FIRST EDITION

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Forward

I remember when I started learning programming to which my first language was 6502 Assembler. It was to program a Commodore 64 and right from the beginning I learned the lowest level development possible.

Literally every piece of the Commodore 64 was understood as it was a simple machine. There was absolutely no abstraction layer of any kind.

Everything we did we had an absolute mastery of however it was a very simple architecture.

Microcontrollers are small systems without an operating system and are also very simple in their design. They are literally everywhere from your toaster to your fridge to your TV and billions of other electronics that you never think about.

Most microcontrollers are developed in the C programming language which has its roots to the 1970’s however dominates the landscape.

We will take our time and learn the basics of C utilizing a Pico microcontroller.

Below are items you will need for this book.

Raspberry Pi Pico
https://www.amazon.com/Raspberry-Pi-Pico-RP2040-microcontroller/dp/B092S2KCV2

Raspberry Pi Pico Debug Probe
https://www.amazon.com/GeeekPi-Raspberry-Connetor-RP2040-Microcontroller/dp/B0C5XNQ7FD

Electronics Soldering Iron Kit
https://www.amazon.com/Electronics-Adjustable-Temperature-ControlledThermostatic/dp/B0B28JQ95M?th=1

Premium Breadboard Jumper Wires
https://www.amazon.com/Keszoox-Premium-Breadboard-Jumper-Raspberry/%20dp/B09F6X3N79

Breadboard Kit
https://www.amazon.com/Breadboards-Solderless-BreadboardDistribution-Connecting/dp/B07DL13RZH

6x6x5mm Momentary Tactile Tact Push Button Switches
https://www.amazon.com/DAOKI-Miniature-Momentary-Tactile-Quality/dp/B01CGMP9GY

WS2812 NeoPixel Array
https://www.amazon.com/BTF-LIGHTING-Individual-Addressable-Flexible-Controllers/dp/B088BTYJH6

RYLR998 UART 915 MHz Lora Module w/ Antenna
https://www.amazon.com/REYAX-RYLR998-Interface-Antenna-Transceiver/dp/B099RM1XMG

NRF24L01+ Wireless Transceiver Module 2.4 G Wireless Transceiver Module
https://www.amazon.com/HiLetgo-NRF24L01-Wireless-Transceiver-Module/dp/B00LX47OCY

NOTE: The item links may NOT be available but the descriptions allow you to shop on any online or physical store of your choosing.

Let’s begin...

Table Of Contents

Chapter 1: hello, world

We begin our journey building the traditional *hello, world* example in Embedded C.

We will then reverse engineer each binary in GDB.

To setup our environment we will follow the details in the link below which covers all operating systems.

https://www.raspberrypi.com/documentation/microcontrollers/raspberry-pi-pico.html#technical-specification

The next thing we will setup is the Raspberry Pi Pico Debug Probe as there are detailed instructions below as well to get started.

https://www.raspberrypi.com/documentation/microcontrollers/debug-probe.html#about-the-debug-probe

A **PicoW-A4-Pinout.pdf** file exists in the GitHub repo as well to help find the respective pins.

If you do not have Git installed, here is a link to install git on Windows, MAC and Linux.

https://git-scm.com/book/en/v2/Getting-Started-Installing-Git

Clone the repo to whatever folder you prefer.

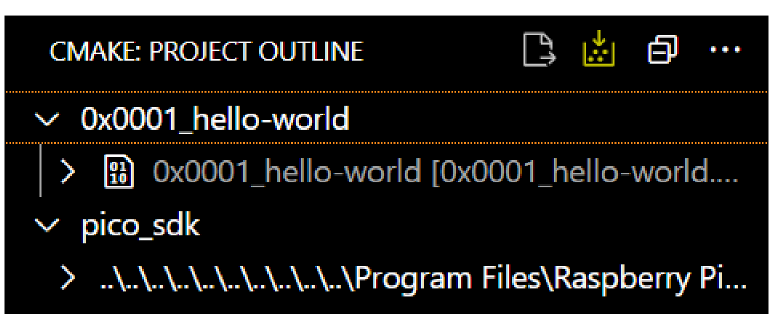
```
git clone https://github.com/mytechnotalent/Embedded-Hacking.git
```

Open VS Code and click **File** then **Open Folder …** then click on the **Embedded-Hacking** folder and then select **0x0001_hello-world**.

Give it a few minutes to initialize.

It may ask you for an active kit of which you will choose Pico ARM GCC.

On the left-hand side of the VS code window is a Cmake button. It looks like a triangle with a wrench through it. Click on the center icon to build all projects (highlighted in yellow below).



Now we are ready to flash our code onto the Pico.

Press and hold the push button we attached to the breadboard while pressing the white BOOSEL button on the Pico then release the white BOOTSEL button on the Pico and then release the push button we attached to the breadboard.

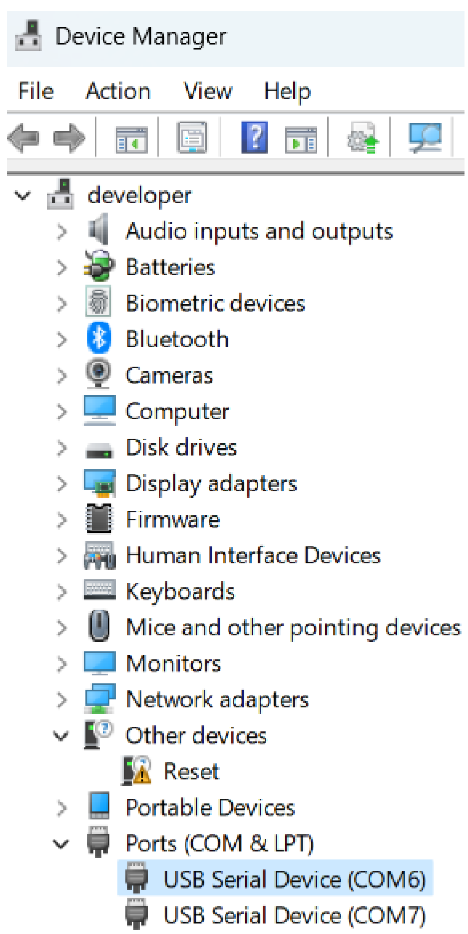
This will open up a file explorer window to copy our **0x0001_hello-world.uf2** firmware into the **RPI-RP2** drive.

```
drag and drop 0x0001_hello-world.uf2 file from the build directory to the RPI-RP2
```

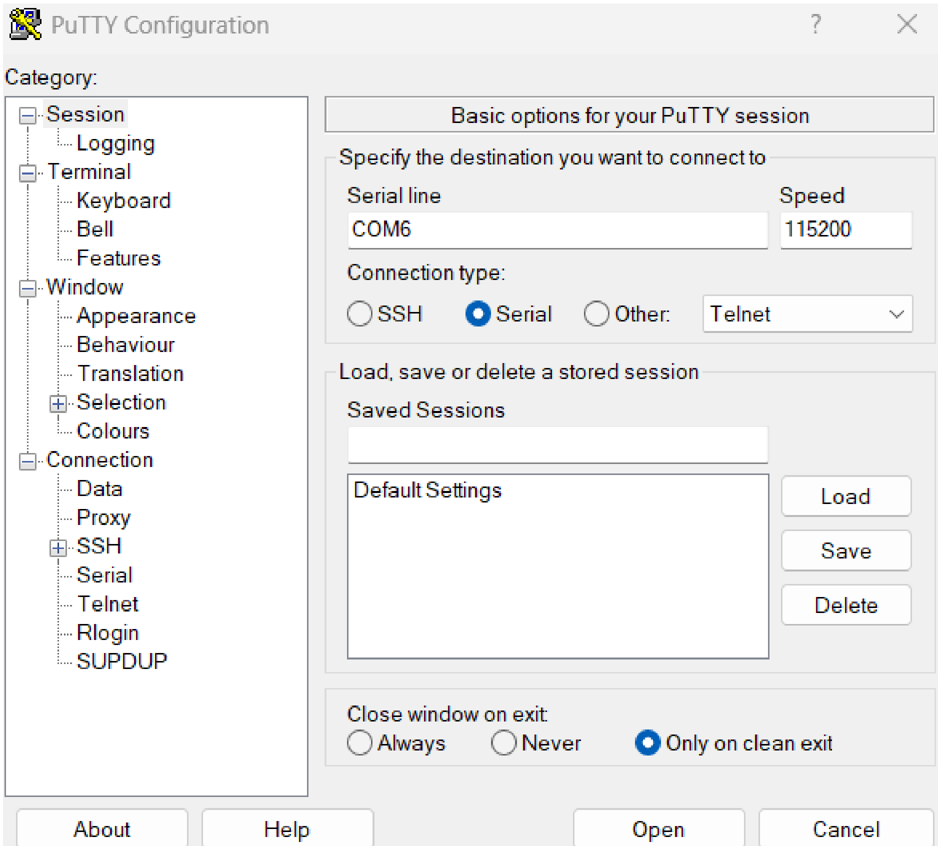
We need to download a serial monitor to interact with our Pico. If you are on Windows download PuTTY as the link is below.

https://www.putty.org

If you are on Windows you can open up the Device Manager and look for the COM port that will be used to connect PuTTY to. There are at minimum two ports one for the Pico UART and the other for the Pico Debug Probe. Try both and one of them will be UART that we are looking for.



Next step is to run PuTTY.



You want to put in your COM port, in my case COM6, and click the Open button.

If you are on MAC or Linux you can follow the instructions in the below link to use minicom.

https://www.raspberrypi.com/documentation/microcontrollers/debug-probe.html#serial-connections

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    stdio_init_all();

    while (true)
        printf("hello, world\r\n");
}
```

Let’s break down this code.

```
#include <stdio.h>
```

This line includes the stdio.h header file, which contains declarations for standard input and output functions.

```
#include "pico/stdlib.h"
```

This line includes the pico/stdlib.h header file, which contains declarations for various Raspberry Pi Pico standard library functions.

```
int main(void)
```

The above line declares the main() function, which is the entry point for all C and Python programs.

```
stdio_init_all();
```

This line initializes the standard input and output system.

```
while (true)
```

This line starts a while loop that will run forever.

```
printf("hello, world\r\n");
```

This line prints the message, *"hello, world"*, to the console.

When we open up our terminal we will see, *hello, world*, as expected being printed over and over in the terminal.

In our next lesson we will debug hello, world using the ARM embedded GDB with OpenOCD to which we will actually connect LIVE to our running Pico!

Chapter 2: Debugging hello, world

Today we debug!

Before we get started, we are going DEEP and I mean DEEP! Please do not get discouraged as I will take you through literally every single step of the binary but we need to start small.

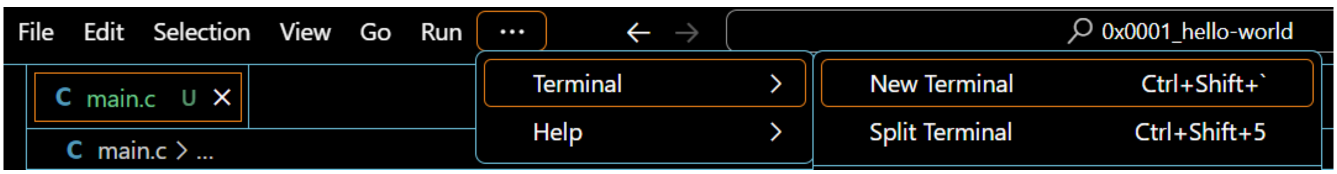
Assembler is not natural to everyone and I have another FREE book and primer on Embedded Assembler below if you feel you need a good primer. PLEASE take the time to read this book if you are new to this so that you can get the full benefit of this book.

https://github.com/mytechnotalent/Embedded-Assembler

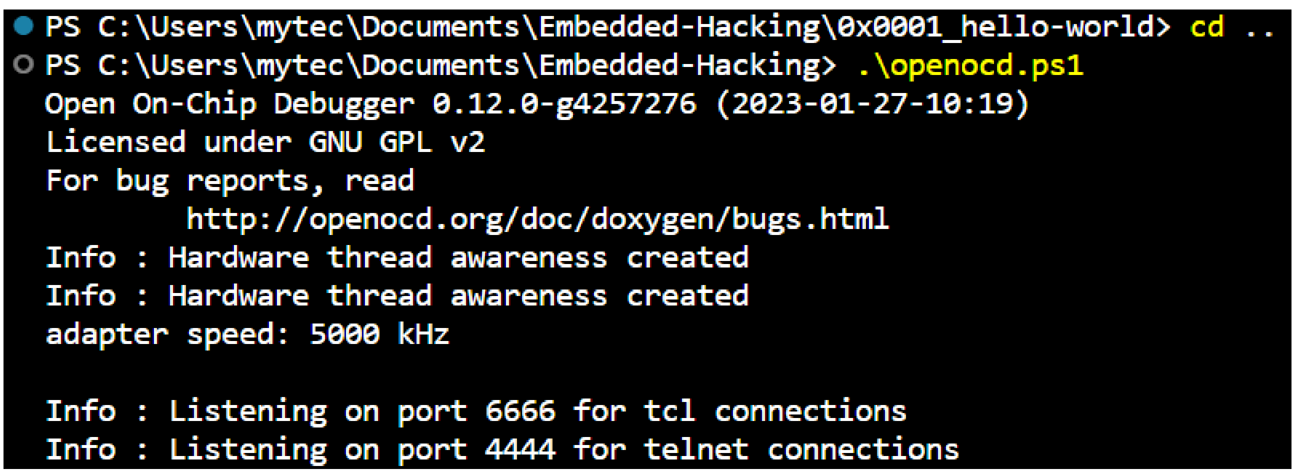
I am going to work within Windows as the majority of people I have polled for the book operate within Windows.

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```



```
PS C:\Users\mytec\Documents\Embedded-Hacking\0x0001_hello-world> cd ..
PS C:\Users\mytec\Documents\Embedded-Hacking> .\openocd.ps1
Open On-Chip Debugger 0.12.0-g4257276 (2023-01-27-10:19)
Licensed under GNU GPL v2
For bug reports, read
        http://openocd.org/doc/doxygen/bugs.html
Info : Hardware thread awareness created
Info : Hardware thread awareness created
adapter speed: 5000 kHz

Info : Listening on port 6666 for tcl connections
Info : Listening on port 4444 for telnet connections
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0001_hello-world.bin
```

```
PS C:\Users\mytec\Documents\Embedded-Hacking\0x0001_hello-world> cd .\build\
PS C:\Users\mytec\Documents\Embedded-Hacking\0x0001_hello-world\build> arm-none-eabi-gdb .\0x0001_hel
lo-world.bin
GNU gdb (GNU Arm Embedded Toolchain 10.3-2021.10) 10.2.90.20210621-git
Copyright (C) 2021 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.
Type "show copying" and "show warranty" for details.
This GDB was configured as "--host=i686-w64-mingw32 --target=arm-none-eabi".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<https://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
    <http://www.gnu.org/software/gdb/documentation/>.

For help, type "help".
Type "apropos word" to search for commands related to "word"...
"016ffbd4s": not in executable format: file format not recognized
(gdb)
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

```
(gdb) target remote :3333
Remote debugging using :3333
warning: No executable has been specified and target does not support
determining executable automatically.  Try using the "file" command.
warning: multi-threaded target stopped without sending a thread-id, using first non-exited thread
0x000000ea in ?? ()
(gdb) monitor reset halt
[rp2040.core0] halted due to debug-request, current mode: Thread
xPSR: 0xf1000000 pc: 0x000000ea msp: 0x20041f00
[rp2040.core1] halted due to debug-request, current mode: Thread
xPSR: 0xf1000000 pc: 0x000000ea msp: 0x20041f00
(gdb)
```

We need to touch base on what XIP is within the RP2040 MCU or microcontroller. This is the actual chip that powers the Pico.

XIP is called Execute In Place and is capable of directly executing code from non-volatile storage (such as flash memory) without the need to copy the code to random-access memory (RAM) first. Instead of loading the entire program into RAM, XIP systems fetch instructions directly from their storage location and execute them on the fly.

We see our PC or program counter is currently at 0x000000ea which is very low in memory.

Our goal is to find the main function within our binary to reverse engineer it. Before our main function there will be a large amount of setup code to include the vector table which will handle hardware interrupts and exceptions within our firmware which will be at the address close to the beginning of 0x10000000.

Our XIP address starts at 0x10000000 so lets examine 1000 instructions and look for a *push {r4, lr}* instruction which would indicate our main stack frame being called.

