up to the C++20 standard. The debugger is implemented as a library. We will call this the backend of the debugger. A command line interface was also developed, through which the users might interact with the debugger. This will be called the frontend of the debugger.

The implemented debugger consists of two main parts. The first one aims to support native (instruction) level debugging. This part works without **any** debugging information whatsoever, ensuring it can be used by the students immediately. The second part focuses on source-level debugging and is described in section 4.4.

The native debugger is split into two additional layers to make it more modular. The first layer is called a `Process`. It is an interface representing the debuggee process. The implementation of this interface is responsible for dealing with the concrete architecture, the API of that architecture, and the communication with the debuggee. One implementation is provided for the T86 VM. For instance, it has a method called `ReadText` and `WriteText`. The internals of these methods use the `PEEKTEXT` and `POKETEXT` API we described. Outside of this class, the communication API is never used. If, in the future, another virtual machine is made, for whichever architecture, it is only needed to implement this interface. The rest of the debugger can be used as-is.

Another layer is the `Native` class, which implements the complicated logic behind a debugger, like setting a breakpoint, handling single-step, and so forth. It is the primary bread and butter of the native part of the debugger. Most algorithms are similar to the Linux debugger implementation presented in section 2.2.1. For illustration, in figure 4.3 we show a snippet of code used to create a breakpoint. It first reads the text at the address where we want to set the breakpoint. The breakpoint opcode then rewrites this text, and the backup of the text is stored.

When we arrive at the breakpoint and want to continue further, we need to unset the breakpoint, i.e., replace the breakpoint opcode in the T86 program with the backup we saved, do a native-level single step, and write the breakpoint back.

Since breakpoints change the underlying code of the debuggee, we need to be careful when presenting information to the user. If we printed the text that we get from the debuggee, it might contain the `BKPT` instructions we set earlier. We need to mix it with

```
SoftwareBreakpoint CreateSoftwareBreakpoint(uint64_t address) {
    auto opcode = GetSoftwareBreakpointOpcode();
    // Read the text at the breakpoint address
    auto backup = process->ReadText(address, 1).at(0);
    // Rewrite it with the breakpoint opcode
    std::vector<std::string> data = {std::string(opcode)};
    process->WriteText(address, data);
    // Check that it was truly written
    auto new_opcode = process->ReadText(address, 1).at(0);
    if (new_opcode != opcode) {
        Error(...);
    }
    // Create a breakpoint object which keeps the text backup
    return SoftwareBreakpoint{backup, true};
}
```

Figure 4.3 Debugger code in the `Native` class to enable a breakpoint.

the backup code stored in breakpoints to show the assembly of the program correctly.

The debugger also has a step-out and step-over functionality. The step-over sets a breakpoint at the next instruction if the current instruction is a call instruction. There is, however, one big problem with this approach, and that is a recursive function. If a function is recursive, the recursive call might hit this breakpoint. To prevent that, we look at the current value of the `BP` register. The value of this register should be different in the recursive calls because it is set in each function prologue. If the value of the register is the same when the break happens, we consider the step-out procedure complete. Otherwise, we will ignore the breakpoint hit and continue the program execution.

With the step-out, we do single steps until we find a `RET` instruction. We cannot use normal single steps but must use the step-over functionality. Normal steps would cause us to enter a function and execute the `RET` instruction there, which would mess with the algorithm.

The Native class uses a `DebugEvent` structure which indicates what caused the VM to stop. It is implemented as a `variant` object consisting of multiple structures, for instance, the `BreakpointHit` or the `WatchpointTrigger` structure. It is a variant because the watchpoint also needs to convey information about an address that caused the break, as do breakpoints. It could also signal if the break was caused by reading or writing to the memory cell, although for now, the T86 VM only interrupts on writing.

