Analysis of GCC's optimization feature

Author: Jorge Andrés Pietra Santa Ochoa

October 27th, 2019

1 Abstract

When we refer to Compiler Optimization, we refer to the process through which a compiler tries to optimize of maximize some of the aspects of a computer program. Commonly, the goal is to minimize a program's execution time, memory requirements and even the power consumption of said computer program. This is all done throught the analysis and identification of a programming language's patterns in order to create a binary executable that is easier for the CPU to read, interpret and process.

2 Introduction

More often than not, programming language engineers make performance one of the most important aspects to take into account when creating and designing a compiler so that the programs created by the language are as fast as they can be. One of the most common ways to know just how fast the compiler is is through the process of "benchmarking", which is basically comparing the results of one product, service or process (in this case we're benchmarking a process) using some key "comparators" that will make it evident for whoever is analyzing the results which one is better. In this specific case of analysis, we will be comparing the execution times of the binaries created by GCC when no optimizations are done, compared to the time taken by the file created when using optimization level 3.

3 Objective

In this document, we will analyze the assembly code generated by GCC with no optimizations and the code generated when we use the optimization parameter on level 3. The results might not be drastically different, but we should be able to observe at least some difference between the two.

4 Development

To be as transparent as possible, here are the specs of the machine that will be used to run these tests:

Computer Model	Macbook Pro 15 Mid-2018
Operating System	macOS 10.15 Catalina
Procesor Number	8750H
#Cores	6
#Threads	12
Base Speed	2.20 GHz
Turbo Speed	4.10 GHz

Table 1: Machine specs

The machine we're using for these tests is what the industry considers "highend", so the time it will take for our computer to execute the files could be considerably faster than the average machine, so it might be a good idea to run these tests on your computer to observe the difference it might make on your specific setup.

The code we will be analyzing in this document is fairly simple, but it should give us an insigth of how much of a difference optimization can really make. Given the following C function:

We will initialize a one-million-element array for the proc function to go through. We will later compile and execute the files generated by GCC.

First, let us take a look to both the unoptimized and optimized assembly codes generated by GCC, and see what the differences are:

5 Unoptimized Assembly Code:

```
./nonOpt:
                 file format Mach-O 64-bit x86-64
Disassembly of section __TEXT, __text:
_{-}text:
100000 \, \text{ed}0:
                             pushq
                                        %rbp
                 55
100000 \, \text{ed} 1:
                 48
                     89 e5
                                        movq
                                                    %rsp, %rbp
100000 \, \text{ed} 4:
                 48 89 7d f8
                                                    %rdi, -8(%rbp)
                                        movq
                             00 00
                                                                90, -12(\% \text{rbp})
100000 \,\mathrm{ed}8:
                 c7 45 f4
                                       00 00
                                                    movl
100000 \, \text{edf}:
                 c7 45 f0
                              00
                                  00
                                       00 00
                                                                90, -16(\% \text{rbp})
                                                    movl
100000 ee6:
                     7d f0 40 42 0f
                                           00
                                                                1000000, -16(\% \text{rbp})
                 81
                                                    cmpl
100000 \, \text{eed}:
                     8d 1f
                              00
                                  00
                                      00
                                                               31 < proc + 0x42 >
                 0 f
                                                    jge
                                                    -8(\%\text{rbp}), \%\text{rax}
100000 \,\mathrm{ef3}:
                 48
                     8b 45
                              f8
                                        movq
                                                    -16(\%\text{rbp}), \%\text{rcx}
100000 \,\mathrm{ef7}:
                 48
                     63 4d
                              f0
                                        movslq
                                                    (\%rax,\%rcx,4), \%edx
100000 \, \text{efb}:
                 8b 14
                          88
                                        movl
100000 efe:
                 03 55 f4
                                        addl
                                                    -12(\%\text{rbp}), \%\text{edx}
```

```
100000 \, \text{fol} \, 1:
                 89 55 f4
                                                     \%edx, -12(\%rbp)
                                         movl
                                                     -16(\%rbp), \%eax
100000 \, \text{fo} \, 4:
                 8b 45 f0
                                         movl
100000 \, \mathrm{fo7}:
                 83 c0
                          01
                                          addl
                                                     $1, %eax
100000 f0a:
                 89 45
                          f0
                                         movl
                                                     \%eax, -16(\%rbp)
100000 \, \text{fod}:
                 e9 d4
                          ff
                               ff ff
                                                     -44 < -proc +0x16 >
                                         jmp
                 8b 45 f4
                                                     -12(\%rbp), %eax
100000 \, \text{f} \, 12:
                                         movl
1000000 f15:
                 5d
                                         %rbp
                             popq
100000 \, \text{f} \, 16:
                 c3
                             retq
                                                                             (\% rax, \% rax)
100000 \, \text{f} \, 17:
                 66 Of 1f 84 00 00 00 00 00
                                                                 nopw
                                         %rbp
100000 f20:
                 55
                             pushq
                      89
100000 f21:
                 48
                          e_5
                                         movq
                                                     %rsp, %rbp
                                                     $32, \%rsp
100000 f24:
                 48
                     83
                          ec 20
                                         subq
                     45 fc 00 00 00 00
                                                                 90, -4(\% \text{rbp})
100000 f28:
                 c7
                                                     movl
100000 f 2 f:
                 bf
                     00 09 3d 00
                                         movl
                                                     $4000000, %edi
100000 \, f34:
                 e8
                      2b 00 00 00
                                                     43 < dyld_stub_binder + 0x100000f64 >
                                          callq
100000 f39:
                 48
                     89 45
                              f0
                                                     %rax, -16(%rbp)
                                         movq
                     8b 7d f0
                                                     -16(\%\text{rbp}), \%\text{rdi}
100000 \, \mathrm{f3d}:
                 48
                                         movq
                      8a ff
                              f f
                                                     -118 <_proc>
100000 \, \text{f41}:
                 e8
                                   f f
                                          callq
100000 \, \text{f} \, 46:
                 48
                      8d 3d 47
                                   00
                                       00 00
                                                     leaq
                                                                 71(% rip), %rdi
100000 \, \text{f4d}:
                 89
                      c6
                             movl
                                         %eax, %esi
                 b0 00
                                         $0, %al
100000 \, \text{f4f}:
                             movb
                 e8 14 00 00 00
                                                     20 < dyld_stub_binder + 0x100000f6a >
100000 \,\mathrm{f} \,51:
                                         callq
100000 \, \text{f} \, 56:
                 31
                     f6
                                         %esi, %esi
                             xorl
100000f58:
                 89 45 ec
                                         movl
                                                     \%eax, -20(\%rbp)
100000 \, \text{f} \, 5 \, \text{b}:
                 89 f0
                                         %esi, %eax
                             movl
100000 \, \text{f} \, 5 \, \text{d}:
                 48
                      83 c4 20
                                         addq
                                                     $32, %rsp
100000 \, \text{f} \, 61:
                 5d
                                         %rbp
                             popq
100000 \, \text{f62}:
                 c3
                             retq
_proc:
                             pushq
100000 \, \text{ed}0:
                 55
                                         %rbp
                 48 89 e5
100000 \, \text{ed} 1:
                                                     %rsp, %rbp
                                         movq
                 48 89 7d f8
                                                     %rdi, -8(%rbp)
100000 \,\mathrm{ed}4:
                                         movq
100000 \, \text{ed} 8:
                 c7
                     45
                          f4