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

```
(gdb) x/1000i 0x10000000
...
0x10000304:  push    {r4, lr}
```

This is our main program. If you are new to Assembler, do NOT be discouraged as we will take this step-by-step!

We first need to have an understanding of how memory is layed out within the Pico and specifically the RP2040 chip. The RP2040 uses a dual-core ARM Cortex-M0+ processor. We begin with the concepts of the stack and heap as they are fundamental to understanding memory management in embedded systems.

The stack is a region of memory used for managing function calls and local variables. It grows and shrinks automatically as functions like main are called and return. Each time a function is called, a stack frame is created to store local variables and return addresses. The stack pointer (SP) register keeps track of the current position in the stack.

The RP2040 has a dedicated stack for each core, as it is a dual-core processor. The stack size is typically defined in the linker script or project configuration and is limited by the available RAM.

Push: Adding data to the stack (e.g., pushing function parameters).
Pop: Removing data from the stack (e.g., popping values after a function call).

The stack pointer is a register that keeps track of the current position in the stack. It is automatically adjusted during function calls and returns.

If the stack grows beyond its allocated size, it can lead to a stack overflow, causing unpredictable behavior or crashes. In contrast, the heap is a region of memory used for dynamic memory allocation. It is managed by the programmer, and memory must be explicitly allocated and deallocated.

Dynamically allocated memory using functions like malloc() or new in C or C++. It is useful for managing variable-sized data structures. The heap on the RP2040 is typically part of the RAM region. The size of the heap is not fixed and can be adjusted based on application requirements.

We can allocate and deallocate memory on the heap. Allocation: Obtaining a block of memory from the heap. Deallocation: Returning a block of memory to the heap.

Over time, as memory is allocated and deallocated, the heap may become fragmented, making it challenging to find contiguous blocks of memory.

The RP2040 uses the C standard library's memory allocation functions (malloc(), free()) to manage the heap. The size of the heap is often defined in the linker script or project configuration. Both the stack and heap are typically located in RAM.

We will not be covering dynamic memory allocation as we will utilize safer strategies for memory handling.

The RP2040 has a limited amount of RAM, so careful management is crucial. Code is stored in Flash memory, and it's executed directly from there.

There are also general-purpose registers that are essential for program execution, data manipulation, and control flow. Below is an overview of these registers:

ARM Cortex-M0+ General-Purpose Registers:

1. r0 - r12 (Register 0 - Register 12):
These are general-purpose registers used for temporary storage of data during program execution.

r0 is often used as a scratch register or for holding function return values.
r1 to r3 are also commonly used for passing function arguments.

r4 to r11 are generally used for holding variables and intermediate values.

2. r13 - Stack Pointer (SP):
r13 is the Stack Pointer (SP), which points to the current top of the stack.

The stack, as previously discussed, is used for storing local variables and managing function calls.

3. r14 - Link Register (LR):
r14 is the Link Register (LR), used to store the return address when a function is called.

Upon a function call, the address of the next instruction to be executed is stored in LR.

4. r15 - Program Counter (PC):
r15 is the Program Counter (PC), which holds the memory address of the next instruction to be fetched and executed.

When a branch or jump instruction is encountered, the new address is loaded into PC.

5. Application Program Status Register (APSR):
Contains status flags such as zero flag (Z), carry flag (C), negative flag (N), etc.

The APSR reflects the status of the ALU (Arithmetic Logic Unit) after arithmetic operations.

6. Program Status Register (PSR):
Combines the APSR with other status information.
Contains information about the current operating mode and interrupt status.

7. Control Register (CONTROL):
Contains the exception number of the current Interrupt Service Routine (ISR).

Bit 0 is the privilege level bit, determining whether the processor is in privileged or unprivileged mode.

Let’s discuss usage and considerations below.

Function Calls:

R0 to R3 are used to pass arguments to functions.
LR is used to store the return address.

The stack (SP) is used to store local variables.

Branch and Jump:

PC is updated to the new address during branch or jump instructions.
Status Registers:

APSR flags are used for conditional branching and checking the outcome of arithmetic/logic operations.
Stack Usage:

The stack (SP) is used for managing function calls and local variables.

Now let’s examine our main function.

```
(gdb) x/5i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x1000406c
   0x1000030a:  ldr     r0, [pc, #8]    ; (0x10000314)
   0x1000030c:  bl      0x10003ff4
   0x10000310:  b.n     0x1000030a
```

let’s set a breakpoint to our main function.

```
(gdb) b *0x10000304
Breakpoint 1 at 0x10000304
Note: automatically using hardware breakpoints for read-only addresses.
(gdb) c
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 1, 0x10000304 in ?? ()
```

Let’s re-examine our main function and we will see an arrow pointing to the instruction we are about to execute. Keep in mind, we have NOT executed it yet.

```
(gdb) x/5i 0x10000304
=> 0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x1000406c
   0x1000030a:  ldr     r0, [pc, #8]    ; (0x10000314)
   0x1000030c:  bl      0x10003ff4
   0x10000310:  b.n     0x1000030a
```

We are about to start off pushing the R4 register and the LR register to the stack.

Keep in mind, the base pointer (BP) is not a register in the RP2040 ARM Cortex-M0+ architecture, and therefore, it is not present as a dedicated register like in some other architectures such as x86. Instead, the ARM Cortex-M0+ architecture relies on the use of the stack pointer (SP) and the link register (LR) for managing the stack during function calls.

In ARM Cortex-M0+, the stack pointer (SP or r13) is typically used to point to the top of the stack, and it is adjusted dynamically as functions are called and return. The link register (LR or r14) is used to store the return address when a function is called. The base pointer, as seen in some other architectures like x86 (EBP), is not explicitly used or available in the same way.

In the context of the RP2040 and ARM Cortex-M0+, you would primarily rely on the stack pointer (SP) and link register (LR) for managing the stack and tracking return addresses during function calls. The base pointer concept is not part of the standard conventions for this architecture.

As stated, the LR register contains the return address to return to after main finishes. Keep in mind, we are using a micro-controller so main will be in an infinite loop and will never return.

We have not executed our first main Assembler function yet so let’s first examine what our stack contains.

```
(gdb) x/10x $sp
0x20042000:     0x00000000      0x00000000      0x00000000      0x00000000
0x20042010:     0x00000000      0x00000000      0x00000000      0x00000000
0x20042020:     0x00000000      0x00000000
```

Now lets step-into which means take a single step in Assembler.

```
(gdb) si
0x10000306 in ?? ()
(gdb) x/5i 0x10000304
   0x10000304:  push    {r4, lr}
=> 0x10000306:  bl      0x1000406c
   0x1000030a:  ldr     r0, [pc, #8]    ; (0x10000314)
   0x1000030c:  bl      0x10003ff4
   0x10000310:  b.n     0x1000030a
```

Now let’s review our stack.

```
(gdb) x/10x $sp
0x20041ff8:     0x10000264      0x10000223      0x00000000      0x00000000
0x20042008:     0x00000000      0x00000000      0x00000000      0x00000000
0x20042018:     0x00000000      0x00000000
```

We can see that we have two new addresses that were pushed onto our stack.

To prove this, let’s look at the values of R4 and LR.

```
(gdb) x/x $r4
0x10000264:     0x00004700
(gdb) x/x $lr
0x10000223:     0x00478849
```

Keep in mind, the stack grows downward so we first see the LR pushed to the top of the stack. Our stack pointer is currently at 0x20041ff8.

```
(gdb) x/x $sp+4
0x20041ffc:     0x10000223
```

We see the stack pointer was first at 0x20041ffc and then it was pushed DOWN to 0x20041ff8.

```
(gdb) x/x $sp
0x20041ff8:     0x10000264
```

I hope this helps you understand how the stack works. We will continue to examine the stack throughout this book.

Let's step-over the next instruction as it is a call to our below C-SDK function which is not of interest to as it simply sets up the MCU peripherals to communicate.

```
stdio_init_all();
```

Because we are working with a binary without any symbol info we need to do two steps which are *si* and then *ret* to return out of the function call.

```
(gdb) x/5i 0x10000304
   0x10000304:  push    {r4, lr}
=> 0x10000306:  bl      0x1000406c
   0x1000030a:  ldr     r0, [pc, #8]    ; (0x10000314)
   0x1000030c:  bl      0x10003ff4
   0x10000310:  b.n     0x1000030a
(gdb) si
0x1000406c in ?? ()
(gdb) ret
Make selected stack frame return now? (y or n) y
#0  0x1000030a in ?? ()
(gdb) x/5i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x1000406c
=> 0x1000030a:  ldr     r0, [pc, #8]    ; (0x10000314)
   0x1000030c:  bl      0x10003ff4
   0x10000310:  b.n     0x1000030a
```

Now we are about to load the value INSIDE of a memory address at 0x10000314 into R0. The *r0, [pc, #8]* means take the value at the current program counter and add 8 to it and take that address's value and store it into R0. This is a pointer which means we are pointing to the value inside that address.

Let's *si* one step and examine what is inside *r0* at this point.

```
(gdb) x/x $r0
0x10006918:     0x6c6c6568
```

Hmm… This does not look like an address however it does look like ascii chars to me. Let's look at an ascii table.

https://www.asciitable.com

We see 0x6c is l and we see it again so another l and 0x65 is e and 0x68 is h.

This is our hello, world string however it is backward! The reason is memory is stored in reverse byte order or little endian order from memory to registers within the MCU.

We can see the full pointer to this char array or string by doing the below.

```
(gdb) x/s $r0
0x10006918:     "hello, world\r"
```

This has been quite a bit of information but please take the time and work through this several times and I again encourage you to read the FREE Embedded Assembler if you want a deeper dive into this.

https://github.com/mytechnotalent/Embedded-Assembler

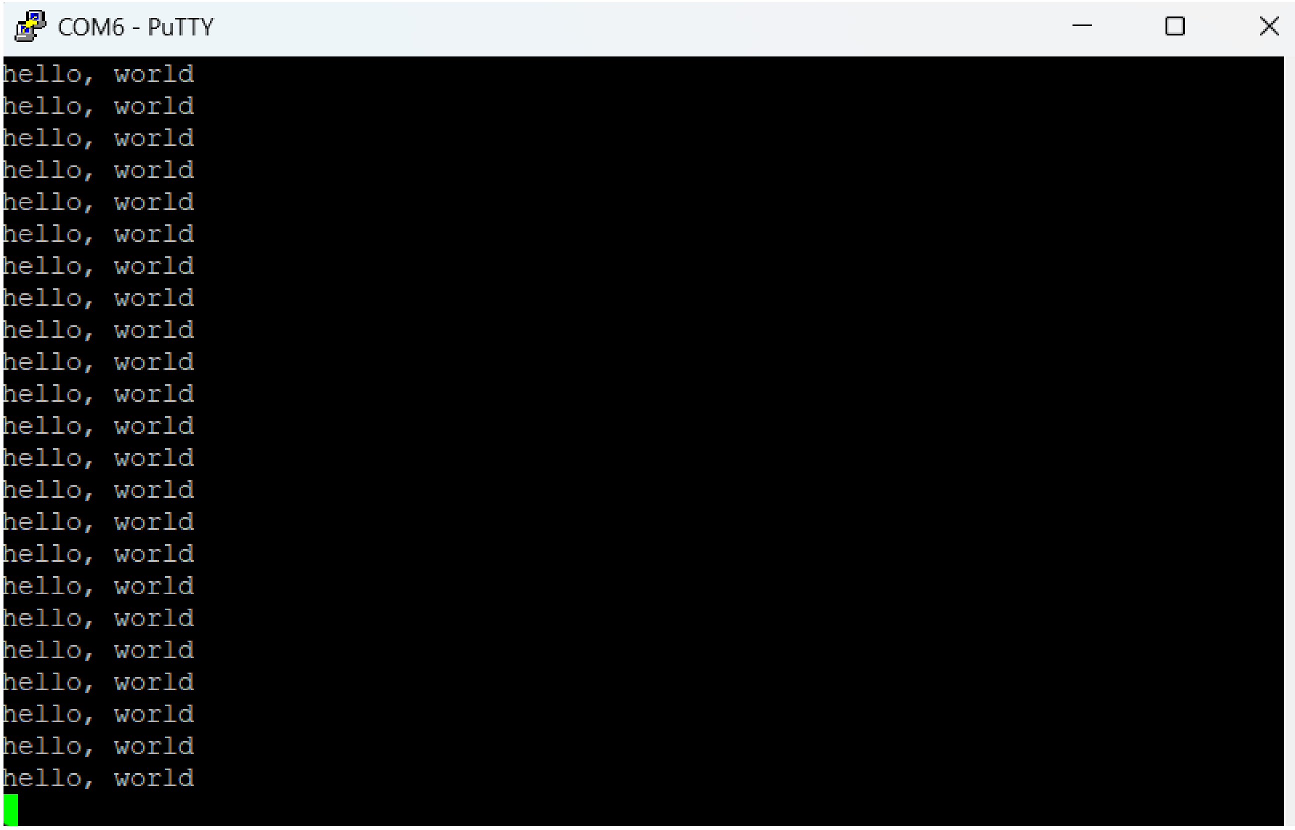
In our next lesson we will hack this hello, world program!

Chapter 3: Hacking hello, world

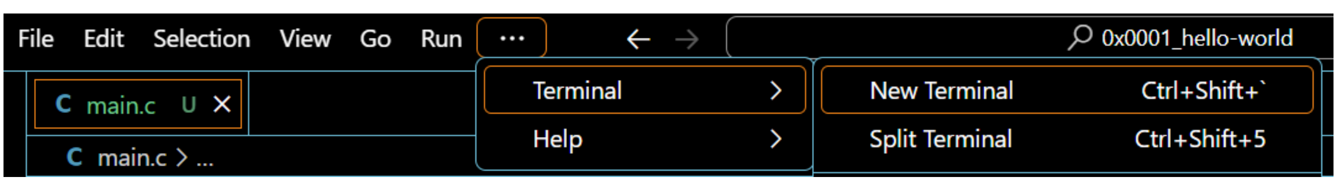
Today we hack!

Lets run OpenOCD to get our remote debug server going.

Let's run our serial monitor and observe hello, world in the infinite loop.



Open up a terminal within VSCode.




```
cd ..
```

```
.\openocd.ps1
```

```
PS C:\Users\mytec\Documents\Embedded-Hacking\0x0001_hello-world> cd ..
PS C:\Users\mytec\Documents\Embedded-Hacking> .\openocd.ps1
Open On-Chip Debugger 0.12.0-g4257276 (2023-01-27-10:19)
Licensed under GNU GPL v2
For bug reports, read
        http://openocd.org/doc/doxygen/bugs.html
Info : Hardware thread awareness created
Info : Hardware thread awareness created
adapter speed: 5000 kHz

Info : Listening on port 6666 for tcl connections
Info : Listening on port 4444 for telnet connections
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0001_hello-world.bin
```

```
PS C:\Users\mytec\Documents\Embedded-Hacking\0x0001_hello-world> cd .\build\
PS C:\Users\mytec\Documents\Embedded-Hacking\0x0001_hello-world\build> arm-none-eabi-gdb .\0x0001_hel
lo-world.bin
GNU gdb (GNU Arm Embedded Toolchain 10.3-2021.10) 10.2.90.20210621-git
Copyright (C) 2021 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.
Type "show copying" and "show warranty" for details.
This GDB was configured as "--host=i686-w64-mingw32 --target=arm-none-eabi".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<https://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
    <http://www.gnu.org/software/gdb/documentation/>.

For help, type "help".
Type "apropos word" to search for commands related to "word"...
"016ffbd4s": not in executable format: file format not recognized
(gdb)
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

```
(gdb) target remote :3333
Remote debugging using :3333
warning: No executable has been specified and target does not support
determining executable automatically.  Try using the "file" command.
warning: multi-threaded target stopped without sending a thread-id, using first non-exited thread
0x000000ea in ?? ()
(gdb) monitor reset halt
[rp2040.core0] halted due to debug-request, current mode: Thread
xPSR: 0xf1000000 pc: 0x000000ea msp: 0x20041f00
[rp2040.core1] halted due to debug-request, current mode: Thread
xPSR: 0xf1000000 pc: 0x000000ea msp: 0x20041f00
(gdb)
```

We notice our hello, world within the serial monitor is halted as expected.

Let's re-examine main.

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

```
(gdb) x/5i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x1000406c
   0x1000030a:  ldr     r0, [pc, #8]    ; (0x10000314)
   0x1000030c:  bl      0x10003ff4
   0x10000310:  b.n     0x1000030a
```

The first thing we need to do to hack our system LIVE is to set the pc to the address right before the call to printf and then set a breakpoint and then continue.