Here is a summarization of the features the native debugger offers:

- Breakpoints - Can set, unset, enable and disable software breakpoints.
- Watchpoints - Can set and unset watchpoints on memory writes.
- Single stepping - Can do native level step into, which executes current instruction, out, which runs the program until it leaves current function and over, which treats function calls as a single instruction.
- Text manipulation - Can read and write into the debuggee text area, effectively allowing to overwrite the running code.

- Data manipulation - Can read and write into the program memory area.
- Register manipulation - Can manipulate with normal, float and debug registers.

4.4 Debugging Source Code

With the solid foundation represented by the native part of the debugger, we can extend it by providing some form of source-level debugging. For this part, we need to remember that the debugger will only be used by students. As such, we ought to have a somewhat simpler debugging information format than DWARF, but we certainly can take inspiration from it.

As we previously mentioned, the executable with T86 code is separated into sections. The `.text` and `.data` sections are for the VM. We will introduce new sections where debugging information will be stored. All those sections will have `.debug_` prefix. The simplest new section is `.debug_source`, which should contain the original source code which was compiled into this executable. This later allows us, with the combination of other information, to display the source code lines.

The main philosophy of the source-level debugger is to allow an arbitrary amount of debug information. For instance, the user can generate information about one function only, and for that function, source debugging capabilities will work, but not for any other. This means that users can generate debugging information incrementally.

In the NI-GEN course, students are creating compilers from the TinyC language. This is a small subset of the C language. It has simpler grammar and only the following types: `int`, `double`, `char`, pointers, structured types, and static arrays. We aim to support all of the TinyC language in our source layer of the debugger.

The debugger is, however, not only limited to TinyC language. Any imperative language that can be encoded with the following debugging information is suitable to be debugged at the source level. We show an example of this in a provided test case for the debugger where we debug the LLVM IR. It can be found as an attachment to the thesis on path `impl/src/dbg-cli/tests/sources/llvm.ir`. We also provide documentation for developers who wish to generate this debugging information in the thesis attachment on path `impl/docs/source-info.md`.

The logic behind the source level debugging is mostly handled by the `Source` class. It also stores all of the source level mapping, which we are about to describe below. Some of the methods work closely with the `Native` class to achieve functionality. That should not come as a surprise, as we said, source-level debugging is built upon native-level debugging.

4.4.1 Line Information and Source Code

The line information is encoded in a table, where every row is: `<line>:<address>`. This is far simpler than the DWARF way, described in section 2.3.2.1. We do not care about being space efficient, so we did a table instead of a virtual machine specification. We also feel like this should be entry-level debugging information so that students are not discouraged outright. It misses some information that DWARF had, like columns. It still, however, proves quite sufficient for most cases. The information should be stored in the `.debug_line` section.

With this information, we are able to do source-level breakpoints. It is not necessary to specify every line in the program. The debugger will refuse to put a source-level

```
DIE_compilation_unit: {
DIE_function: {
    ATTR_name: main,
    ATTR_begin_addr: 0,
    ATTR_end_addr: 10,
    DIE_scope: {
        ATTR_begin_addr: 0
        ATTR_begin_addr: 10
        DIE_variable: {
            ATTR_name: d,
        },
    }
}
}
```

Figure 4.4 Debugging function information for the T86 debugger.

breakpoint on some line if it does not have the necessary information. If the source code is also provided, we can show the user on which line is the debugged program currently paused. The source code should be under the `.debug_source` section, which must be the last section in the executable.

4.4.2 Debugging Information Format

In the line information, we provided a straightforward format. However, we will need a more sophisticated structure to describe some advanced constructs of the source code. We will draw inspiration from the DWARF debugging information entries. Take a look at figure 4.4, which shows an example of such debugging information. It has a tree-like structure which, in some ways, mimics the original program. The nodes of this tree are also called debugging information entries (DIEs). Those entries can have other entries as their children, and each entry has a tag that is part of its name (for example, the `compilation_unit` tag). They can also have attributes that describe their properties. As can be seen, this is very similar to the DWARF debugging information format. Unlike DWARF, it will be a text format. This allows us to generate the format easily and to spot mistakes quickly. We do not want the students to debug their generated debugging information.