                               00 00 00 00
                                                     movl
                                                                 \$0, -12(\% \text{rbp})
100000 \, \text{edf}:
                 c7
                      45
                          f0
                               00 00
                                        00 00
                                                     movl
                                                                 \$0, -16(\% \text{rbp})
100000 \, \mathrm{ee6}:
                 81
                      7d f0
                              40 42 0f 00
                                                     cmpl
                                                                 1000000, -16(\%rbp)
                 0f 8d 1f 00
                                   00
100000 \, \text{eed}:
                                       0.0
                                                                 31 < proc + 0x42 >
                                                     jge
                 48 8b 45 f8
100000 \, \text{ef3}:
                                                     -8(\% \text{rbp}), \% \text{rax}
                                         movq
                 48 63 4d f0
                                                     -16(\%\text{rbp}), \%\text{rcx}
100000 \, \text{ef7}:
                                         movsla
                 8b 14 88
                                                     (\% \operatorname{rax}, \% \operatorname{rcx}, 4), \% \operatorname{edx}
100000 \, \text{efb}:
                                         movl
                 03 55 f4
                                                     -12(\%rbp), %edx
100000 efe:
                                         addl
100000 \, \text{fol} \, 1:
                 89
                      55
                          f4
                                                     \%edx, -12(\%rbp)
                                         movl
100000 \, \text{fo} \, 4:
                 8b 45 f0
                                                     -16(\%\text{rbp}), %eax
                                         movl
                 83 c0 01
                                                     $1, %eax
100000 \, \mathrm{fo7}:
                                         addl
100000 \, \mathrm{f0a}:
                 89 45 f0
                                         movl
                                                     \%eax, -16(\%rbp)
100000 \, \text{fod}:
                 e9 d4 ff
                              ff ff
                                         jmp
                                                     -44 < proc + 0x16 >
100000 f12:
                 8b 45 f4
                                         movl
                                                     -12(\%rbp), %eax
                                         %rbp
100000 \,\mathrm{f} \,15:
                 5d
                             popq
100000 f16:
                 c3
                             retq
100000 \, \text{f} \, 17:
                 66 Of 1f 84 00 00 00 00 00
                                                                             (\% rax, \% rax)
                                                                 nopw
```

```
_{\mathtt{main}} :
100000 f20:
                55
                           pushq
                                     %rbp
100000 f21:
                48 89 e5
                                      movq
                                                %rsp, %rbp
100000 f24:
                48 83 ec 20
                                                 $32, %rsp
                                      subq
                c7 45 fc 00 00 00 00
                                                           90, -4(\% \text{rbp})
100000 f28:
                                                 movl
                bf 00 09 3d 00
                                                 $4000000, %edi
100000 f 2 f:
                                      movl
100000 f34:
                    2b 00 00 00
                                                 43 < dyld_stub_binder + 0x100000f64 >
                e8
                                      callq
100000 f39:
                48 89 45 f0
                                      movq
                                                %rax, -16(%rbp)
                   8b 7d f0
                                                 -16(\%\text{rbp}), \%\text{rdi}
100000 f3d:
                48
                                      movq
100000 \, \text{f} \, 41:
                e8
                    8a ff
                            ff ff
                                      callq
                                                 -118 < proc >
                   8d 3d 47 00 00 00
                                                           71(% rip), %rdi
100000 f46:
                48
                                                 leaq
                                     %eax, %esi
100000 \, \text{f4d}:
                89 c6
                           movl
100000 \, \text{f4f}:
                b0 00
                           movb
                                      $0, %al
100000 \, \text{f} \, 51:
                e8
                   14 00 00 00
                                      callq
                                                 20 < dyld_stub_binder + 0x100000f6a >
                           xorl
                                             \% \mathrm{esi}
100000 \, \text{f} \, 56:
                31 f6
                                     %esi,
                                      movl
                                                \%eax, -20(\%rbp)
100000 \, \text{f} \, 58:
                89 45 ec
                89 f0
                                     %esi,
                                             %eax
100000f5b:
                           movl
100000f5d:
                48
                    83 c4 20
                                      addq
                                                 $32, %rsp
100000 \, \text{f} \, 61:
                5d
                                     %rbp
                           popq
100000 \, \text{f} \, 62:
                c3
                           retq
                    section __TEXT, __stubs:
Disassembly
                οf
_stubs:
100000 \, \text{f64}:
                ff 25 96 10 00 00
                                                jmpq
                                                            *4246(% rip)
100000 f6a:
                ff 25 98 10 00 00
                                                jmpq
                                                            *4248(\% \text{ rip})
Disassembly of
                    section __TEXT, __stub_helper:
__stub_helper:
                                                           4249(\% \text{ rip}), \% \text{r}11
100000 \, \text{f} \, 70:
                4c 8d 1d 99 10 00 00
                                                 leaq
                41 53
                           pushq
                                     %r11
100000\,\mathrm{f}77:
100000 \, \text{f} \, 79:
                ff 25 81 00 00 00
                                                jmpq
                                                            *129(% rip)
                90
100000 \, \text{f} \, 7 \, \text{f}:
                           nop
100000\,\mathrm{f}\,80:
                68 00 00 00 00
                                                 $0
                                      pushq
                                                 -26 < -stub-helper >
                e9
100000 \, f85:
                    e6 ff ff
                               f f
                                      jmp
100000 \, f8a:
                68 0e 00 00 00
                                      pushq
                                                 $14
100000 f8f:
                e9 dc ff ff
                                      jmp
                                                 -36 < -stub-helper >
```