```
(gdb) set $pc = 0x1000030c
(gdb) b *0x1000030c
Breakpoint 1 at 0x1000030c
Note: automatically using hardware breakpoints for read-only addresses.
(gdb) c
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 1, 0x1000030c in ?? ()
```

The next thing we need to do is hijack the value of hello, world from 0x10000314 and create our own data within SRAM and fill it with a hacked malicious string ;)

```
(gdb) set {char[14]} 0x20000000 = {'h','a','c','k','y',',','
','w','o','r','l','d','\r','\0'}
(gdb) x/s 0x20000000
0x20000000:     "hacky, world\r"
```

Now to need to hijack the address inside r0 which is 0x10000314 and change it to our hacked address in SRAM and verify our hack.

```
(gdb) set $r0 = 0x20000000
(gdb) x/x $r0
0x20000000:     0x68
(gdb) x/s $r0
0x20000000:     "hacky, world\r"
```

Now let’s continue and execute our hack!

```
(gdb) c
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 1, 0x1000030c in ?? ()
```

Let’s verify our hack!

BOOM! We did it! We successfully hacked our LIVE binary! You can see *hacky*, world now being printed to our serial monitor!

“With great power comes great responsibility!”

Imagine we were in an enemy ICS industrial control facility, say a nuclear power enrichment facility, and we had to hack the value of one of their centrifuges.

After we hacked the centrifuges, we need to make sure the value that the Engineers are seeing on their monitor shows normal.

THIS IS EXACTLY HOW WE WOULD DO THIS!

In our next lesson we will discuss Embedded System analysis.

Chapter 4: Embedded System Analysis

We are working with a microcontroller so there is no operating system in use. This is what we refer to as bare-metal programming.

Let’s first review the RP2040 datasheet and examine a few areas of interest before we start to examine our hello world binary.

On page 25 of the RP2040 datasheet, we see area 2.2. Address Map.

We see that ROM begins at 0x00000000 and something called XIP begins at 0x10000000. We also see SRAM starting at 0x20000000 and our microcontroller peripherals start at 0x40000000.

Let’s break these down.

Base Address: 0x00000000
ROM is where the initial firmware, often referred to as "boot ROM" or "mask ROM," resides. It contains the code executed at startup. This code typically initializes essential system components and sets up the system for further program execution. Since it is read-only, this memory is used for storing permanent and unchangeable instructions.

Base Address: 0x10000000
XIP is a mechanism that allows the microcontroller to execute code directly from external Flash memory. In systems with XIP capability, the microcontroller fetches and executes instructions directly from the external Flash, eliminating the need to load the entire program into RAM first. This can be advantageous in embedded systems where RAM is limited.

Base Address: 0x20000000
SRAM is volatile memory used for storing data that needs to be accessed quickly during program execution. Unlike Flash memory (used for ROM and XIP), SRAM loses its contents when power is turned off. It is used for variables, stack, and other dynamic data during program execution.

Base Address: 0x40000000
Microcontroller peripherals include various hardware components like GPIO (General Purpose Input/Output), UART (Universal Asynchronous Receiver-Transmitter), SPI (Serial Peripheral Interface), I2C (Inter-Integrated Circuit), timers, and other controllers. These peripherals are memory-mapped, meaning they have specific addresses in the microcontroller's address space. By reading from and writing to these addresses, you can configure and interact with the various hardware features of the microcontroller.

Understanding these memory regions is crucial for bare-metal programming because you'll be directly manipulating these memory addresses to control the behavior of the microcontroller. For example, configuring GPIO pins, setting up communication peripherals, or managing interrupts involves writing to specific addresses within the peripheral memory space.

When writing a "hello world" program in bare-metal, you typically need to set up the stack, initialize necessary peripherals, and write your program code. Since there's no operating system, you have full control over the hardware and must handle everything from initialization to execution.

Another important area of the datasheet is 2.8.3. Bootroom Contents.

Address	Contents	Description
0x00000000	32-bit pointer	Initial boot stack pointer
0x00000004	32-bit pointer	Pointer to boot reset handler function
0x00000008	32-bit pointer	Pointer to boot NMI handler function
0x0000000c	32-bit pointer	Pointer to boot Hard fault handler function
0x00000010	'M', 'u', 0x01	Magic
0x00000013	byte	Bootrom version
0x00000014	16-bit pointer	Pointer to a public function lookup table
0x00000016	16-bit pointer	Pointer to a public data lookup table
0x00000018	16-bit pointer	Pointer to a helper function

Let’s break down these items in more detail and the bootroom contents exist between 0x00000000 and 0x0000001F.

Initial Boot Stack Pointer (0x00000000):
This 32-bit pointer indicates the initial stack pointer value when the device boots. The stack pointer is a register that points to the top of the stack, and it's crucial for managing function calls and storing local variables.

Pointer to Boot Reset Handler Function (0x00000004):
This 32-bit pointer indicates the address of the function that will be executed when the microcontroller is reset. The reset handler typically initializes essential system components and sets up the environment for the main program.

Pointer to Boot NMI Handler Function (0x00000008):

NMI stands for Non-Maskable Interrupt. This pointer points to the function that will handle non-maskable interrupts, which are interrupts that cannot be disabled or ignored.

Pointer to Boot Hard Fault Handler Function (0x0000000C):
This pointer indicates the address of the function that will handle hard faults. Hard faults occur when the microcontroller encounters an error that cannot be handled by the normal program flow.

Magic and Bootrom Version (0x00000010 to 0x00000013):
The values 'M', 'u', 0x01 represent a magic number that helps verify the integrity of the bootrom. This is a common technique to ensure that the bootloader or bootrom code is valid.
Bootrom version information is also provided.

Pointer to Public Function and Data Lookup Tables (0x00000014 to 0x00000017):
These pointers lead to lookup tables that likely contain information about public functions and data. Public functions could include services provided by the bootloader that are accessible to user code.

Pointer to Helper Function (0x00000018):
This pointer points to a helper function that may provide essential services during the boot process.

The Vector Table is a critical part of the microcontroller's startup process. It contains pointers to various exception and interrupt handlers. In ARM Cortex-M microcontrollers, the Vector Table is located at the beginning of the program memory.

The first entry in the Vector Table is the initial stack pointer.
The second entry is the address of the reset handler function.
Subsequent entries are usually addresses of exception and interrupt handlers.

These handlers include the NMI handler, Hard Fault handler, and others. When an exception or interrupt occurs, the microcontroller looks up the corresponding address in the Vector Table and jumps to that location to execute the associated handler code.
Understanding and, if necessary, customizing the Vector Table is crucial for bare-metal programming, as it allows you to define how the microcontroller responds to various events during its operation.

There are a number of tools to examine our firmware.

"Firmware" and a "regular application" are terms that refer to different types of software, and their distinction lies in their intended use and functionality.

Firmware is a specialized type of software that is embedded in hardware devices to control their specific functionalities. It is designed to interact closely with the hardware components of a device, providing low-level control and management. Firmware is typically stored in non-volatile memory (such as Flash memory) and is responsible for initializing the hardware and facilitating the communication between hardware and higher-level software.

In the context of the RP2040 microcontroller, firmware refers to the low-level software that is executed on the microcontroller itself. This includes the initial boot code, device initialization, and drivers for various peripherals. The firmware for RP2040 is often responsible for setting up the system, configuring peripherals, and providing a foundation for higher-level software to run on the microcontroller.

A regular application, on the other hand, is a software program designed to perform specific tasks or functions on a computing device. Unlike firmware, applications are generally written to run on top of an operating system and are more abstracted from the hardware. They leverage the services provided by the operating system and interact with the hardware through well-defined APIs (Application Programming Interfaces).

For RP2040, a regular application would be a program written to run on the microcontroller but not involved in the low-level control of hardware. Instead, it interacts with the hardware through APIs provided by the firmware. This application might perform specific tasks, such as sensor data processing, communication, or control functions, utilizing the capabilities of the microcontroller.

The Executable and Linkable Format (ELF) is a common file format for executables, object code, shared libraries, and even core dumps. It is a standard format used for binaries in many software development environments.

In the context of RP2040 development, the ELF format is often used to represent the compiled binary of both firmware and regular applications. The ELF file contains sections like text (executable code), data (initialized and uninitialized data), and various other sections that define the structure and layout of the binary. Tools in the development process, such as compilers and linkers, generate and manipulate ELF files.

In summary, firmware on RP2040 refers to the low-level software responsible for managing and controlling hardware, while a regular application is a higher-level program designed to perform specific tasks. Both firmware and regular applications for RP2040 can be represented in the ELF format, providing a standardized way to organize and distribute executable binaries.

We will revisit our hello world binary and take a deeper look into how this all works. Keep in mind we debugged with the .bin file which had no symbols or helpful locators of where things are as in the real-world of reverse engineering you will rarely get symbols.

I bring this up as to no confuse you as we are going to examine the elf binary which is a .bin file with symbols in it’s simplest explanation.

Let’s do some firmware analysis!

Open VS Code and click **File** then **Open Folder …** then click on the **Embedded-Hacking** folder and then select **0x0001_hello-world**.

Give it a few minutes to initialize.

It may ask you for an active kit of which you will choose Pico ARM GCC.

Let’s open up a terminal and take a look at our first tool.

The arm-none-eabi-objdump command is a tool used in the ARM development environment to display information about object files. The -h option specifies that you want to display the section headers of the ELF (Executable and Linkable Format) file.

When you run the **arm-none-eabi-objdump -h** command on a specific ELF binary file (in this case, .build\0x0001_hello-world.elf), it provides detailed information about the various sections in that ELF file.

Let's break down what this command will show and how it relates to the RP2040 ELF binary:

Section Headers:

Sections are parts of the ELF file that organize and hold specific types of data. Section headers contain information about each section, such as its name, type, virtual address, size, and other attributes.

Output Format:
The output of the **arm-none-eabi-objdump -h** command typically includes a table with columns representing different attributes of each section.

The columns may include:
Name: The name of the section.
Size: The size of the section in bytes.
VMA (Virtual Memory Address): The virtual memory address at which the section is loaded into memory.
LMA (Load Memory Address): The load memory address, which is the same as VMA for most sections.
Offset: The offset of the section in the file.
Align: The alignment requirement for the section.

For the RP2040 microcontroller, the ELF binary would contain sections that represent different parts of the program, including code sections, data sections, and potentially sections related to microcontroller-specific features.

The ELF file for RP2040 would likely include sections for the bootloader, firmware, and potentially user applications. The bootloader, for example, might reside at a specific address in the memory space, and the ELF file's section headers would provide details about the location and size of the bootloader code and data.

The information provided by the section headers is crucial for understanding how the ELF file is mapped into the memory space of the RP2040. This includes the starting addresses of various sections and their sizes, which are essential for programming and debugging embedded systems.

In summary, running **arm-none-eabi-objdump -h** on the RP2040 ELF binary will show detailed information about the sections within the binary, helping developers understand how different parts of the program are organized in memory and how they relate to the RP2040 microcontroller's architecture.

Let’s run the following.

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

```
arm-none-eabi-objdump -h .\build\0x0001_hello-world.elf

.\build\0x0001_hello-world.elf:     file format elf32-littlearm

Sections:
Idx Name          Size      VMA       LMA       File off  Algn
  0 .boot2        00000100  10000000  10000000  00001000  2**0
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  1 .text         00006818  10000100  10000100  00001100  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  2 .rodata       00001758  10006918  10006918  00007918  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  3 .binary_info  00000028  10008070  10008070  00009070  2**2
                  CONTENTS, ALLOC, LOAD, DATA
  4 .ram_vector_table 000000c0  20000000  20000000  00009cb8  2**2
                  CONTENTS
  5 .data         00000bf8  200000c0  10008098  000090c0  2**4
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
  6 .uninitialized_data 00000000  20000cb8  20000cb8  00009d78  2**0
                  CONTENTS
  7 .scratch_x    00000000  20040000  20040000  00009d78  2**0
                  CONTENTS
  8 .scratch_y    00000000  20041000  20041000  00009d78  2**0
                  CONTENTS
  9 .bss          00000d94  20000cb8  20000cb8  00009cb8  2**3
                  ALLOC
 10 .heap         00000800  20001a4c  20001a4c  00009d78  2**2
                  CONTENTS, READONLY
 11 .stack_dummy  00000800  20041000  20041000  0000a580  2**5
                  CONTENTS, READONLY
 12 .ARM.attributes 00000028  00000000  00000000  0000ad80  2**0
                  CONTENTS, READONLY
 13 .comment      00000049  00000000  00000000  0000ada8  2**0
                  CONTENTS, READONLY
 14 .debug_info   00025b3b  00000000  00000000  0000adf1  2**0
                  CONTENTS, READONLY, DEBUGGING, OCTETS
 15 .debug_abbrev 00006d3c  00000000  00000000  0003092c  2**0
                  CONTENTS, READONLY, DEBUGGING, OCTETS
 16 .debug_aranges 00001400  00000000  00000000  00037668  2**3
                  CONTENTS, READONLY, DEBUGGING, OCTETS
 17 .debug_ranges 00004bd0  00000000  00000000  00038a68  2**3
                  CONTENTS, READONLY, DEBUGGING, OCTETS
 18 .debug_line   0001804f  00000000  00000000  0003d638  2**0
                  CONTENTS, READONLY, DEBUGGING, OCTETS
 19 .debug_str    00007638  00000000  00000000  00055687  2**0
                  CONTENTS, READONLY, DEBUGGING, OCTETS
 20 .debug_frame  00002ac0  00000000  00000000  0005ccc0  2**2
                  CONTENTS, READONLY, DEBUGGING, OCTETS
 21 .debug_loc    00018ed3  00000000  00000000  0005f780  2**0
                  CONTENTS, READONLY, DEBUGGING, OCTETS
```

1. .boot2 Section:

Size: 256 bytes (0x100)
VMA (Virtual Memory Address): 0x10000000
LMA (Load Memory Address): 0x10000000
File Offset: 0x1000
Attributes: CONTENTS, ALLOC, LOAD, READONLY, CODE
This section likely contains the bootloader code. It is read-only, loaded into memory at the specified address (0x10000000), and contains executable code.

2. .text Section:
Size: 26680 bytes (0x6818)
VMA: 0x10000100
LMA: 0x10000100
File Offset: 0x1100
Attributes: CONTENTS, ALLOC, LOAD, READONLY, CODE
This is the main code section (.text) of your program. It is read-only, loaded into memory at 0x10000100, and contains the executable instructions of your program.

3. .rodata Section:
Size: 5976 bytes (0x1758)
VMA: 0x10006918
LMA: 0x10006918
File Offset: 0x7918
Attributes: CONTENTS, ALLOC, LOAD, READONLY, DATA
This section likely contains read-only data (constants, strings, etc.) used by your program. It is loaded into memory at 0x10006918.

4. .binary_info Section:
Size: 40 bytes (0x28)
VMA: 0x10008070
LMA: 0x10008070
File Offset: 0x9070
Attributes: CONTENTS, ALLOC, LOAD, DATA
This section contains binary information. It is loaded into memory at 0x10008070.

5. .ram_vector_table Section:
Size: 192 bytes (0xC0)
VMA: 0x20000000
LMA: 0x20000000
File Offset: 0x9CB8
Attributes: CONTENTS
This section likely contains the vector table for interrupts. It's loaded into RAM at 0x20000000.
6. .data Section:
Size: 3064 bytes (0xBF8)

VMA: 0x200000C0
LMA: 0x10008098
File Offset: 0x90C0
Attributes: CONTENTS, ALLOC, LOAD, READONLY, CODE
This is the initialized data section. It includes initialized global and static variables. It is loaded into RAM at 0x200000C0.

7. .uninitialized_data Section:
Size: 0 bytes
VMA: 0x20000CB8
LMA: 0x20000CB8
File Offset: 0x9D78
Attributes: CONTENTS
This section is for uninitialized data. It's likely that the .bss section will fulfill the same purpose.

8-11. .scratch_x, .scratch_y, .bss, .heap Sections:
These sections represent scratch memory, uninitialized data, heap, and stack.

12-20. Debug Sections:
These sections contain debugging information (.ARM.attributes, .comment, .debug_info, .debug_abbrev, .debug_aranges, .debug_ranges, .debug_line, .debug_str, .debug_frame, .debug_loc).

Understanding these sections is crucial for debugging and memory management. The .text section contains the main code, .data contains initialized data, and .bss is for uninitialized data.
The .ram_vector_table is essential for interrupt handling, and other sections provide additional details and support for debugging.

When programming the RP2040, it's important to know where each section is loaded in memory, especially when dealing with limited resources in embedded systems. The memory map and section headers provide insight into how your code and data are organized in the memory space of the microcontroller.

Let’s examine our next tool.

The -D option in the arm-none-eabi-objdump command stands for "disassemble." When used, it instructs the objdump tool to display the disassembly of the entire ELF file, including all sections. Let's break down how this option works and why it's relevant.