For instance, the tag `DIE_function` represents a function. As attributes, it has a name, beginning address, and end address. With this additional information, we can set a breakpoint on a function name. We can also display in which function we are located when a break happens.

It also has one direct child, a `DIE_scope`. The scope entry is mainly used for keeping track of which variables are currently active because the T86 (or any other assembly language in general) has no notion of scopes. In the scope entry in the example, only one variable called `d` exists. Thanks to those entries, we can list currently active variables. We, however, often need to examine the value of a variable. To achieve this, information about the location and the variable type is needed. Global variables should be outside of a function, as descendants of the `compilation_unit` entry.

The type information is encoded as a standalone entry. Currently, four type entries

```
DIE_primitive_type: {
    ATTR_name: int,
    ATTR_id: 0,
    ATTR_size: 1,
},
DIE_pointer_type: {
    ATTR_type: 0,
    ATTR_id: 1,
    ATTR_size: 1
},
```

Figure 4.5 Debugging type information for the T86 debugger, showing an `int` primitive type and a pointer to `int` type.

are present, one for primitive types (`int`, `double`, or `char`), one for pointers, one for structured types (`struct` or `class` in C++), and one for static arrays. Other types can be easily added in the future. The types are saved as separate entries, and as such, we need some way to link them together with the variables. We will use the `ATTR_id` attribute to achieve this. This attribute should be unique for every entry, having a similar role to the `id` attribute of HTML elements [43]. The variables themselves have the `ATTR_type` attribute, which will have an id of the type as its value. An example of a pointer type that points to an int type is in figure 4.5. If we had a variable that is a pointer to an `int` type, it would need to have the `ATTR_type: 1` attribute because the id of a pointer type to integer is one.

The primitive types need to have their size. For T86, this is the number of memory cells it occupies, which will almost always be one since one memory cell is 64 bits. It also has a name for its primitive type. Currently, three are supported:

- `int` - A signed integer.
- `float` - A floating point number.
- `char` - A number representing an ASCII character.

Additionally, we also support pointer types (including pointers to pointers), static arrays, and structured types, which are a bit more complicated. They need to have a list of members which are stored in the structure. For each member, an offset from the beginning of the structure must also be specified. It also must provide a size because the compiler might align it, and it may be larger than the sum of the size of its members.

With this information, we can show the type of a variable. Nevertheless, the most valuable thing is its value. Variables are either stored in memory, registered, or optimized out completely. We will follow DWARF's footsteps and provide a virtual machine specification.

The virtual machine is a stack-based one. After all instructions are executed, the value at the top of the stack represents the resulting location. It can either be a register or a memory offset. We offer several examples of programs for the virtual machine:

- `PUSH R0` - Pushes the register `R0`. No instructions remain, so the resulting location is the `R0` register.

- `PUSH BP; PUSH -2; ADD` - Pushes the `BP` register and the `-2` offset onto the stack. The `ADD` instruction pops two values from the stack and adds them together. If the value is a register, the value that is stored in that register is taken. The result from the addition is pushed back onto the stack.
- `BASE_REG_OFFSET -2` - Does the exact same chain of operations as the previous example. Since the variables are often stored in memory at some offset from the base pointer, we provide this short hand.

There is also a dereference instruction, which dereferences a value in memory. That can be useful for tracking the location of pointed variables. This virtual machine is also easily extendable. With this kind of power, the location of variables can almost be arbitrary and not only tied to a register or an offset from the base register. This information is stored in a variable entry attribute called `ATTR_location`. If all this information is provided, we know where the variable is stored and may look up its value. Together with the type information, we might also properly interpret the value and report it to the user.

4.4.3 Source Expressions

We could make a very straightforward implementation of getting variable value by its name. It is only a matter of finding the variable entry with the correct name and interpreting its location and type. However, we often need to inspect some more complicated expressions. For example, we may want to display some struct member or a value at which pointer points.