6 Optimized Assembly Code:

```
./opt3:
                file format Mach-O 64-bit x86-64
Disassembly of section __TEXT, __text:
__text:
100000 \, de0:
                                    %rbp
                          pushq
100000 \, \mathrm{de1}:
               48 89 e5
                                    movq
                                              %rsp, %rbp
                                              %xmm0, %xmm0
100000 \, \mathrm{de4}:
               66 0f ef c0
                                    pxor
                   24 00 00 00
                                               $36, %eax
100000 \, \mathrm{de8}:
               b8
                                    movl
100000 \, \text{ded}:
               66 0 f
                       ef c9
                                              %xmm1, %xmm1
                                    pxor
                                                                   \%cs:(\%rax,\%rax)
100000 \, \mathrm{df1}:
               66 2e 0f 1f 84 00 00 00 00 00
                                                         nopw
```

```
0f 1f 44 00 00
                                     nopl
                                                (\% rax, \% rax)
100000 dfb:
                f3 0 f
                        6f 94
                                87 70 ff ff
                                                                     -144(\% \text{rdi}, \% \text{rax}, 4), %xmr
100000e00:
                                               ff
                                                           movdqu
100000e09:
                66 0 f
                       fe
                            d0
                                     paddd
                                                %xmm0, %xmm2
100000e0d:
                f3 0 f
                        6 f
                            44
                                    80
                                                movdqu
                                                           -128(\% \text{rdi}, \% \text{rax}, 4), \% \text{mm0}
100000e13:
                66 Of fe
                           c1
                                     paddd
                                                %xmm1, %xmm0
                f3 0 f
                        6\,\mathrm{f}
                           4c 87 90
                                                movdqu
100000e17:
                                                          -112(\% \text{rdi}, \% \text{rax}, 4), \% \text{xmm1}
                f3 Of 6f 5c 87 a0
100000 \, \text{e1d}:
                                                movdqu = -96(\%rdi,\%rax,4), \%xmm3
                f3 0 f
                       6f 64
                                                movdqu = -80(\%rdi,\%rax,4), \%xmm4
100000e23:
                                                %xmm1, %xmm4
                                     paddd
100000e29:
                66 0f fe
                           e1
                66 0 f
                        fе
                                                %xmm2, %xmm4
                            e2
                                     paddd
100000 \,\mathrm{e}2\mathrm{d}:
                        6 f
100000e31:
                f3 0 f
                            54 87 c0
                                                movdqu = -64(\%rdi,\%rax,4), \%xmm2
                                                %xmm3, %xmm2
                        fе
100000e37:
                66 0 f
                            d3
                                     paddd
                                     paddd
                66 0 f
                       fе
                            d0
                                                %xmm0, %xmm2
100000e3b:
100000 \, \mathrm{e}3 \, \mathrm{f}:
                f3
                   0 f
                       6 f
                            4c 87 d0
                                                movdqu
                                                          -48(\% \text{rdi},\% \text{rax},4), \% \text{xmm1}
100000e45:
                f3
                   0 f
                       6f 5c 87
                                    e0
                                                movdqu
                                                          -32(\% \text{rdi},\% \text{rax},4), \% \text{xmm}3
100000e4b:
                f3
                   0 f 6 f 44
                                87 f0
                                                movdqu = -16(\%rdi,\%rax,4), \%xmm0
                                                %xmm1, %xmm0
100000e51:
                66 0f fe
                           c1
                                     paddd
                                                %xmm4, %xmm0
                66 0f fe
                                     paddd
100000e55:
                            c4
                                                (%rdi,%rax,4), %xmm1
100000e59:
                f3
                   0 \, \mathrm{f}
                        6 f
                            0c
                                     movdqu
100000e5e:
                66 0 f
                        fе
                            cb
                                     paddd
                                                %xmm3, %xmm1
                                     paddd
                                                %xmm2, %xmm1
100000e62:
                66 \, 0 \, f
                       fе
                            ca.
                48 83 c0
                            28
                                                $40, %rax
100000e66:
                                     addq
                   3d 64 42
                                                           $1000036, %rax
100000e6a:
                                                cmpq
                   8 e
100000e70:
                75
                          jne
                                     -114 < -proc +0x20 >
100000e72:
                66 0 f
                       fe c8
                                     paddd
                                                %xmm0, %xmm1
                        70
                                                $78, %xmm1, %xmm0
100000e76:
                66 0 f
                            c1 4e
                                     pshufd
100000e7b:
                66 \, 0 \, \mathrm{f}
                        fe
                                                %xmm1, %xmm0
                            c1
                                     paddd
                                                $229, %xmm0, %xmm1
                66 0 f
                        70 \ c8 \ e5
100000 \,\mathrm{e}\,7\,\mathrm{f}:
                                     pshufd
                                                %xmm0, %xmm1
                66 0f fe
100000e84:
                           c8
                                     paddd
100000e88:
                66