```
arm-none-eabi-objdump -D .\build\0x0001_hello-world.elf | less
```

arm-none-eabi-objdump: The main command for disassembling and inspecting binary files in the ARM embedded toolchain.

-D: This option tells objdump to disassemble the contents of the ELF file. It means that the tool will convert the machine code instructions in the binary file into human-readable assembly language instructions. The disassembly output will include not only the code sections but also information about other sections like data, symbols, and more.

.\build\0x0001_hello-world.elf: This is the path to the ELF file that you want to analyze. Replace this with the actual path to your compiled program.

| less: The pipe (|) operator is used to send the output of objdump to the less command. less is a pager program that allows you to scroll through large amounts of text one screen at a time.

The -D option is crucial for gaining a comprehensive understanding of the program. It disassembles the entire content of the ELF file, providing insights into the machine-level instructions generated by the compiler.

Disassembling all sections means that you get information about not only the code sections (.text), but also other sections like data (.data, .bss), symbols, and potentially debug information. This can be valuable for debugging, analyzing memory usage, and understanding the structure of your program.

The Vector Table, which contains addresses of interrupt and exception handlers, is included in the disassembly. By disassembling all sections, you can locate the Vector Table and understand how the microcontroller responds to different events.
Memory Layout Visualization:

The disassembly output includes information about the memory layout, showing where different sections are loaded in memory. This is particularly important in embedded systems where memory usage is critical.

Disassembly is a powerful tool for debugging and optimization. It allows you to inspect the generated machine code, identify potential issues, and optimize the code for size or performance.
By using the -D option in objdump, you obtain a detailed disassembly of your program, providing a deep insight into how the high-level code you wrote is translated into low-level machine instructions for the target microcontroller. This is invaluable for embedded systems development, especially when working with resource-constrained devices like the RP2040.

The -D option in arm-none-eabi-objdump instructs the tool to disassemble the contents of the ELF file, providing a human-readable representation of the machine code instructions. However, disassembling data as if it were instructions can result in nonsense output because the tool interprets arbitrary data as if it were executable code. Let's explore why this can happen:

One of the issues with this tool is that the data sections are misinterpreted. The -D option doesn't discriminate between code sections (text) and data sections. It attempts to disassemble all sections in the ELF file. This means that sections containing non-executable data, such as initialized or uninitialized variables, will be disassembled as if they were instructions.

Data sections might contain values that, when interpreted as instructions, result in nonsensical or invalid opcodes. For example, a sequence of bytes representing ASCII characters or numeric values might not make sense when treated as executable instructions.

When disassembling data, you might see output that appears to be assembly instructions, but these are essentially meaningless in terms of program execution. It can be misleading and confusing, especially if you're expecting only code sections to be disassembled.
Symbol Confusion:

The disassembler might attempt to interpret data values as symbolic instructions, leading to the creation of pseudo-instructions that don't correspond to any valid machine code. This can make it challenging to distinguish between actual instructions and arbitrary data.

Example:
Consider a simple data section that contains an array of 32-bit integers:

```
// Data section
int data_array[] = {0x12345678, 0xAABBCCDD, 0xDEADBEEF};
```

When disassembling this data section with -D, the tool might interpret the data values as instructions and attempt to disassemble them. However, these values don't represent valid ARM instructions, leading to nonsense output.

Another import part of this analysis is the Vector Table. The Vector Table is a critical part of ARM Cortex-M microcontrollers. It contains addresses of interrupt service routines (ISRs) and is usually located at the beginning of the program memory. Let's discuss how you can find and interpret the Vector Table in the disassembly output:

Scroll through the disassembled code using the arrow keys. The Vector Table is typically located at the beginning of the disassembly output.

In the Vector Table, you should see a list of addresses at the beginning of the disassembly, each corresponding to a specific interrupt or exception.

The first entry in the Vector Table is the address of the Reset Handler, which is the starting point of your program. It's the address where the microcontroller jumps to when it is powered on or reset.

Following the Reset Handler, you'll find addresses for other exception handlers, such as NMI, Hard Fault, and various interrupts. Understand the Addresses:

Each address in the Vector Table points to the corresponding handler function or routine that should be executed when the associated interrupt or exception occurs.

For example, if you see an address like 0x10000100 in the disassembly output, it likely corresponds to the Reset Handler. The exact details will depend on your specific program and the configuration of your microcontroller.

By examining the disassembly output with objdump, you can gain insights into how your code is translated into machine instructions, identify key sections such as the Vector Table, and understand the flow of control in your program.

```
arm-none-eabi-objdump -D .\build\0x0001_hello-world.elf | less

.\build\0x0001_hello-world.elf:     file format elf32-littlearm


Disassembly of section .boot2:

10000000 <__boot2_start__>:
10000000:       4b32b500        blmi    10cad408 <__flash_binary_end+0xca4778>
10000004:       60582021        subsvs  r2, r8, r1, lsr #32
10000008:       21026898                        ; <UNDEFINED> instruction:
0x21026898
1000000c:       60984388        addsvs  r4, r8, r8, lsl #7
10000010:       611860d8        ldrsbvs r6, [r8, -r8]
10000014:       4b2e6158        blmi    10b9857c <__flash_binary_end+0xb8f8ec>
10000018:       60992100        addsvs  r2, r9, r0, lsl #2
```

```
1000001c:       61592102        cmpvs   r9, r2, lsl #2
10000020:       22f02101        rscscs  r2, r0, #1073741824     ; 0x40000000
10000024:       492b5099        stmdbmi fp!, {r0, r3, r4, r7, ip, lr}
10000028:       21016019        tstcs   r1, r9, lsl r0
1000002c:       20356099        mlascs  r5, r9, r0, r6
10000030:       f844f000                        ; <UNDEFINED> instruction:
0xf844f000
10000034:       42902202        addsmi  r2, r0, #536870912      ; 0x20000000
10000038:       2106d014        tstcs   r6, r4, lsl r0
1000003c:       f0006619                        ; <UNDEFINED> instruction:
0xf0006619
10000040:       6e19f834        mrcvs   8, 0, APSR_nzcv, cr9, cr4, {1}
10000044:       66192101        ldrvs   r2, [r9], -r1, lsl #2
10000048:       66182000        ldrvs   r2, [r8], -r0
1000004c:       f000661a                        ; <UNDEFINED> instruction:
0xf000661a
10000050:       6e19f82c        cdpvs   8, 1, cr15, cr9, cr12, {1}
10000054:       6e196e19        mrcvs   14, 0, r6, cr9, cr9, {0}
10000058:       f0002005                        ; <UNDEFINED> instruction:
0xf0002005
1000005c:       2101f82f        tstcs   r1, pc, lsr #16 ; <UNPREDICTABLE>
10000060:       d1f94208        mvnsle  r4, r8, lsl #4
10000064:       60992100        addsvs  r2, r9, r0, lsl #2
10000068:       6019491b        andsvs  r4, r9, fp, lsl r9
1000006c:       60592100        subsvs  r2, r9, r0, lsl #2:
…
```

The contents are quite large but when you run this on your own you will see the extent of the result. The key is this is everything and you need to ignore the data representation of attempted Assembler code as noted above.

Let’s examine our next tool.

The -d flag in the arm-none-eabi-objdump command specifies that you want to disassemble the executable sections of the ELF file. Here's what the -d flag does:

arm-none-eabi-objdump -d .\build\0x0001_hello-world.elf | less
arm-none-eabi-objdump: The main command for disassembling and inspecting binary files in the ARM embedded toolchain.

-d: This option stands for "disassemble." It instructs objdump to disassemble the contents of the ELF file. Unlike the -D option, which disassembles all sections, the -d option specifically focuses on the code sections (text sections) of the program.

.\build\0x0001_hello-world.elf: This is the path to the ELF file that you want to analyze. Replace this with the actual path to your compiled program.

| less: The pipe (|) operator is used to send the output of objdump to the less command. less is a pager program that allows you to scroll through large amounts of text one screen at a time.

The -d option is useful when you specifically want to focus on disassembling the code sections of your program. This is typically the section where the machine code instructions of your program's executable code reside (commonly named .text).

The output of the -d option is human-readable assembly code. It provides a translation of the machine code instructions into mnemonic instructions that are easier for a human to understand.

Disassembling the code helps you understand the flow of your program at the assembly level. You can see the instructions that make up each function and analyze the control flow between different parts of your code.

The disassembled code is often used for debugging and analysis. It allows you to inspect the generated machine code, identify potential issues, and understand how the high-level code you wrote is translated into low-level instructions for the target microcontroller.

Example:
If you have a simple C program like:

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    stdio_init_all();

    while (true)
        printf("hello, world\r\n");
}
```

This command below will output the disassembled code for the .text section, showing the assembly instructions generated by the compiler for your main function and any other code in the program.

The -d option is particularly useful when you are interested in examining the assembly representation of the machine code instructions in the code sections of your ELF file.

```
arm-none-eabi-objdump -d .\build\0x0001_hello-world.elf | less

.\build\0x0001_hello-world.elf:     file format elf32-littlearm

Disassembly of section .boot2:
```

```
10000000 <__boot2_start__>:
10000000:       4b32b500        .word   0x4b32b500
10000004:       60582021        .word   0x60582021
10000008:       21026898        .word   0x21026898
1000000c:       60984388        .word   0x60984388
10000010:       611860d8        .word   0x611860d8
10000014:       4b2e6158        .word   0x4b2e6158
10000018:       60992100        .word   0x60992100
…
```

Like our previous command, the results are many pages long but will be good to run in your terminal to get an idea of how our binary looks which starts at 0x10000000 XIP as we discussed prior.

Let’s examine our next tool.

The arm-none-eabi-objdump -s command is used to display the content of sections in a binary file. The -s option specifies that you want to view the contents of sections, and it is often used for inspecting the raw data within different sections of an ELF (Executable and Linkable Format) file. Let's break down what the command does:

arm-none-eabi-objdump -s .\build\0x0001_hello-world.elf | less

arm-none-eabi-objdump: The main command for disassembling and inspecting binary files in the ARM embedded toolchain.

-s: This option tells objdump to display the contents of sections in a binary file. Unlike the -d option, which disassembles the code sections into human-readable assembly language, the -s option displays the raw data within the specified sections.

.\build\0x0001_hello-world.elf: This is the path to the ELF file that you want to analyze. Replace this with the actual path to your compiled program.

| less: The pipe (|) operator is used to send the output of objdump to the less command, allowing you to scroll through large amounts of text one screen at a time.

Relevance of -s and Displaying Section Contents:

The -s option is used to view the raw binary data within specific sections of the ELF file. This can include code sections, data sections, symbol tables, and more.

By inspecting the contents of sections, you gain insights into how different types of data are organized in memory. This is crucial for understanding the memory layout of your program and for debugging purposes.

For non-code sections, such as .data or .rodata, the -s option allows you to inspect the actual data values stored in these sections. This is valuable for understanding the initialized and constant data used by your program.

The -s option can also be used to inspect symbol tables and other debug-related sections. This is important for debugging tools and for understanding the relationship between high-level source code and low-level machine code.
Inspecting section contents is helpful for low-level analysis, especially when you need to understand how specific data or code is laid out in memory. It complements the information provided by disassembly (-d) by giving you a more direct view of the raw binary data stored in different sections of your executable.

```
arm-none-eabi-objdump -s .\build\0x0001_hello-world.elf | less

.\build\0x0001_hello-world.elf:     file format elf32-littlearm

Contents of section .boot2:
 10000000 00b5324b 21205860 98680221 88439860  ..2K! X`.h.!.C.`
 10000010 d8601861 58612e4b 00219960 02215961  .`.aXa.K.!.`.!Ya
 10000020 0121f022 99502b49 19600121 99603520  .!.".P+I.`.!.`5
 10000030 00f044f8 02229042 14d00621 196600f0  ..D..".B...!.f..
 10000040 34f8196e 01211966 00201866 1a6600f0  4..n.!.f. .f.f..
 10000050 2cf8196e 196e196e 052000f0 2ff80121  ,..n.n.n. ../..!
 10000060 0842f9d1 00219960 1b491960 00215960  .B...!.`.I.`.!Y`
 10000070 1a491b48 01600121 9960eb21 1966a021  .I.H.`.!.`.!.f.!
 10000080 196600f0 12f80021 99601649 14480160  .f.....!.`.I.H.`
 10000090 01219960 01bc0028 00d00047 12481349  .!.`...(...G.H.I
…
```

Like many of the previous commands, we are only showing the first page.

Let’s explore our next command.

The arm-none-eabi-readelf command is a tool that displays information about ELF (Executable and Linkable Format) files. The -a option in the command stands for "all," and it instructs readelf to display all available information about the ELF file. The | less part of the command pipes the output through the less command, allowing you to scroll through the information one screen at a time.

Here's a breakdown of what the command does:

arm-none-eabi-readelf -a .\build\0x0001_hello-world.elf | less
arm-none-eabi-readelf: This is the command for reading and displaying information about ELF files in the ARM embedded toolchain.

-a: This option tells readelf to display all available information about the ELF file. This includes information about the ELF header, program headers, section headers, symbol tables, and more.

.\build\0x0001_hello-world.elf: This is the path to the ELF file that you want to analyze. Replace this with the actual path to your compiled program.
| less: The pipe (|) operator is used to send the output of readelf to the less command, allowing you to scroll through large amounts of text one screen at a time.

The -a option provides a comprehensive overview of the ELF file. It includes information about the ELF header, program headers, section headers, symbol tables, and more. This is valuable for understanding the structure and contents of the binary.

The ELF header contains essential information about the binary, such as the architecture, entry point, program header table offset, section header table offset, and other metadata.
Program Headers:

Program headers provide information about how the ELF file should be loaded into memory. This includes details about the different segments of the program, such as code and data segments.

Section headers provide information about the various sections in the ELF file, including code sections, data sections, symbol tables, and more. This helps in understanding the layout of data and code in the binary.

Symbol tables contain information about symbols (functions, variables) present in the binary. This is crucial for debugging and understanding the relationship between high-level source code and low-level machine code.

When running the command, you will see a detailed output that includes information about the ELF header, program headers, section headers, symbol tables, and other relevant information about the structure and content of your ELF file.

This command is particularly useful for gaining a deep understanding of the ELF file, especially when you need detailed information beyond what is provided by tools like objdump. It's a versatile tool for inspecting various aspects of the binary, making it valuable in the context of embedded systems development and low-level programming.

```
arm-none-eabi-readelf -a .\build\0x0001_hello-world.elf | less

ELF Header:
```

```
  Magic:   7f 45 4c 46 01 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF32
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           ARM
  Version:                           0x1
  Entry point address:               0x100001e9
  Start of program headers:          52 (bytes into file)
  Start of section headers:          524904 (bytes into file)
  Flags:                             0x5000200, Version5 EABI, soft-float ABI
  Size of this header:               52 (bytes)
  Size of program headers:           32 (bytes)
  Number of program headers:         3
  Size of section headers:           40 (bytes)
  Number of section headers:         26
  Section header string table index: 25

Section Headers:
  [Nr] Name              Type            Addr     Off    Size   ES Flg Lk Inf Al
  [ 0]                   NULL            00000000 000000 000000 00      0   0  0
  [ 1] .boot2            PROGBITS        10000000 001000 000100 00  AX  0   0  1
  [ 2] .text             PROGBITS        10000100 001100 006818 00  AX  0   0  8
  [ 3] .rodata           PROGBITS        10006918 007918 001758 00   A  0   0  8
  [ 4] .binary_info      PROGBITS        10008070 009070 000028 00  WA  0   0  4
  [ 5] .ram_vector_table PROGBITS        20000000 009cb8 0000c0 00   W  0   0  4
…
```

Like the rest, this is just a small section you can try this out on your own to get the full contents.

There are two more useful commands to review.