The debugger has a built-in interpreter for such expressions. It builds an AST from the expression and interprets it using an AST walk [35]. The AST interpreter leverages the `Native` class to fetch variable values. The interpreter supports almost all C operators, including the assignment operator. It, however, has stricter typing than C. An example of such an expression is `foo[2]->bar + 3`. This is a very powerful feature, as it allows one to easily inspect or modify various variables or expressions. If a user wishes to modify part of an array, there is no need to use the raw memory or register setters. Instead, it is possible to write `array[x] = y`.

The AST nodes are distinguished by types. They also need to store the location of the expression if it is an expression that can appear on the left-hand side of the assignment operator. Examples of expressions that must store the location: `a`, `*(a + 1)`, `a[5]`, while the following expressions do not have any locations because they cannot appear on the left side of the assignment operator: `a + 1`, `5`, `array[0] * y`.

4.5 Frontend

We provide two command-line interface programs. The first one is for the T86. It runs the given T86 program on the virtual machine. The second application leverages the debugger library to create a command line interface for the debugger. It provides many commands, and its manual can be found in the thesis attachment under path `impl/docs/debugging.md`. Additionally, table A.1 shows examples of usage of the CLI compared to the GDB debugger.

The main priority of the CLI is to make the debugger easy to use. It consists of several commands, one of them is `breakpoint set 5`, which will set a source-level breakpoint on

```
Process stopped, reason: Software breakpoint hit at line 11
function main at 7-18; active variables: a, b
      9:    int b = 6;
     10:    swap(&a, &b);
@->  11:    print(a);
     12:    print(b);
     13:}
```

Figure 4.6 Example of the debugger CLI reporting a breakpoint hit.

the fifth line of the program. It is, however, not necessary to write the whole command. Any prefix will do, like `b s 5`. The CLI leverages the *linenoise* [44] library to make the REPL satisfying to use.

The CLI also displays various information on program stop, like why the program stopped, on which address or line, and prints the surrounding lines of assembly or source. The CLI can also list breakpoints and display their locations in the disassembly or the source code. Figure 4.6 provides an example of a breakpoint hit report. The debugger had all debugging information available here. It can show the line in the source code where the breakpoint happened, name the offending function, and variables in scope.

When variable values are printed, the format tries to accommodate their type. For example, variables that are arrays or pointers to the `char` type print the value of the variable as a string literal.

Chapter 5
Evaluation

This chapter aims to assess the effectiveness of the debugger. Speed is measured to evaluate whether the debugger has any performance impact when debugging standard and computative demanding programs. We also evaluate its feature richness and ease of use, comparing it to state-of-the-art debuggers like the GDB.

5.1 The Development Process

The development of the thesis was done in a GitHub repository. The power of GitHub was leveraged not only for keeping history but also for recording issues, planning the development, or ensuring that the repository is in a consistent and working state via GitHub actions, which runs tests before a pull request is accepted. The actions run on two operating systems, Ubuntu and MacOS, ensuring the project works on both.

The project itself contains numerous tests. The code is tested via unit tests using the `GoogleTest` [45] framework. These tests cover almost all parts of the code. It also has integration tests for T86 CLI and the debugger CLI. Martin Prokopič created a TinyC to T86 compiler as part of his thesis [46]. He was kind enough to send the implementation to us so that we could generate various tests more easily. As a result, most of the integration tests were generated by the said compiler. The integration tests for the T86 CLI run the program and check if its output is the same as the expected one. The debugger CLI is also checked against the expected output. Its input, however, is not only the file that will be debugged but also the series of commands that will be executed. The tests can be found in the thesis attachment on path `impl/src/dbg-cli/tests`.

5.2 Ease of Use and User Testing

We followed the interface of the GDB closely so that the users were familiar with the debugger before even running it. However, we choose to diverge on some of the features. For example, the GDB uses the `stepi` command for single stepping. This form has a common prefix with the `step` command. We, however, expect our users to use assembly-level debugging more often than source-level debugging, so we choose the `istep` command instead. The two commands have no shared prefix, so typing `is` is enough.