                   0f 7e c8
                                     movd
                                                %xmm1, %eax
                5d
                                     %rbp
100000 \, \mathrm{e8c}:
                          popq
100000 \, \text{e}8\text{d}:
                c3
                          retq
                66
                   90
100000 e8e:
                          nop
100000e90:
                55
                          pushq
                                     %rbp
100000e91:
                48
                    89 e5
                                     movq
                                                %rsp, %rbp
100000e94:
                bf 00 09 3d 00
                                     movl
                                                $4000000, %edi
                e8 c4 00 00 00
                                                196 <dyld_stub_binder+0x100000f62>
100000e99:
                                     callq
100000e9e:
                66 0 f
                       еf
                           c0
                                                %xmm0, %xmm0
                                     pxor
                b9 1d 00 00
                                                $29. %ecx
100000 \,\mathrm{ea2}:
                                     movl
                66 0 f
                                     pxor
                                                %xmm1, %xmm1
100000 \,\mathrm{ea7}:
                       ef c9
                                     26 < main + 0x37 >
100000 eab:
                eb 1a
                          jmp
100000 \, \text{ead}:
                0 f
                   1 f
                        00
                                     nopl
                                                (\% rax)
                                                          -16(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm} 0
100000 \, \mathrm{eb0}:
                f3
                   0 \, \mathrm{f}
                        6f 44 88 f0
                                                movdqu
                f3 Of 6f Oc 88
                                                (\%rax,\%rcx,4), \%xmm1
100000 eb6:
                                     movdqu
100000 ebb:
                66 0f fe c2
                                     paddd
                                                %xmm2, %xmm0
100000 \, \mathrm{ebf}:
                66
                   0f fe
                            cb
                                     paddd
                                                %xmm3, %xmm1
100000 \,\mathrm{ec}3:
                48
                   83 c1
                            20
                                     addq
                                                \$32, \%rcx
                f3 Of 6f 5c
                                   90
                                                          -112(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm}3
                                88
                                                movdqu
100000 \,\mathrm{ec}7:
                                                %xmm0, %xmm3
100000 \, \text{ecd}:
                66 0f fe
                            d8
                                     paddd
100000 \, \text{ed} 1:
                f3 0f 6f
                            44
                                                movdqu = -96(\%rax,\%rcx,4), \%xmm0
```

```
100000 ee7:
                 f3 0 f
                          6f 54
                                                    movdqu
                                                                -48(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm} 2
100000 \, \text{eed}:
                 66 0f fe
                             d1
                                                    %xmm1, %xmm2
                                        paddd
                 66 0f fe
                             d3
                                                    %xmm3, %xmm2
100000 \, \text{ef1}:
                                        paddd
                 f3 0f 6f
100000 \, \text{ef } 5:
                              5 \,\mathrm{c}
                                  88 e0
                                                    movdqu
                                                               -32(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm} 3
                                                    %xmm4, %xmm3
                 66 \, 0 \, \mathrm{f}
                          fе
                              dc
100000 \, \text{efb}:
                                        paddd
100000 \, \text{eff}:
                 66 Of fe
                              d8
                                        paddd
                                                    %xmm0, %xmm3
                 48 81
                          f9
                              3d 42 0f 00
                                                                $999997, %rcx
100000 \, \text{fo} \, 3:
                                                    cmpq
100000 \, \text{foa}:
                 75
                     a4
                             jne
                                         -92 < main + 0x20 >
                                                    %xmm2, %xmm3
100000 \, \text{foc}:
                 66
                     0 \, \mathrm{f}
                          fе
                              da
                                        paddd
                     0 f
                          70
                                                    $78, %xmm3, %xmm0
100000 \, \text{f} \, 10:
                 66
                              c3
                                  4 e
                                         pshufd
                                                    \%xmm3, \%xmm0
100000 \,\mathrm{f} \,15:
                 66
                     0 \, \mathrm{f}
                         fe
                              c3
                                         paddd
100000 f19:
                 66
                     0 f 70
                              c8
                                                    $229, %xmm0, %xmm1
                                        pshufd
100000 \, \text{fle}:
                 66
                     0f fe
                              c8
                                        paddd
                                                    %xmm0, %xmm1
                                                    %xmm1, %esi
100000 f22:
                 66 0f 7e
                              се
                                        movd
                 03 b0 e4
                              08
                                  3d 00
                                                    addl
                                                                3999972(%rax), %esi
100000 \,\mathrm{f} \,26:
                                                                3999976(%rax), %esi