The arm-none-eabi-nm command is a tool that displays symbol information from object files or executables. The command you provided, arm-none-eabi-nm .\build\0x0001_hello-world.elf | less, is using nm to display symbol information for the specified ELF (Executable and Linkable Format) file and piping the output through the less command for easier navigation.

arm-none-eabi-nm .\build\0x0001_hello-world.elf | less

arm-none-eabi-nm: This is the command for displaying symbol information from object files or executables in the ARM embedded toolchain.

.\build\0x0001_hello-world.elf: This is the path to the ELF file that you want to analyze. Replace this with the actual path to your compiled program.

| less: The pipe (|) operator is used to send the output of nm to the less command, allowing you to scroll through large amounts of text one screen at a time.

The nm displays information about symbols in the ELF file. Symbols include functions, variables, and other program entities. This information is crucial for understanding the structure of your program at the symbol level.

For each symbol, nm provides its address in memory. This is useful for understanding where functions and variables are located within the program's memory space.

Symbols are categorized into different types, such as functions, variables, or sections. This helps you quickly identify the role of each symbol in your program.

Symbol information is essential for debugging. When you encounter issues in your program, knowing the addresses and types of symbols can aid in identifying problems and understanding the program's behavior.

nm is often integrated into build systems or used as part of the development process to inspect and analyze ELF files. It can be part of scripts or automation workflows for examining symbols and addresses.

Example Output:
You will see an output that lists symbols along with their addresses and types. Here's a simplified example:

```
08000100 T _start
08000104 T main
08000120 T printf
08000200 D data_variable
T: Indicates a code symbol (function).
D: Indicates a data symbol (variable).
```

08000100, 08000104, etc.: The address in memory.
By inspecting the symbol table, you can gain insights into the structure of your program, understand the memory layout, and use the information for debugging and analysis. It's a valuable tool for low-level programming and embedded systems development.

```
arm-none-eabi-nm .\build\0x0001_hello-world.elf | less
10006888 t ____aeabi_idiv0_veneer
10006858 t ____aeabi_ldiv0_veneer
20000b30 t ____assert_func_veneer
20000b20 t ____wrap___aeabi_lmul_veneer
20000b60 t ____wrap_memcpy_veneer
```

```
20000b50 t ____wrap_memset_veneer
10006908 t ___hw_endpoint_buffer_control_update32_veneer
10003534 t __aeabi_bits_init
10003a76 t __aeabi_dfcmple_guts
10003bc0 T __aeabi_double_init
10003d00 T __aeabi_float_init
20000b08 W __aeabi_idiv0
20000b08 W __aeabi_ldiv0
10003d88 T __aeabi_mem_init
10002290 T __assert_func
20000b90 t __best_effort_wfe_or_timeout_veneer
10007c8c r __bi_188.0
100002ac t __bi_22
100002a0 t __bi_30
10007be8 r __bi_33.4
10007bf4 r __bi_34.5
10000294 t __bi_38
10007b7c r __bi_44
10000288 t __bi_50
10007b88 r __bi_75
10007b94 r __bi_81
10008094 d __bi_ptr188.4
10008070 d __bi_ptr22
10008074 d __bi_ptr30
…
```

When you run on your own you will see the entire contents.

Our final command is the strings command.

The arm-none-eabi-strings command is used to extract printable character sequences (strings) from binary files. When applied to an ELF (Executable and Linkable Format) file, it can reveal human-readable strings embedded within the binary. The | less part of the command pipes the output through the less command, allowing you to scroll through large amounts of text one screen at a time.

arm-none-eabi-strings .\build\0x0001_hello-world.elf | less

arm-none-eabi-strings: This is the command for extracting printable strings from binary files in the ARM embedded toolchain.

.\build\0x0001_hello-world.elf: This is the path to the ELF file that you want to analyze. Replace this with the actual path to your compiled program.

| less: The pipe (|) operator is used to send the output of strings to the less command, allowing you to scroll through large amounts of text one screen at a time.

The strings command helps you identify and inspect human-readable text within the binary. This includes strings used in your code, such as debug messages, error messages, and other informative text.

Extracted strings can be useful for debugging and analysis. By reviewing the strings present in the binary, you may gain insights into the behavior of the program and identify specific points of interest.

It allows you to verify that constants or string literals in your code are present in the binary as expected. This is particularly useful for confirming that messages and constants defined in your source code are correctly included in the compiled binary.

Analyzing strings in a binary is also a common practice for security analysis. It can help identify sensitive information or hardcoded credentials that should not be exposed in a production binary.

You'll see a mix of strings that are part of your code, standard library functions, and potentially other information embedded in the binary. By examining these strings, you can gain a better understanding of the content and functionality of the compiled program. Keep in mind that not all strings extracted may be directly visible in your source code; some might be library or system-related.

```
arm-none-eabi-strings .\build\0x0001_hello-world.elf | less
```

```
2K! X`
aXa.K
pG      H
`SL{
RPT"
""@     *
K#+p
"iF(
FWFNFEF
FdDch
#hZ@
`CFc`BF
!hy@
-J.H
*K,JZb
`'K[l
XpGD
h@"b@
F`DA`
FaD     J
K#CC
FWFNFEF
FRFAFHF
VKVJ
VKSJ
```

```
GKCJ
+K+J
KZFAFR
RASC
…
```

Keep parsing through the output. You should see our hello, world sting in there.

You can use grep to find specifically what you are looking for like this.

```
arm-none-eabi-strings .\build\0x0001_hello-world.elf | grep -i "hello"
```

```
 hello, world
0x0001_hello-world
C:/Users/mytec/Documents/Embedded-Hacking/0x0001_hello-world
C:/Users/mytec/Documents/Embedded-Hacking/0x0001_hello-world/main.c
C:\Users\mytec\Documents\Embedded-Hacking\0x0001_hello-world\build
```

I know this was a longer chapter but please take the time and understand these tools and getting a better understanding of what firmware is and in this case how it is specific to the M0+ and RP2040 MCU.

In our next lesson we will have an intro to variables.

Chapter 5: Intro To Variables

In this chapter we are going to introduce the concept of a variable. If we have a series of boxes all layed out in a row and we numbered them from 0 to 9 (we start with 0 in Engineering) and then placed item 0 in box 0 and then item 1 in box 1 all the way to item 9 in box 9.

The boxes in this analogy represents our SRAM. The items are nothing more than variables of different types, which we will discuss later, that are stored in each of these addresses.

For the Developer, you simply provide a type and a name and the compiler will assign to the value to an actual address.

One of the most important considerations is that you have to declare variables before you use them in a program.

The process of **declaration** provides the compiler the size and name of the variable you are creating.

The process of **definition** allocates memory to a variable.

These two processes are usually done at the same time.

Let’s look at some code.

```
uint8_t age;
```

Here we have a data type which is *uint8_t* and the name of the variable which is *age*.

The data type determines how much space a variable is going to occupy in memory. This will signal the compiler to allocate space for it.

A semicolon signals to the compiler that a statement is complete. In our case the statement was the *uint8_t age*.

The *uint8_t* type takes up 1 byte of memory it is an unsigned integer type that can store a value between 0 and 255.

If you declare a value during declaration it is referred to as **initialization**.

Let’s open up our folder **0x0005_intro-to-variables**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
```

```
#include "pico/stdlib.h"

int main(void) {
    uint8_t age = 42;

    age = 43;

    stdio_init_all();

    while (true)
        printf("age: %d\r\n", age);
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

The first lines you should be familiar with and if not again refer to Chapter 1 to get re-familiar with those lines.

Let’s break down this code.

```
uint8_t age = 42;
```

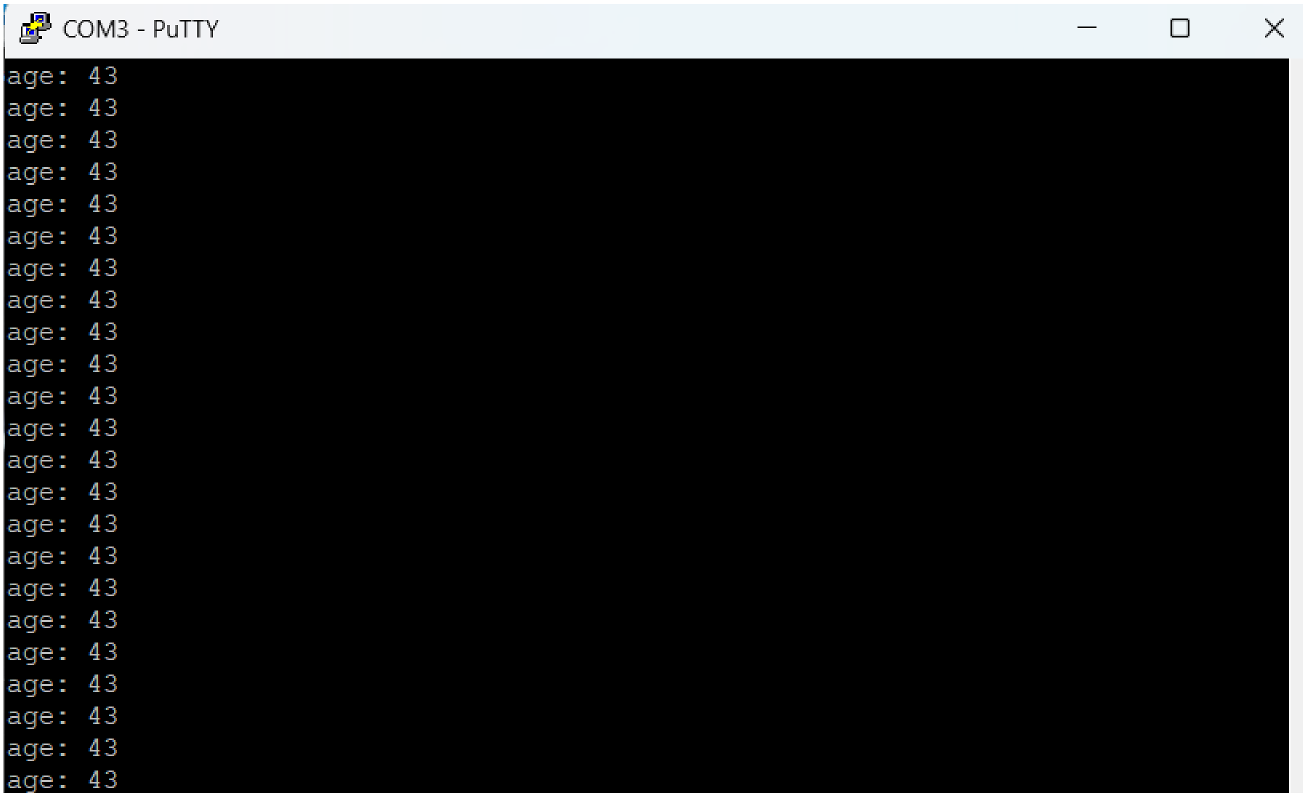
We start by declaring and initializing the variable to hold a 1 byte unsigned integer and assign the value of 42 to it.

```
age = 43;
```

We then change the value stored in *age* to *43*.

Then inside the while loop we have a *printf* where we print text to indicate that we are going to print the age and then use what we refer to as a **format specifier** which is *%d* to indicate we are using a decimal value and then our new line chars \r\n and then we have the value that will populate *%d* which is *43*.

Let’s open up PuTTY or your terminal editor of choice and we will see our values being printed in an infinite loop.



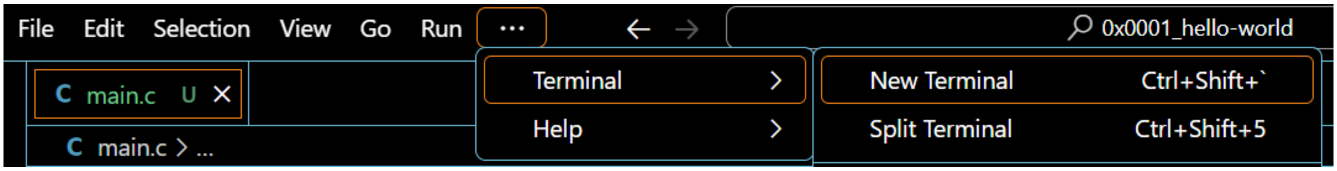
In our next chapter we will debug this.

Chapter 6: Debugging Intro To Variables

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0005_intro-to-variables.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

I want to make sure you REALLY understand what is going on. The XIP is the start of FLASH at 0x10000000. The entry point to our vector table begins with the MSP or master stack pointer and this will be at 0x10000100.

```
(gdb) x/x 0x10000100
0x10000100:     0x20042000
```

This should make sense if not please re-read the last chapter.

We are dealing with a raw binary with no symbols so we have to find our main function.

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
   0x10000308:  push    {r4, lr}
=> 0x1000030a:  bl      0x10004064
   0x1000030e:  ldr     r0, [pc, #8]    ; (0x10000318)
   0x10000310:  movs    r1, #43 ; 0x2b
   0x10000312:  bl      0x1000404c
   0x10000316:  b.n     0x1000030e
```

Let’s do the following.

```
set $pc = 0x10000308
b *0x10000308
c
```

Then we can look at a few instructions.

```
(gdb) x/6i $pc
=> 0x10000308:  push    {r4, lr}
   0x1000030a:  bl      0x10004064
   0x1000030e:  ldr     r0, [pc, #8]    ; (0x10000318)
   0x10000310:  movs    r1, #43 ; 0x2b
   0x10000312:  bl      0x1000404c
   0x10000316:  b.n     0x1000030e
(gdb)
```

We see 43 decimal being moved into r1 however we do not see the 42 initialized value as the compiler optimized that away as it then assigned 43 into it to be called by the printf function.

In our next lesson we will hack this!

Chapter 7: Hacking Intro To Variables

Let’s pick up where we were in our last lesson and set a breakpoint on the line after the assignment of decimal 43.

```
(gdb) b *0x10000312
Breakpoint 2 at 0x10000312
(gdb) c
```

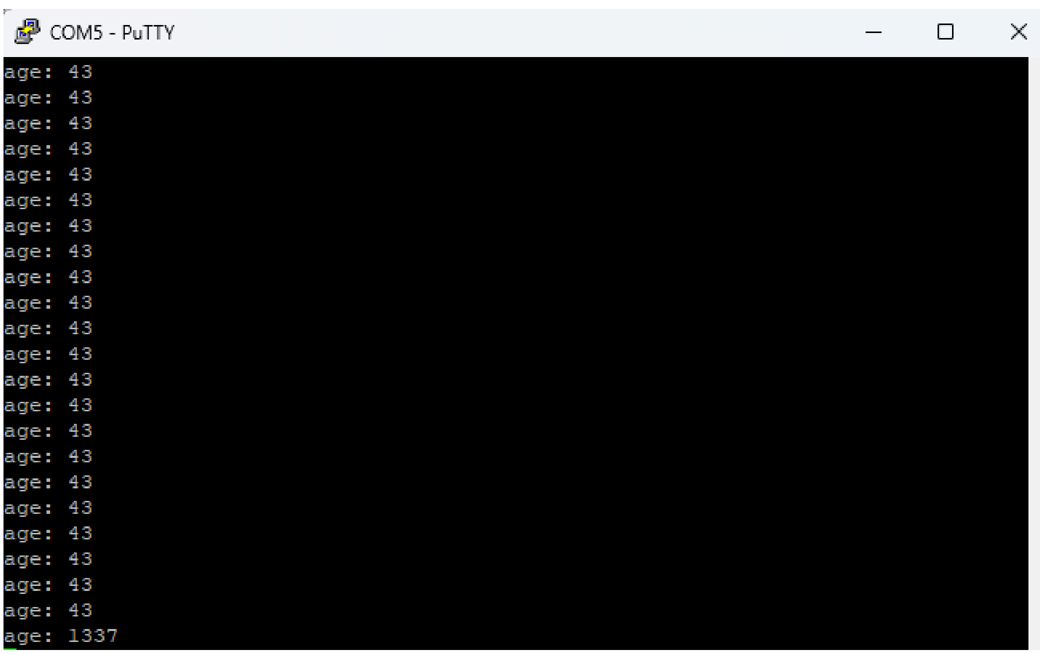
Let’s examine what is in r1.

```
(gdb) x/x $r1
0x2b:   0x701c18d1
```

Let’s hack r1!