The program is run via `run`, this starts the VM, but the program is paused. In GDB, one has to use the `start` command to get equivalent behavior, `run` runs the program without stopping at the beginning. When we did a brief user testing, it was not very clear to the user. However, renaming the command `run` to `start` would cause it to have the same prefix as `step`. Considering this, we have decided to leave the command as `run`.

There are other minor changes; most of them come from the fact that we prioritize assembly-level debugging, whereas GDB focuses more on the source level. We provide a short list of examples of commands that have different syntax in GDB and in our debugger in the appendix A.1.

One student already tested the debugger and said the experience was "quite pleasant." There were a few minor things that he did not like and offered solutions for (for example, the usage message can only be displayed after the debuggee program is executed, meaning the `run` command must be invoked first), most of which we took to heart and corrected. Additionally, Martin Prokopič, who provided us with the TinyC compiler, used the debugger to debug the code his compiler generated. The NI-GEN students also use the repository, although no official feedback was collected because it is too early in the semester.

5.3 Performance

In this section, we will measure how much the performance can suffer if the program is being debugged. We will also look at which debugging features hurt performance most. The benchmarking will be performed on two programs: a quicksort [47] algorithm and a naive prime number checker. Both of these programs were generated by the previously mentioned TinyC to T86 compiler [46]. The compiler performed no optimizations. The code for benchmarking can be found in the thesis attachment on path `impl/src/benchmarks`.

We scaled the data the programs work with so that their runtime without the debugger is similar. The main difference is that the prime number checker is loop-based, while the quicksort one uses recursion. This will make a difference since some of the algorithms are making decisions based on the `CALL` instruction, like step over.

We will measure the speed on the following cases:

- No debugger - Run the T86 Virtual machine without the debugger.
- Connected - Connect the debugger and let the program continue.
- Breakpoint - Connect the debugger and set a breakpoint at a hot spot of the program. For quicksort, this will be the main recursive function. For primes, it will be the body of the loop. When a breakpoint is hit, the program is continued, and no further action is taken.
- Breakpoint and memory - Same as before, but at every breakpoint hit, read a 100 cells of memory and the `IP` register.
- Step over - Step over a computationally expensive function. For quicksort, it is the `quicksort` function; for primes, it is the `is_prime` function.
- Step out - Set a breakpoint in the most expensive function and run the program. Remove the breakpoint on the first hit and step out of the function. The expensive functions are the same as in the previous test.

Test Case	Quicksort		Prime numbers	
	Time	Slowdown	Time	Slowdown
No debugger	7.91s	–	10.51s	–
Connected	8.89s	1.12	12.33s	1.17
Breakpoint	8.73s	1.10	30.32s	2.88
Breakpoint and memory	9.98s	1.26	31.85s	3.03
Step over	8.91s	1.12	11.53s	1.09
Step out	8.36s	1.05	130.81s	12.37

Table 5.1 Performance comparison when using various features of the debugger. Each case was run five times, and the average was taken. The time is in seconds.

The results are in table 5.1. It is apparent that just having the debugger connected introduces a minor slowdown. The breakpoints, however, do cause a significant slowdown on the first glance. In the quicksort case, the program had 641 breakpoint hits, while in the prime numbers, it had 101265 hits. With this amount of breakpoint hits, the slowdown is acceptable because such an amount of breakpoint hits will very rarely be experienced. Additional reading of memory and registers did not cause any significant slowdown.

The step-over result is not very surprising. It puts a breakpoint after the call and runs the program, so the result should be roughly the same as case number one. Step out is stepping over until a return is encountered. This works well in the recursive function because it skips a large part of the program. However, in the prime case, which is implemented via a loop, it severely slows down the program because it essentially single steps through the entire function. This is something that could be improved in the future because the presented case here might happen in production usage. Besides that, most debugger features did not cause significant slowdowns, so the debugger is suitable for use.