100000 \, \text{f2c}:
                 03
                     b0 e8
                              08
                                  3d 00
                                                    addl
100000 \, \text{f32}:
                 03
                     b0
                          ec
                             08
                                   3d
                                       00
                                                    addl
                                                                3999980(%rax), %esi
                     b0
                         f0
                              08
                                                                3999984(\% \text{rax}), \% \text{esi}
100000 \, f38:
                 03
                                  3d 00
                                                    addl
                 03 b0 f4
                                                                3999988(%rax), %esi
                             08
                                  3d 00
100000 \, \mathrm{f3e}:
                                                    addl
100000 \, \text{f44}:
                 03
                     b0 f8
                              08
                                  3d 00
                                                                3999992(%rax), %esi
                                                    addl
                                                    addl
100000 \, \text{f4a}:
                 03 b0 fc
                              08 3d 00
                                                                3999996(%rax), %esi
100000 \, \text{f} \, 50:
                 48
                     8d 3d 3d 00
                                       00 00
                                                    leaq
                                                                61(% rip), %rdi
100000 \, \text{f} \, 57:
                 31
                     c0
                             xorl
                                        %eax, %eax
100000 \, \text{f} \, 59:
                     0a\ 00\ 00\ 00
                                         callq
                                                    10 < dyld_stub_binder + 0x100000f68 >
                 e8
                                        %eax, %eax
100000 \, \text{f} \, 5 \, \text{e}:
                 31
                     c0
                             xorl
                 5d
                                        %rbp
100000 \, \text{f} \, 60:
                             popq
100000 \, \text{f} \, 61:
                 c3
                             retq
_proc:
100000 \, \mathrm{de0}:
                             pushq
                 55
                                        %rbp
                                                    %rsp, %rbp
100000 de1:
                 48
                     89 e5
                                        movq
100000 \, \mathrm{de4}:
                 66
                     0 f
                         ef c0
                                         pxor
                                                    %xmm0, %xmm0
100000 \, de8:
                 b8
                     24
                          00 00
                                  00
                                        movl
                                                    $36, %eax
                 66 0 f
                                                    %xmm1, %xmm1
100000 \, ded:
                          e f
                             c9
                                         pxor
                 66 \ 2e \ 0f
100000 \, df1:
                              1 f
                                  84
                                       00 00 00 00 00
                                                                nopw
                                                                           \%cs:(\%rax,\%rax)
                                                    (\% rax, \% rax)
100000 \, dfb:
                 0 f
                     1 f
                          44
                              00
                                 00
                                         nopl
                 f3 Of 6f 94
                                  87 70 ff ff ff
                                                                            -144(\% \text{rdi}, \% \text{rax}, 4), %xmr
100000e00:
                                                                movdqu
                 66 0 f
                          fе
                              d0
                                        paddd
                                                    %xmm0, %xmm2
100000e09:
100000e0d:
                 f3 0 f
                          6 f
                              44 87 80
                                                    movdqu
                                                                -128(\% \text{rdi},\% \text{rax},4), \% \text{xmm}0
                                        paddd
100000e13:
                 66 0 f
                          fе
                             c1
                                                    %xmm1, %xmm0
                 f3 0 f
                          6 f
                              4c 87
                                       90
                                                    movdqu
                                                                -112(\% \text{rdi}, \% \text{rax}, 4), \% \text{xmm1}
100000e17:
                                                                -96(\% \text{rdi},\% \text{rax},4), %xmm3
100000 \,\mathrm{e1d}:
                 f3
                     0 f
                          6f 5c 87
                                       a0
                                                    movdqu
100000e23:
                 f3
                     0f 6f 64 87 b0
                                                    movdqu
                                                               -80(\% \text{rdi}, \% \text{rax}, 4), \% \text{xmm} 4
100000e29:
                 66
                    0f fe
                              e1
                                        paddd
                                                    %xmm1, %xmm4
                                                    %xmm2, %xmm4
                 66 0 f
                         fe
                                        paddd
100000 \,\mathrm{e}2\mathrm{d}:
                              e2
                 f3 0 f
                          6 f
                                                    movdqu = -64(\%rdi,\%rax,4), \%xmm2
100000e31:
                              54
                                  87 c0
                                                    %xmm3, %xmm2
100000e37:
                 66 \, 0 \, \mathrm{f}
                         fе
                              d3
                                        paddd
```