```
(gdb) set $r1 = 1337
(gdb) x/x $r1
0x539:  0xc3702a35
```

Let’s open PuTTY or our terminal emulator of choice.



Success! We hacked it! In our next lesson we will look at uninitialized variables.

Chapter 8: Uninitialized Variables

In this chapter we are going to examine what happens in memory when we create variables that are not initialized.

Let’s open up our folder **0x0008_unitialized-variables**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    uint8_t age;

    stdio_init_all();

    while (true)
        printf("age: %d\r\n", age);
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

The only difference is that we have no idea what the value will be inside of *age* or do we?

In other versions of C you would see garbage data if a value is uninitialized however what we see in the C Pico SDK is that like other modern compilers, if you have a value that is not initialized, it will get assigned to the .bss section of memory.

The entire .bss section is assigned an address in RAM via the linker and does not reside in the binary or flash.

When the Pico boots, behind the scenes memset which is a C standard lib function is zeroing out the entire .bss so this is why these values are in fact 0.

When you initialize a variable it will go into the .data section.

When you initialize a constant it will go into the .rodata section.
Let’s flash and examine the binary.

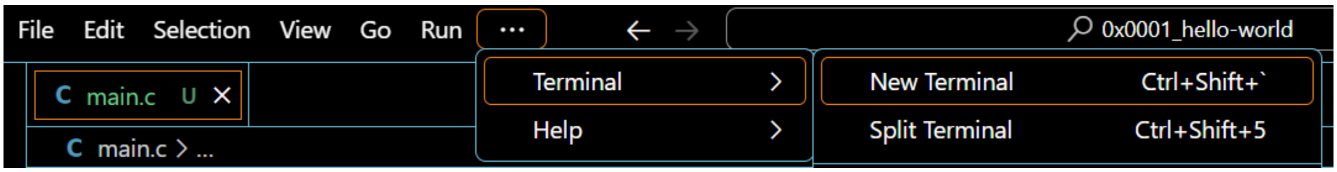
In our next lesson we will debug this.

Chapter 9: Debugging Uninitialized Variables

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0008_uninitialized_variables.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Remeber, the XIP is the start of FLASH at 0x10000000. The entry point to our vector table begins with the MSP or master stack pointer and this will be at 0x10000100.

```
(gdb) x/x 0x10000100
0x10000100:     0x20042000
```

This should make sense if not please re-read the last few chapters.

We are dealing with a raw binary with no symbols so we have to find our main function.

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting at offset 304.

```
0x10000304:  push    {r4, lr}
0x10000306:  movs    r4, #0
0x10000308:  bl      0x10004070
0x1000030c:  movs    r1, r4
0x1000030e:  ldr     r0, [pc, #8]    ; (0x10000318)
0x10000310:  bl      0x10004058
0x10000314:  b.n     0x1000030c
0x10000316:  nop
```

We know that 308 offset is our C SDK init which we have seen before.

Let’s set a breakpoint after the *ldr* instruction and see what is going on.

```
(gdb) b *0x10000310
Breakpoint 1 at 0x10000310
Note: automatically using hardware breakpoints for read-only addresses.
(gdb) c
Continuing.
Thread 1 "rp2040.core0" hit Breakpoint 1, 0x10000310 in ?? ()
(gdb) x/x $r0
0x10006920:     0x3a656761
(gdb) x/s $r0
0x10006920:     "age: %d\r\n"
```

We see our age variable however what does it store? If you look at the *movs r4, #0* it tells us our answer. In the last chapter we talked about how initialized variables were init to 0.

In our next chapter we will hack this!

Chapter 10: Hacking Uninitialized Variables

Let's pick up where we were in our last lesson and set a breakpoint on the line after the assignment of decimal 0.

```
(gdb) b *0x10000308
Breakpoint 2 at 0x10000308
(gdb) c
```

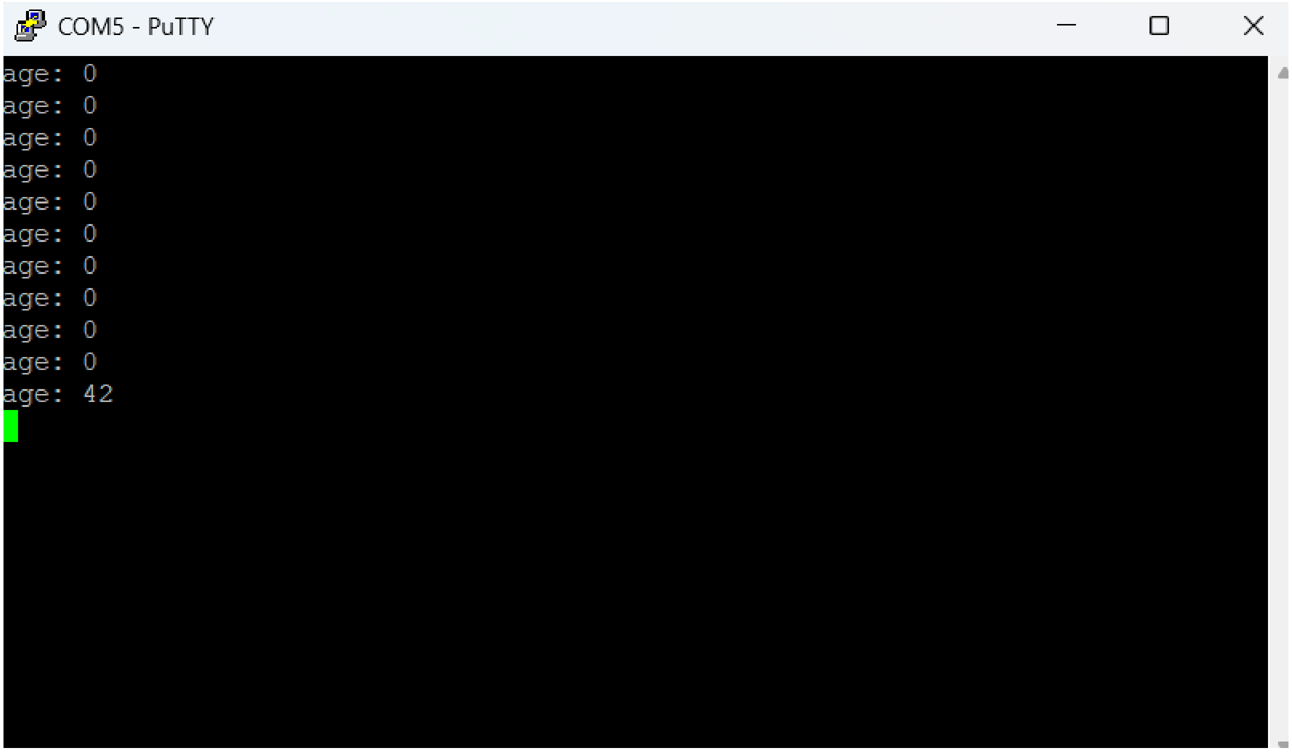
Let's examine what is in r4.

```
(gdb) x/x $r4
0x0:    0x0
```

Let's hack r4!

```
(gdb) set $r4 = 42
(gdb) x/x $r4
0x2a:   0xf7
```

Let's open PuTTY or our terminal emulator of choice.



Hooray! We hacked to 42! In our next lesson we will handle the integer data type.

Chapter 11: Integer Data Type

In this chapter we are going to discuss the integer data type. We have already covered examples with this however this book's goal is to continue to reinforce learning so that you have a mastery of the embedded process.

Let's open up our folder **0x000b_integer-data-type**.

Now let's review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    uint8_t age = 0;
    int8_t range = 0;

    age = 43;
    range = -42;

    stdio_init_all();

    while (true) {
        printf("age: %d\r\n", age);
        printf("range: %d\r\n", range);
    }
}
```

Let's flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

The first lines you should be familiar with and if not again refer to Chapter 1 to get re-familiar with those lines.

Let's break down this code.

```
uint8_t age = 0;
```

We start by declaring and initializing the variable to hold a 1 byte unsigned integer and assign the value of 0 to it.

```
age = 43;
```

We then change the value stored in *age* to *43*.

We also create another signed 8-bit integer.

```
int8_t range = 0;
```

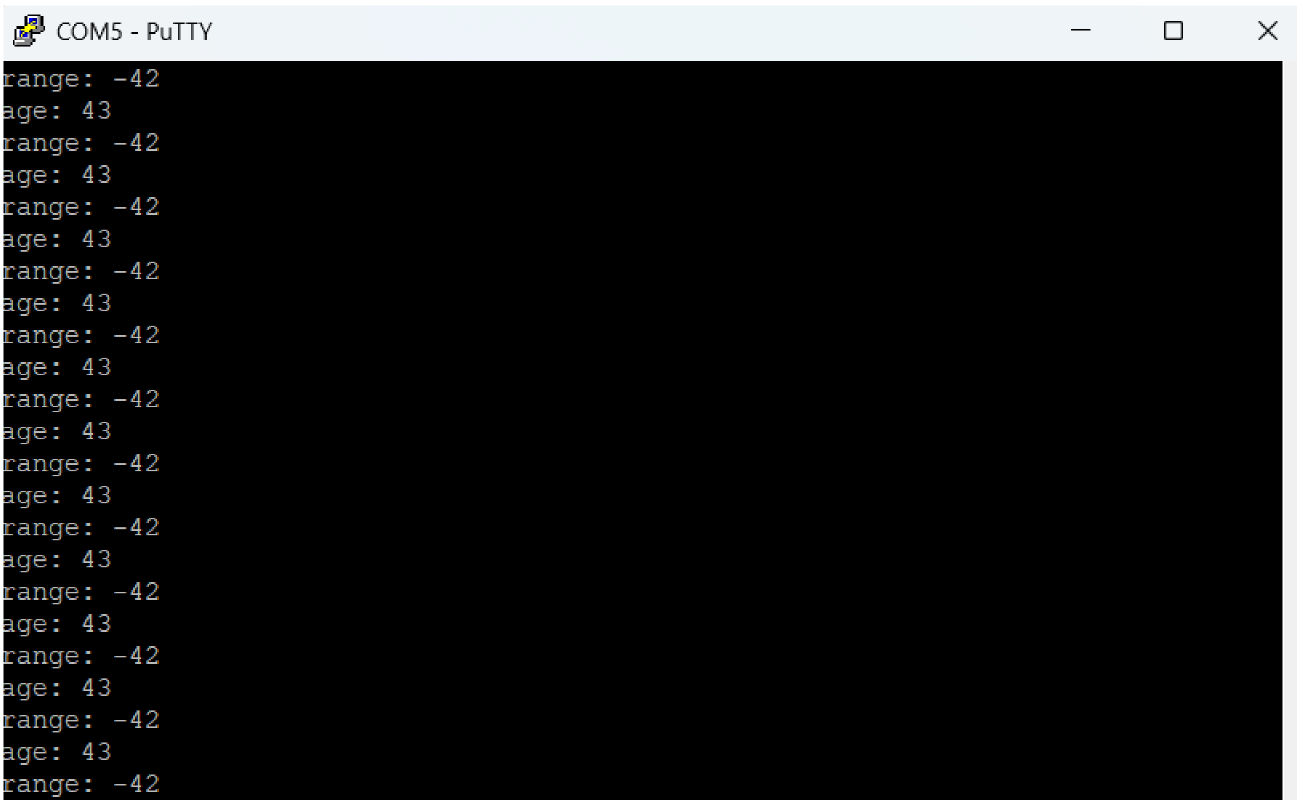
Then we assign a value to it.

```
range = -42
```

Then inside the while loop we have a *printf* where we print text to indicate that we are going to print the age and then use what we refer to as a **format specifier** which is *%d* to indicate we are using a decimal value and then our new line chars \r\n and then we have the value that will populate *%d* which is *43*.

We also print out the value of range which is -42.

Let’s open up PuTTY or your terminal editor of choice and we will see our values being printed in an infinite loop.



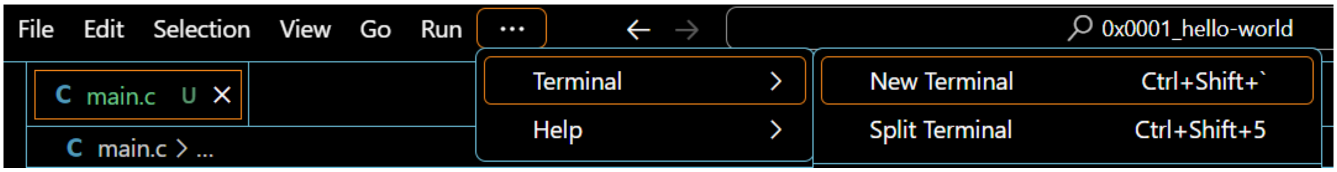
In our next chapter we will debug this.

Chapter 12: Debugging Integer Data Type

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x000b_integer-data-type.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
=> 0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003be8
   0x1000030a:  movs    r1, #43 ; 0x2b
   0x1000030c:  ldr     r0, [pc, #16]   ; (0x10000320)
   0x1000030e:  bl      0x10003bd0
   0x10000312:  movs    r1, #42 ; 0x2a
   0x10000314:  negs    r1, r1
   0x10000316:  ldr     r0, [pc, #12]   ; (0x10000324)
   0x10000318:  bl      0x10003bd0
   0x1000031c:  b.n     0x1000030a
```

Let’s do the following.

```
b *0x10000304
c
```

Then we can look at a few instructions.

```
(gdb) x/10i $pc
=> 0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003be8
   0x1000030a:  movs    r1, #43 ; 0x2b
   0x1000030c:  ldr     r0, [pc, #16]   ; (0x10000320)
   0x1000030e:  bl      0x10003bd0
   0x10000312:  movs    r1, #42 ; 0x2a
   0x10000314:  negs    r1, r1
   0x10000316:  ldr     r0, [pc, #12]   ; (0x10000324)
   0x10000318:  bl      0x10003bd0
   0x1000031c:  b.n     0x1000030a
```

We see 43 decimal being moved into r1 and later we see 42 decimal being moved into r1 and then we see the negs instruction which will negate this to provide our -42 and then with each decimal value being loaded into r1 we call printf respectivly.

In our next lesson we will hack this!

Chapter 13: Hacking Integer Data Type

Let’s pick up where we were in our last lesson and set a breakpoint on the line after the assignment of decimal 42.

```
(gdb) b *0x1000030a
Breakpoint 2 at 0x1000030a
(gdb) c
```

Let’s examine what is in r1.

```
(gdb) x/x $r1
0x2b:   0xeb20041f
```

Let’s hack r1!

```
(gdb) set $r1 = 1337
(gdb) x/x $r1
0x539:  0xc3702a35
```

Let’s hack r1 again for our second value!

```
(gdb) b *0x10000312
Breakpoint 3 at 0x10000312
(gdb) c
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 3, 0x10000312 in ?? ()
(gdb) si
0x10000314 in ?? ()
(gdb) x/x $r1
0x2a:   0x1c18d1f7
(gdb) set $r1 = 66
(gdb) x/1i $pc
=> 0x10000314:  negs    r1, r1
```

Let’s open PuTTY or our terminal emulator of choice.

Success! We hacked it! In our next lesson we will look at the floating-point data type.

Chapter 14: Floating-Point Data Type

In this chapter we are going to discuss the floating-point data type.

Let’s open up our folder **0x000e_floating-point-data-type**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    float fav_num = 42.5;

    stdio_init_all();

    while (true)
        printf("fav_num: %f\r\n", fav_num);
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

The first lines you should be familiar with and if not again refer to Chapter 1 to get re-familiar with those lines.

Let’s break down this code.

```
float fav_num = 42.5;
```

We start by declaring and initializing the variable to hold a float and assign the value of 42.5 to it.

Then inside the while loop we have a *printf* where we print text to indicate that we are going to print the *fav_num* and then use what we refer to as a **format specifier** which is *%f* to indicate we are using a float value and then our new line chars \r\n and then we have the value that will populate *%f* which is *42.5*.

Let’s open up PuTTY or your terminal editor of choice and we will se our values being printed in an infinite loop.

COM3 - PuTTY

```
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
fav_num: 42.500000
```

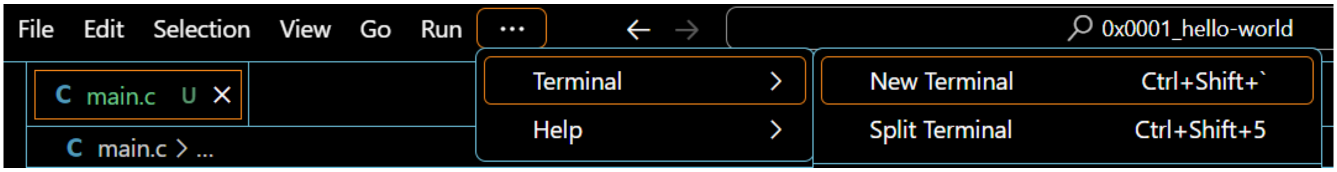
In our next chapter we will debug this.

Chapter 15: Debugging Floating-Point Data Type

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x000e_floating-point-data-type.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
0x10000308 :  push    {r4, lr}
0x1000030a:   bl       0x10003b80
0x1000030e:   ldr      r0, [pc, #12]    ; (0x1000031c)
0x10000310:   movs     r2, #0
0x10000312:   ldr      r3, [pc, #12]    ; (0x10000320)
0x10000314:   bl       0x10003b68
```

```
0x10000318:  b.n     0x1000030e
0x1000031a:  nop                     ; (mov r8, r8)
```

We see two values being loaded in the first at 0x1000031c.

```
(gdb) x/s *0x1000031c
0x10003e60:     "fav_num: %f\r\n"
```

We see another at 0x10000320.

```
(gdb) x/f 0x10000320
0x10000320:     42.500012410475414
```

And there we have it! In our next lesson we will hack this value.