We tried to debug the prime numbers case with the GDB debugger. The program was compiled by the GCC compiler without any optimizations. The program was the same, except we used a much larger prime number to make the running time similar to T86. Trying the last two cases (step-over and step-in), the GDB introduced almost no slowdown compared to when running the program without the GDB debugger attached. This shows that there is definitely room for improvement.

Chapter 6
Conclusion

6.1 Summary

We explored debugging capabilities of modern CPU architectures. We also described how debugging is supported at various layers, from operating systems to compilers. Then, we discuss the T86 architecture and its insufficient debugging support. We remedy this by adding a debugging API inspired by modern architectures. We also created a native and source-level debugger, which is production ready and already used in the NI-GEN course at FIT CTU. This debugger is extensible enough that if a new architecture, virtual machine, or source language comes into play, it should be fairly easy to add support for it into the debugger.

The debugger encourages students in the NI-GEN course to investigate how the debugger works, the connection between the generated machine code and the source code, and to emit information about those connections so that the debugger can work at the source level. It can also make their lives easier since the debugger works at the native level without additional work, allowing them to debug the code their compiler generated.

The tool is, along with the enhanced T86 virtual machine, openly available at `https://github.com/Gregofi/t86-with-debug`.

6.2 Future Work

There are many possible improvements to be made. We have created a new executable text format for T86 ISA and, consequently, a parser for that format. Students, however, have to generate this text, which includes not only the instructions themselves but also the debugging information. A builder interface could go a long way, especially for the most commonly used languages in the NI-GEN course.

The native part of the debugger is fairly complete. It can always be extended for new architectures and virtual machines should they emerge. The expression command, which evaluates a TinyC expression, cannot handle function calls. There is also no way to format the output (for instance, to print an integer as a hexadecimal number). The expression interpreter can always be extended to handle other languages.

New types can always be added to the debugging information. For example, we are missing enums, qualifiers like `const` and `mutable`, or more advanced types that are in the

C++ standard library. Those types are not in the TinyC language that is being taught in the NI-GEN course, but the debugger is not strictly tied to the language. Some parts of the program could be optimized, like the step out, which can prove slow, as demonstrated in section 5.3.

The debugger currently does not handle frame information in any way. This could be a helpful addition so that it displays call frames and allows one to step out of them. This would require a new section, which would have to contain enough information to simulate an unwind. The exact mechanism was described in section 2.3.2.4.

The T86 VM generates statistics about the program execution. It records things like pipeline stalls. Since the debugger has the capability to connect the source to the assembly, it could display the code hot spots in the source code directly.

Last but not least, a graphical user interface could be created for the debugger. Currently, it only offers a command line interface. A graphical interface could be more pleasant to work in. Alternatively, it could be hooked to an existing editor, like the Visual Studio Code, which allows the usage of other debuggers like LLDB or GDB.

Appendix A

GDB to T86 Debugger Command Map

Usecase	GDB	T86 DBG
Set a breakpoint at line 5	`br 5`	`br s 5`
Run the process and immediately stop	`start`	`run`
Do an instruction level single step	`stepi`	`istep` `is`
Set a breakpoint on a function named main	`break main`	`br s main`
List all breakpoints	`info break`	`br list`
Show the contents of a variable named a	`p a`	`p a` `expr a`
Disable a breakpoint	`disable <bp-id>`	`br disable <bp-addr>`
List values of registers	`info registers`	`register`
Display value stored in the instruction pointer	`info registers rip`	`reg get IP`

Table A.1 List of examples of how some actions can be achieved in the GDB debugger and in the debugger presented by this thesis.

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Contents of enclosed media

- `readme.txt` ..... Overview of the medium contents
- `impl` ..... Source code of the implementation
- `linux-debugger` ..... Source code of the proof of concept Linux debugger
- `thesis` ..... Source code of the text in LaTeX
- `text` ..... text
  - `thesis.pdf` ..... text in the PDF format