paddd

88

88 c0

b0

%xmm1, %xmm0

-80(% rax, % rcx, 4), \%\xmm1

-64(% rax, % rcx, 4), % xmm 4

movdqu

movdqu

 $100000 \, \text{ed}7$:

100000 edb:

 $100000 \, \mathrm{ee1}$:

66 0f fe c1

f3 0f 6f 4c

6f 64

f3 0 f

```
-32(\% \text{rdi},\% \text{rax},4), \% \text{xmm}3
1000000e45:
                f3 0f 6f 5c
                                 87
                                     e0
                                                 movdqu
100000e4b:
                f3 0 f
                        6f44
                                 87
                                     f0
                                                 movdqu
                                                           -16(\% \text{rdi},\% \text{rax},4), \% \text{mm}0
100000e51:
                66 Of fe c1
                                      paddd
                                                 %mm1, %mm0
                66 Of fe c4
                                      paddd
                                                 %xmm4, %xmm0
100000e55:
                f3 Of 6f Oc 87
                                                 (%rdi,%rax,4), %xmm1
100000e59:
                                      movdqu
                            ^{\mathrm{cb}}
                66 0f fe
                                      paddd
                                                 %xmm3, %xmm1
100000e5e:
                                                 %xmm2, %xmm1
100000e62:
                66 0f fe
                            ca
                                      paddd
                    83 c0
                            28
                                                 $40, %rax
                48
                                      addq
100000e66:
                                                             $1000036, %rax
100000e6a:
                48
                    3d 64 42 0f 00
                                                 cmpq
                                       -114 < proc + 0x20 >
100000e70:
                75
                    8 e
                           jne
100000e72:
                                                 %xmm0, %xmm1
                66
                    0 \, \mathrm{f}
                        fe
                            c8
                                      paddd
100000e76:
                66 0f 70 c1
                                4 e
                                      pshufd
                                                 $78, %xmm1, %xmm0
100000e7b:
                66 0f fe
                            c1
                                                 %xmm1, %xmm0
                                      paddd
                                                 $229, %xmm0, %xmm1
100000e7f:
                66
                   0f 70 c8
                                      pshufd
                                 e_5
                                                 %xmm0, %xmm1
100000e84:
                66 Of fe c8
                                      paddd
                                                 %xmm1, %eax
                66 Of 7e c8
100000e88:
                                      movd
100000 \, \mathrm{e8c}:
                5d
                           popq
                                      %rbp
100000 \, \text{e} \, \text{8d}:
                c3
                           retq
100000e8e:
                66 90
                           nop
_main:
100000e90:
                55
                           pushq
                                      %rbp
100000e91:
                48 89 e5
                                                 %rsp, %rbp
                                      movq
                bf 00 09 3d 00
                                                  $4000000, %edi
100000e94:
                                      movl
100000e99:
                    c4
                        00 00 00
                                                  196 < dyld_stub_binder+0x100000f62>
                                       callq
100000e9e:
                66
                   0 f
                        ef c0
                                                 %xmm0, %xmm0
                                       pxor
                                                 $29, \%ecx
                b9
                    1d 00 00 00
100000 \,\mathrm{ea2}:
                                      movl
                                                 %xmm1, %xmm1
100000 \,\mathrm{ea7}:
                66 0 f
                        ef c9
                                      pxor
                                       26 < main + 0x37 >
100000 eab:
                eb 1a
                           jmp
                        00
                                                 (\% rax)
100000 \, \text{ead}:
                0 f 1 f
                                       nopl
                f3 0 f
                                                 movdqu = -16(\%rax,\%rcx,4), \%xmm0
                        6 f 44
100000 \,\mathrm{eb}0:
                                 88
                                                 (\%rax,\%rcx,4), \%xmm1
100000 \, \mathrm{eb6}:
                f3
                    0 \, \mathrm{f}
                        6f 0c
                                 88
                                      movdqu
100000 ebb:
                66
                    0 \, \mathrm{f}
                        fе
                            c2
                                      paddd
                                                 %xmm2, %xmm0
100000 \, \mathrm{ebf}:
                66 0 f
                        fе
                            cb
                                      paddd
                                                 %xmm3, %xmm1
                48 83 c1
                            20
                                                 \$32, \%rcx
100000 \,\mathrm{ec}3:
                                      addq
                f3 Of 6f 5c 88 90
                                                           -112(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm}3
100000 \,\mathrm{ec}7:
                                                 movdqu
                66 Of fe
                            d8
                                      paddd
                                                 %xmm0. %xmm3
100000 \, \text{ecd}:
                f3 0f 6f 44 88 a0
                                                 movdqu = -96(\%rax,\%rcx,4), \%xmm0
100000 \, \text{ed} 1:
                                                 %xmm1, %xmm0
                66 0 f
                        fe
100000 \,\mathrm{ed}7:
                            c1
                                      paddd
100000 \, \text{edb}:
                f3
                    0 f
                        6 f
                            4 \,\mathrm{c}
                                 88
                                     b0
                                                 movdqu
                                                            -80(\% \text{rax}, \% \text{rcx}, 4), \%\xmm1
                                                            -64(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm} 4
100000 \, \mathrm{ee1}:
                f3
                    0 \, \mathrm{f}
                        6 f
                            64
                                 88
                                     c0
                                                 movdqu
                                                           -48(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm} 2
                f3 0 f
                        6f 54 88 d0
                                                 movdqu
100000 \,\mathrm{ee7}:
100000 \, \text{eed}:
                66 0f fe
                            d1
                                      paddd
                                                 %xmm1, %xmm2
100000 \, \text{ef1}:
                66 0f fe
                            d3
                                      paddd
                                                 %xmm3, %xmm2
100000 \, \text{ef5}:
                f3
                   0f 6f 5c 88 e0
                                                 movdqu
                                                            -32(\% \text{rax}, \% \text{rcx}, 4), \% \text{xmm} 3
                                                 %xmm4, %xmm3
                66 0f fe
                            dc
100000 \, \text{efb}:
                                      paddd
                                                 %xmm0, %xmm3
                66 0 f
100000 \, \text{eff}:
                        fe
                            d8
                                      paddd
100000 \, \text{fo} \, 3:
                48 81 f9
                            3d 42 0f 00
                                                            $999997, %rcx
                                                 cmpq
```