Chapter 16: Hacking Floating-Point Data Type

Let’s pick up where we were in our last lesson and set a breakpoint at the beginning of main and at the end of our main after we assign the value into R3.

```
(gdb) b *0x10000308
Breakpoint 1 at 0x10000308
(gdb) b *0x10000314
Breakpoint 2 at 0x10000314
(gdb) c
```

Let’s examine some instructions.

```
(gdb) x/8i $pc
=> 0x10000308:  push    {r4, lr}
   0x1000030a:  bl      0x10003b80
   0x1000030e:  ldr     r0, [pc, #12]   ; (0x1000031c)
   0x10000310:  movs    r2, #0
   0x10000312:  ldr     r3, [pc, #12]   ; (0x10000320)
   0x10000314:  bl      0x10003b68
   0x10000318:  b.n     0x1000030e
   0x1000031a:  nop                     ; (mov r8, r8)
```

Let’s get to after the step where our 42.5 is assigned into R3.

```
(gdb) si
0x1000030a in ?? ()
(gdb) si
0x10003b80 in ?? ()
(gdb) ret
Make selected stack frame return now? (y or n) y
#0  0x1000030e in ?? ()
(gdb) si
0x10000310 in ?? ()
(gdb) si
0x10000312 in ?? ()
(gdb) si
0x10000314 in ?? ()
```

Let’s look in r3 as it should have our float.

```
(gdb) x/f $r3
0x40454000:     0
```

Uh oh! So now we need to reverse engineer how this works! We know that 0x40454000 is 42.5 so what if we try 0x40455000?

```
(gdb) set $r3 = 0x40455000
(gdb) c
Continuing.
```

In Putty, we see fav_num: 42.625000.

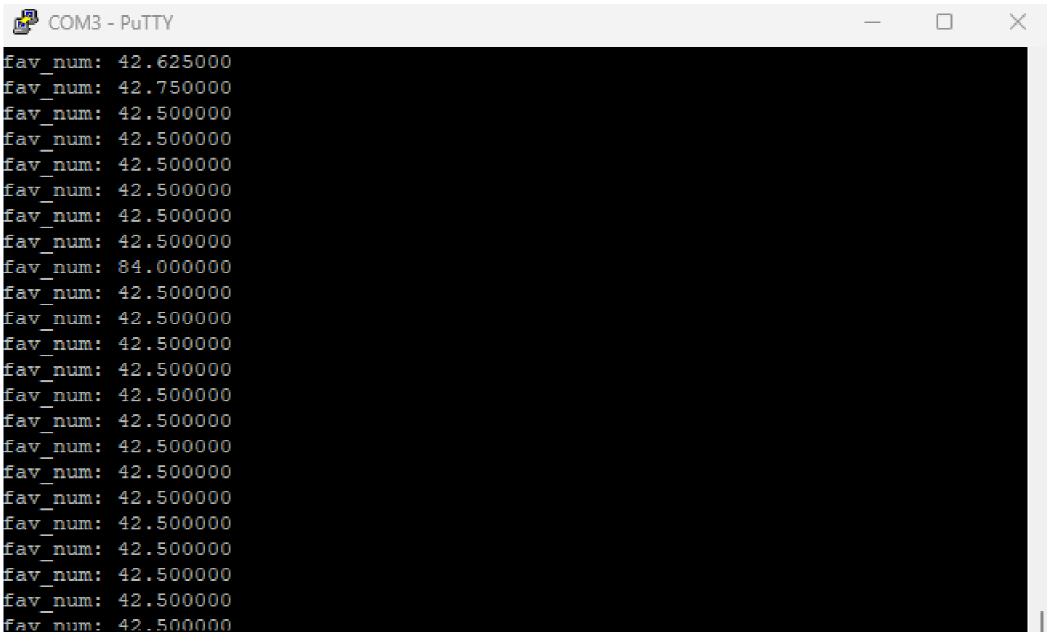
Ok well this is a start! Let’s try another.

```
(gdb) set $r3 = 0x40456000
(gdb) c
Continuing.
```

In Putty, we see fav_num: 42.750000.

```
(gdb) set $r3 = 0x40550000
(gdb) c
Continuing.
```

In Putty, we see fav_num: 84.000000.



Success! We hacked it! In our next lesson we will look at the double floating-point data type.

Chapter 17: Double Floating-Point Data Type

In this chapter we are going to discuss the floating-point data type.

Let’s open up our folder **0x0011_double-floating-point-data-type**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    double fav_num = 42.52525;

    stdio_init_all();

    while (true)
        printf("fav_num: %lf\r\n", fav_num);
}
```

Let’s flash the uf2 file onto the pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

The first lines you should be familiar with and if not again refer to Chapter 1 to get re-familiar with those lines.

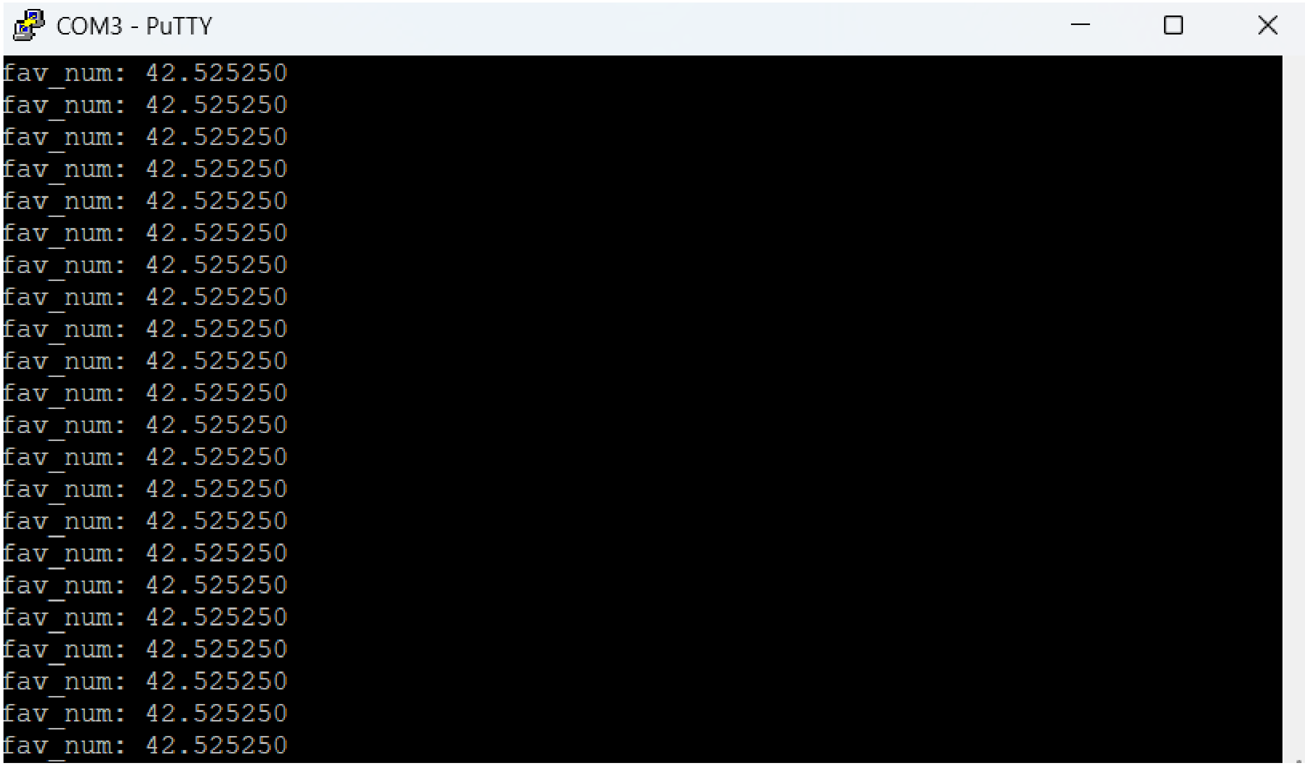
Let’s break down this code.

```
double fav_num = 42.52525;
```

We start by declaring and initializing the variable to hold a souble and assign the value of 42.52525 to it.

Then inside the while loop we have a *printf* where we print text to indicate that we are going to print the fav_num and then use what we refer to as a **format specifier** which is *%lf* to indicate we are using a double value and then our new line chars \r\n and then we have the value that will populate *%f* which is *42.5*.

Let’s open up PuTTY or your terminal editor of choice and we will se our values being printed in an infinite loop.



```
COM3 - PuTTY
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
fav_num: 42.525250
```

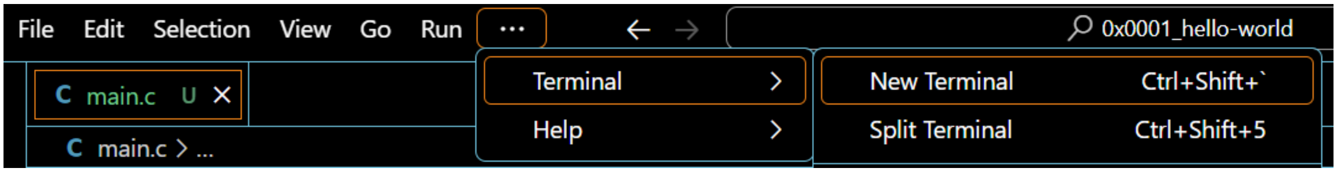
In our next chapter we will debug this.

Chapter 18: Debugging Double Floating-Point Data Type

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0011_double-floating-point-data-type.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let's examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
0x10000304:  push    {r4, lr}
0x10000306:  bl      0x10003be4
0x1000030a:  ldr     r2, [pc, #12]   ; (0x10000318)
0x1000030c:  ldr     r3, [pc, #12]   ; (0x1000031c)
0x1000030e:  ldr     r0, [pc, #16]   ; (0x10000320)
0x10000310:  bl      0x10003bcc
```

```
0x10000314:  b.n     0x1000030a
0x10000316:  nop                      ; (mov r8, r8)
```

We see two values being loaded in the first at 0x10000320.

```
(gdb) b *0x10000310
(gdb) x/s *0x10000320
0x10003eb8:     "fav_num: %lf\r\n"
```

Let’s look at what is in R3.

```
(gdb) x/f $r3
0x4045433b:     0
```

Here we see a different pattern than in our float! In our next lesson we will hack this value.

Chapter 19: Hacking Double Floating-Point Data Type

Let’s pick up where we were in our last lesson and set a breakpoint at the point before we call printf and we assign the value into R3.

```
(gdb) b *0x10000310
Breakpoint 1 at 0x10000310
(gdb) c
Continuing.
```

Let’s examine some instructions.

```
(gdb) x/7i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003be4
   0x1000030a:  ldr     r2, [pc, #12]   ; (0x10000318)
   0x1000030c:  ldr     r3, [pc, #12]   ; (0x1000031c)
   0x1000030e:  ldr     r0, [pc, #16]   ; (0x10000320)
=> 0x10000310:  bl      0x10003bcc
   0x10000314:  b.n     0x1000030a
```

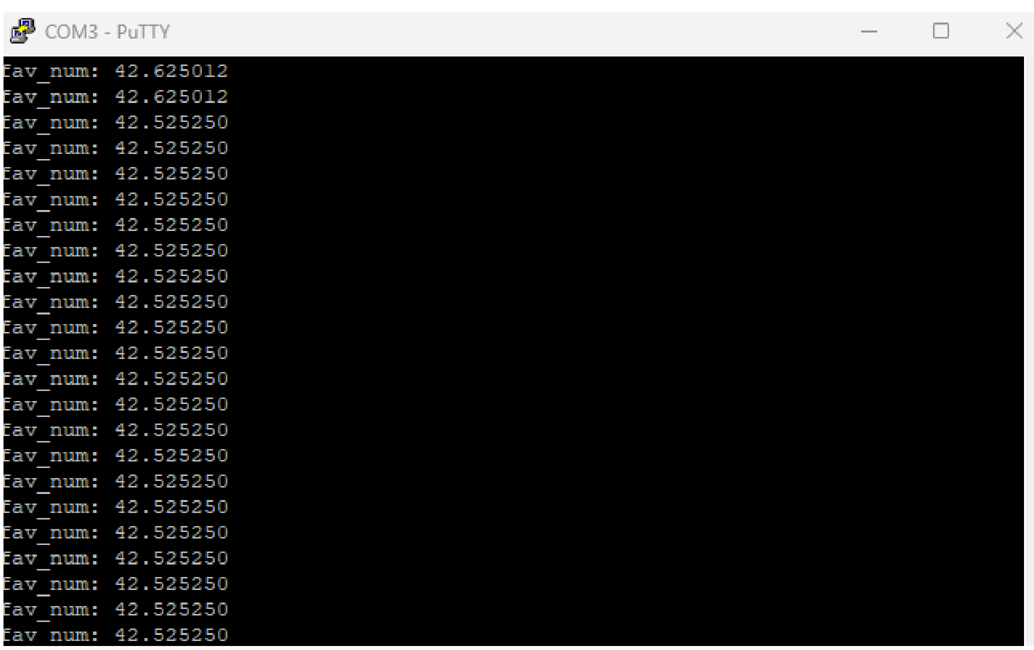
Here we are after that strange value assigned into r3.

```
(gdb) x/f $r3
0x4045433b:     0
```

Once again we need to reverse engineer how this works! We know that 0x4045433b is 42.52525 so what if we try 0x40455000?

```
(gdb) set $r3 = 0x40455000
(gdb) c
Continuing.
```

In Putty, we see fav_num: 42.625012.



Success! We hacked it! In our next lesson we will look at static variables.

Chapter 20: Static Variables

In this chapter we are going to discuss static variables.

Let’s open up our folder **0x0014_static-variables**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    stdio_init_all();

    while (true) {
        static int static_fav_num = 42;
        int regular_fav_num = 42;

        printf("static_fav_num: %d\r\n", static_fav_num);
        printf("regular_fav_num: %d\r\n", regular_fav_num);

        static_fav_num++;
        regular_fav_num++;
    }
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

The first lines you should be familiar with and if not again refer to Chapter 1 to get re-familiar with those lines.

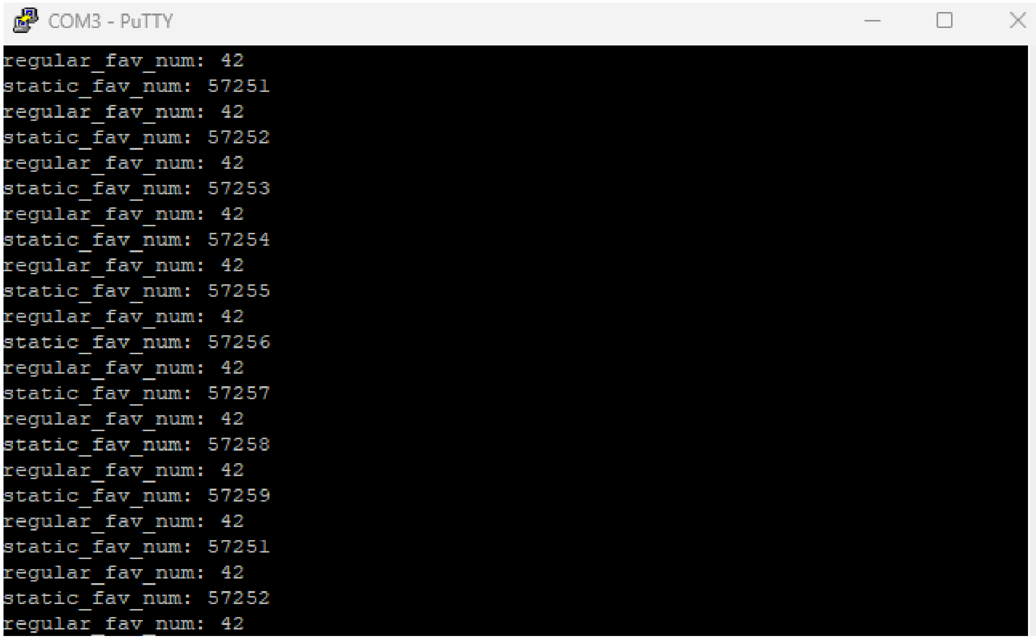
Let’s break down this code.