paddd

%xmm0, %xmm2

movdqu = -48(%rdi,%rax,4), %xmm1

100000e3b:

 $100000 \,\mathrm{e}3\mathrm{f}$:

66 0f fe d0

f3 0f 6f 4c 87 d0

```
100000 f0a:
                75 a4
                                       -92 < -main + 0x20 >
                            jne
                                       paddd
                                                  %xmm2, %xmm3
100000 \, \mathrm{foc}:
                66 0 f
                         fe
                            da
100000 \, \text{f} \, 10:
                66
                    0 f
                         70
                             c3
                                       pshufd
                                                  $78, %xmm3, %xmm0
100000 \, \text{f15}:
                66
                    0 f
                         fe
                             c3
                                       paddd
                                                  %xmm3, %xmm0
100000 f19:
                66 0 f
                         70
                                                  $229, %xmm0, %xmm1
                             c8
                                       pshufd
                                 e_5
                66 0f fe
                                                  %xmm0, %xmm1
100000 \, \text{f1e}:
                            c8
                                       paddd
                                                  %xmm1, %esi
100000 f22:
                66 Of 7e ce
                                       movd
100000f26:
                03 b0 e4
                             08 3d 00
                                                              3999972(%rax), %esi
                                                  addl
                                                             3999976(\% \text{rax}), \% \text{esi}
100000 \, \text{f2c}:
                03 b0 e8 08
                                 3d \ 00
                                                  addl
                03 b0 ec
                                                             3999980(%rax), %esi
100000 f32:
                             08
                                 3d
                                     00
                                                  addl
                                                             3999984(\% \text{rax}), \% \text{esi}
100000 f38:
                03
                    b0
                         f0
                             08
                                 3d
                                     00
                                                  addl
                                                              3999988(%rax), %esi
100000 \, \mathrm{f3e}:
                03
                    b0
                         f4
                             08
                                 3d
                                     00
                                                  addl
                                                             3999992(\% \, \text{rax}), \% \, \text{esi}
                03 b0
                         f8
100000 \, \text{f44}:
                             08
                                 3d
                                     0.0
                                                  addl
100000 \, \text{f4a}:
                03
                    b0
                        fc
                             08
                                 3d
                                     0.0
                                                  addl
                                                             3999996(%rax), %esi
100000f50:
                48
                    8d
                        3d 3d
                                 00
                                     00 00
                                                  leaq
                                                             61(% rip), %rdi
100000 \, \text{f} \, 57:
                31
                     c0
                            xorl
                                       %eax,
                                               %eax
                                                  10 < dyld_stub_binder + 0x100000f68 >
100000 \, \text{f} \, 59:
                e8
                     0a
                         00 00 00
                                       callq
                                       %eax,
                                               %eax
100000 \, \mathrm{f5e}:
                31
                     c0
                            xorl
100000 \, \text{f} \, 60:
                5d
                            popq
                                       %rbp
100000 \, \text{f} \, 61:
                c3
                            retq
                     section __TEXT, __stubs:
Disassembly
                of
_stubs:
100000 \, \text{f} \, 62:
                     25 98 10 00 00
                                                              *4248(% rip)
                                                  jmpq
100000 f68:
                 f f
                     25 9a 10 00 00
                                                  jmpq
                                                              *4250(% rip)
Disassembly of
                     section __TEXT, __stub_helper:
_stub_helper:
100000 \, f70:
                4c 8d 1d 99 10 00 00
                                                  leaq
                                                             4249(\% \text{ rip}), \% \text{r}11
                            pushq
100000 \, \text{f} \, 77:
                41
                     53
                                       %r11
                                                              *129(% rip)
                     25 \ 81 \ 00 \ 00 \ 00
100000 \,\mathrm{f}79:
                 f f
                                                  jmpq
100000 \, \text{f} \, 7 \, \text{f}:
                90
                            nop
                68
                     00 00 00
                                                  $0
100000 f80:
                                 00
                                       pushq
                     e6
                                                  -26 < -stub-helper >
100000 \, f85:
                e9
                        f f
                            f f
                                 f f
                                       _{\rm jmp}
                    0e
                         00 00
                                 00
                                                  $14
100000 f8a:
                68
                                       pushq
100000 f8f:
                e9
                    dc ff
                            ff
                                       jmp
                                                  -36 < -stub-helper >
```

7 Test results

Before conducting the tests, we first calculated the estimated run times using the following formula:

$$\frac{I*CPI}{f}$$

Where I stands for the number of executed instructions, CPI is the average number of Clocks per Instruction, and f is our Clock Frequency. This will give us a time in millisecons.

For the CPIs, we weren't able to find a table that contained the specific CPIs for the Coffee Lake 14nm++ architecture from Intel, but since Coffee Lake is built on the same 14nm process as Kaby Lake, and Kaby Lake is built

on the same 14 nm process as Sylake, we took the table for the enthusiast-grade Skylake-X architecture and figured they would perform similarly given the 14 nm process situation and performance gains reported by reviewers and benchmarks available online.

Having said that, using the CPIs from Skylake-X for our calculations, we obtained an estimated time of 1.2195 ms for the execution of our non-optimized file, whereas for the optimized file, we obtained 4.3488 ms. This is to be expected, since the optimization process opts for a different approach than usual: instead of repeating the same instruction several times, we instead go for more instructions but each one is repeated less times. The estimated latency is not necessarily a definitive equivalent of what is real-world performance, since the CPI is based on averages, and different instructions take different times to execute, so we corroborate our results with the time command provided by bash:

	./nonOptreal	0.00	user	0.00	sys
time 0.10	./opt3 real	0.00	user	0.00	sys
time 0.31	./nonOptreal	0.00	user	0.00	sys
time 0.09	./opt3 real	0.00	user	0.00	sys
time 0.08	./nonOptreal	0.00	user	0.00	sys
time 0.07	./opt3real	0.00	user	0.00	sys
time 0.07	./nonOptreal	0.00	user	0.00	sys
time 0.06	./opt3real	0.00	user	0.00	sys

We ran each one four times: two with from a cold start (that is after leaving the computer idle for some time at below-base speeds -30 minutes was our standard), and two with an already warm CPU, that is, running at the full 4.1 GHz Turbo Frequency that our processor allows us to use.

8 Conclusions

We can observe from our results that even though our estimates were a bit off, perhaps because we were not using the official CPIs for the Coffee Lake processors, but rather the CPI table for an enthusiast-grade lineup of CPUs, we can actually observe a difference between the optimized and unoptimized versions of our files.

From a cold start, the execution times differ vastly, with the unoptimized version taking anywhere from 0.30 to 0.40 seconds to execute, while the optimized version took only around 0.10 seconds. This is a performance gain of nearly 70%. However, when running on a warm CPU, things weren't as drastic as with a cold CPU; the unoptimized program ran only about 0.01 seconds slower than the optimized version, which is still a performance gain, but maybe not as much as we would expect. However, this was using a fairly simple function with a quite simple task. This 0.01 second difference could add up and translate to potentially huge gains when dealing with huge programs.

9 References:

Fog, A. (2019). Lists of instruction latencies, throughputs and micro-operation breakdowns for Intel, AMD, and VIA CPUs. https://www.agner.org/optimize/instruction_tables.pdf