Take note that we are initializing two variables within a while loop.

The *static_fav_num* is a static int and the *regular_fav_num* is a regular int and both are init to 42.

The difference here is that when we iterate through the while loop the *static_int_fav_num* will increase where the *regular_fav_num* will get re-initialized through each run of the loop.

Let’s look at the compilation. We see that that static actually increments.



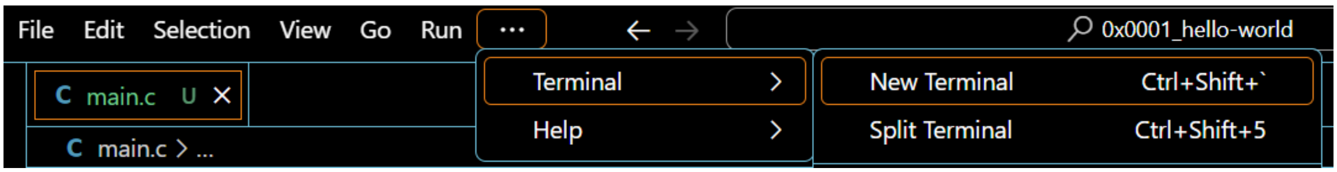
In our next lesson we will debug this.

Chapter 21: Debugging Static Variables

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0014_static-variables.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
   0x10000308:  push    {r4, lr}
   0x1000030a:  bl      0x10003b90
   0x1000030e:  ldr     r4, [pc, #24]   ; (0x10000328)
   0x10000310:  ldr     r1, [r4, #0]
   0x10000312:  ldr     r0, [pc, #24]   ; (0x1000032c)
   0x10000314:  bl      0x10003b78
   0x10000318:  ldr     r0, [pc, #20]   ; (0x10000330)
   0x1000031a:  movs    r1, #42 ; 0x2a
```

```
0x1000031c:  bl      0x10003b78
0x10000320:  ldr     r3, [r4, #0]
0x10000322:  adds    r3, #1
0x10000324:  str     r3, [r4, #0]
0x10000326:  b.n     0x1000030e
```

We see two values being loaded in below, 31a offset is where we load *42* and the *326* offset we jump back to the beginning of our while loop.

```
(gdb) b *0x1000031a
(gdb) b *0x10000326
```

We see our format strings below.

```
(gdb) x/s *0x1000032c
0x10003e70:     "static_fav_num: %d\r\n"
(gdb) x/s *0x10000330
0x10003e88:     "regular_fav_num: %d\r\n"
```

We see our value of 42 as well.

```
(gdb) x/x 0x1000031a
0x1000031a:     0x2a
```

Here I have let the program iterate a bit and when we look at r3 we can see the value of our static variable. When it iterates next it will be *673* decimal as the current value in PuTTY is *672* on s*tatic_fav_num*.

```
(gdb) i r
r0             0x15                21
r1             0x0                 0
r2             0x0                 0
r3             0x2a1               673
r4             0x20000378          536871800
r5             0x20041f01          537140993
r6             0x18000000          402653184
r7             0x0                 0
r8             0xffffffff          -1
r9             0xffffffff          -1
r10            0xffffffff          -1
r11            0xffffffff          -1
r12            0x20000305          536871685
sp             0x20041ff8          0x20041ff8
```

In our next lesson we will hack these values.

Chapter 22: Hacking Static Variables

Let's pick up where we were in our last lesson and set a breakpoint at the point before we call printf and we assign the value into r3.

First we need to make sure we have all the proper breakpoints.

```
(gdb) info breakpoints
Num     Type           Disp Enb Address    What
1       breakpoint     keep y   0x10000308
        breakpoint already hit 2 times
2       breakpoint     keep y   0x10000326
        breakpoint already hit 19 times
3       breakpoint     keep y   0x1000030e
        breakpoint already hit 6 times
4       breakpoint     keep y   0x1000031c
        breakpoint already hit 3 times
```

Let's examine some instructions.

```
(gdb) x/13i 0x10000308
   0x10000308:  push    {r4, lr}
   0x1000030a:  bl      0x10003b90
=> 0x1000030e:  ldr     r4, [pc, #24]   ; (0x10000328)
   0x10000310:  ldr     r1, [r4, #0]
   0x10000312:  ldr     r0, [pc, #24]   ; (0x1000032c)
   0x10000314:  bl      0x10003b78
   0x10000318:  ldr     r0, [pc, #20]   ; (0x10000330)
   0x1000031a:  movs    r1, #42 ; 0x2a
   0x1000031c:  bl      0x10003b78
   0x10000320:  ldr     r3, [r4, #0]
   0x10000322:  adds    r3, #1
   0x10000324:  str     r3, [r4, #0]
   0x10000326:  b.n     0x1000030e
```

Let's set a breakpoint and continue at the call where it is about to print the *static_fav_num*.

```
(gdb) b *0x1000031c
c
```

Let's verify 0x2a or 42 is in r1.

```
(gdb) x/x $r1
0x2a:   0xf7
```

Let's set r1 to be 44.

```
(gdb) set $r1 = 44
```

Let's examine where we are at.

```
(gdb) x/13i 0x10000308
   0x10000308:  push    {r4, lr}
   0x1000030a:  bl      0x10003b90
   0x1000030e:  ldr     r4, [pc, #24]   ; (0x10000328)
   0x10000310:  ldr     r1, [r4, #0]
   0x10000312:  ldr     r0, [pc, #24]   ; (0x1000032c)
=> 0x10000314:  bl      0x10003b78
   0x10000318:  ldr     r0, [pc, #20]   ; (0x10000330)
   0x1000031a:  movs    r1, #42 ; 0x2a
   0x1000031c:  bl      0x10003b78
   0x10000320:  ldr     r3, [r4, #0]
   0x10000322:  adds    r3, #1
   0x10000324:  str     r3, [r4, #0]
   0x10000326:  b.n     0x1000030e
```

Let's first delete all of our breakpoints.

```
(gdb) del br 1
(gdb) del br 2
(gdb) del br 3
(gdb) del br 4
```

We have to set a new breakpoint where R3 is going to store its incremented value into the contents of the address within R4.

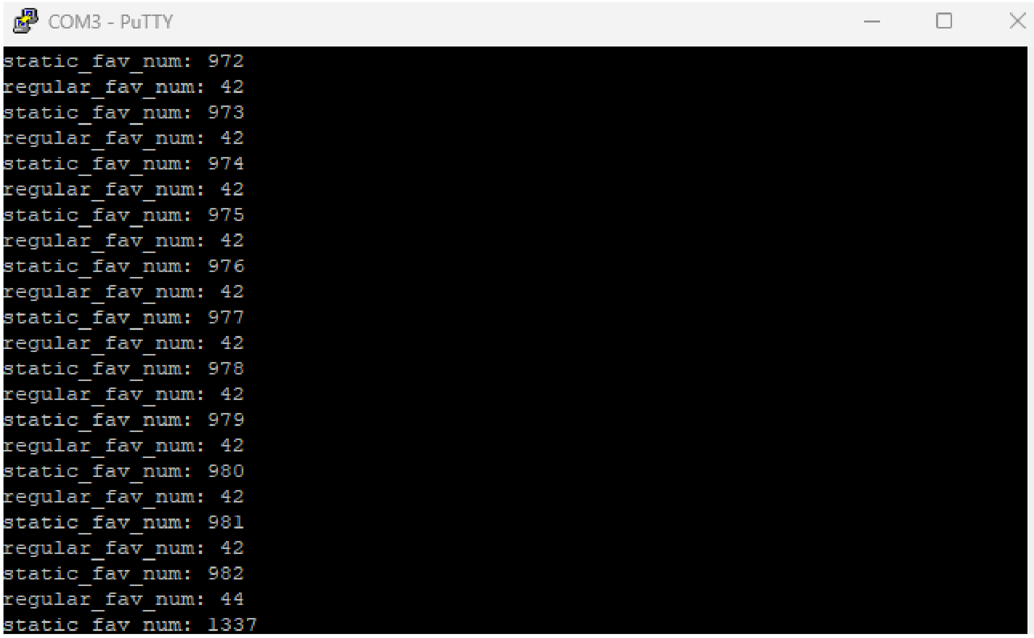
```
(gdb) b *0x10000324
c

0x10000324:  str     r3, [r4, #0]
```

Remember str instructions store the left value into the right value!

Now let's set r3 to 1337 and continue.

```
(gdb) set $r3 = 1337
(gdb) c
Continuing.
```

Let’s look in PuTTY!



Success! We hacked both vars! In our next lesson we will look at constants.

Chapter 23: Constants

In this chapter we are going to discuss constants.

Let’s open up our folder **0x0017_constants**.

Now let’s review our **main.c** file as this is located in the main folder.

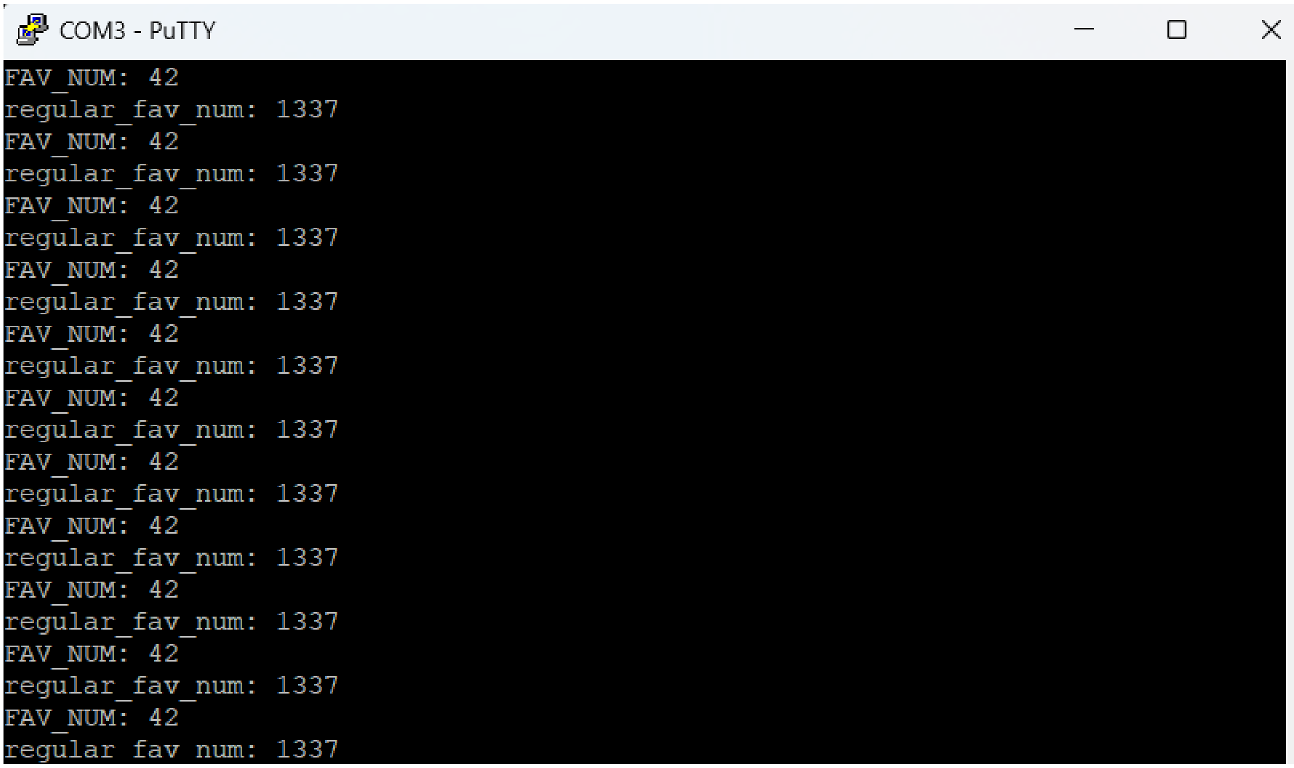
```
#include <stdio.h>
#include "pico/stdlib.h"

#define FAV_NUM 42

const int OTHER_FAV_NUM = 1337;

int main(void) {
    stdio_init_all();

    while (true) {
        printf("FAV_NUM: %d\r\n", FAV_NUM);
        printf("regular_fav_num: %d\r\n", OTHER_FAV_NUM);
    }
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

We can define constants globally by #define them in a global space.

We can also define a constant within the local scope as we do here in main.

Let’s look at the compilation. We see both constants.



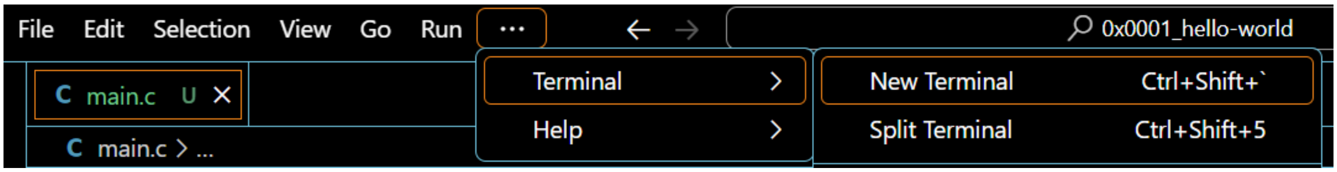
In our next chapter we will debug this.

Chapter 24: Debugging Constants

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0017_constants.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003be8
   0x1000030a:  movs    r1, #42 ; 0x2a
   0x1000030c:  ldr     r0, [pc, #12]   ; (0x1000031c)
   0x1000030e:  bl      0x10003bd0
   0x10000312:  ldr     r1, [pc, #12]   ; (0x10000320)
   0x10000314:  ldr     r0, [pc, #12]   ; (0x10000324)
   0x10000316:  bl      0x10003bd0
```

```
   0x1000031a:  b.n     0x1000030a
```

We see 42 loaded into r1 so that is our global constant. If we examine 2 hex bytes from 0x10000320 we see *0x39* and *0x05* which in decimal is *1337* in little endian format.

```
(gdb) x/2x 0x10000320
0x10000320:     0x39    0x05
```

In our next lesson we will hack these values.

Chapter 25: Hacking Constants

Let’s examine 9 instructions.

```
(gdb) x/9i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003be8
   0x1000030a:  movs    r1, #42 ; 0x2a
   0x1000030c:  ldr     r0, [pc, #12]   ; (0x1000031c)
   0x1000030e:  bl      0x10003bd0
   0x10000312:  ldr     r1, [pc, #12]   ; (0x10000320)
   0x10000314:  ldr     r0, [pc, #12]   ; (0x10000324)
   0x10000316:  bl      0x10003bd0
   0x1000031a:  b.n     0x1000030a
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We saw 42 loaded into r1 so that is our global constant. When we examined 2 hex bytes from 0x10000320 we see *0x39* and *0x05* which in decimal is *1337* in little endian format.

```
(gdb) x/2x 0x10000320
0x10000320:     0x39    0x05
```

Let’s set three breakpoints on our loop.

```
(gdb) b *0x1000030a
Breakpoint 1 at 0x1000030a
Note: automatically using hardware breakpoints for read-only addresses.
(gdb) b *0x10000314
Breakpoint 2 at 0x10000314
(gdb) b *0x1000031a
Breakpoint 3 at 0x1000031a
```

Let’s continue once.

```
(gdb) c
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 1, 0x1000030a in ?? ()
(gdb) x/9i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003be8
=> 0x1000030a:  movs    r1, #42 ; 0x2a
   0x1000030c:  ldr     r0, [pc, #12]   ; (0x1000031c)
   0x1000030e:  bl      0x10003bd0
   0x10000312:  ldr     r1, [pc, #12]   ; (0x10000320)
   0x10000314:  ldr     r0, [pc, #12]   ; (0x10000324)
   0x10000316:  bl      0x10003bd0
   0x1000031a:  b.n     0x1000030a
```

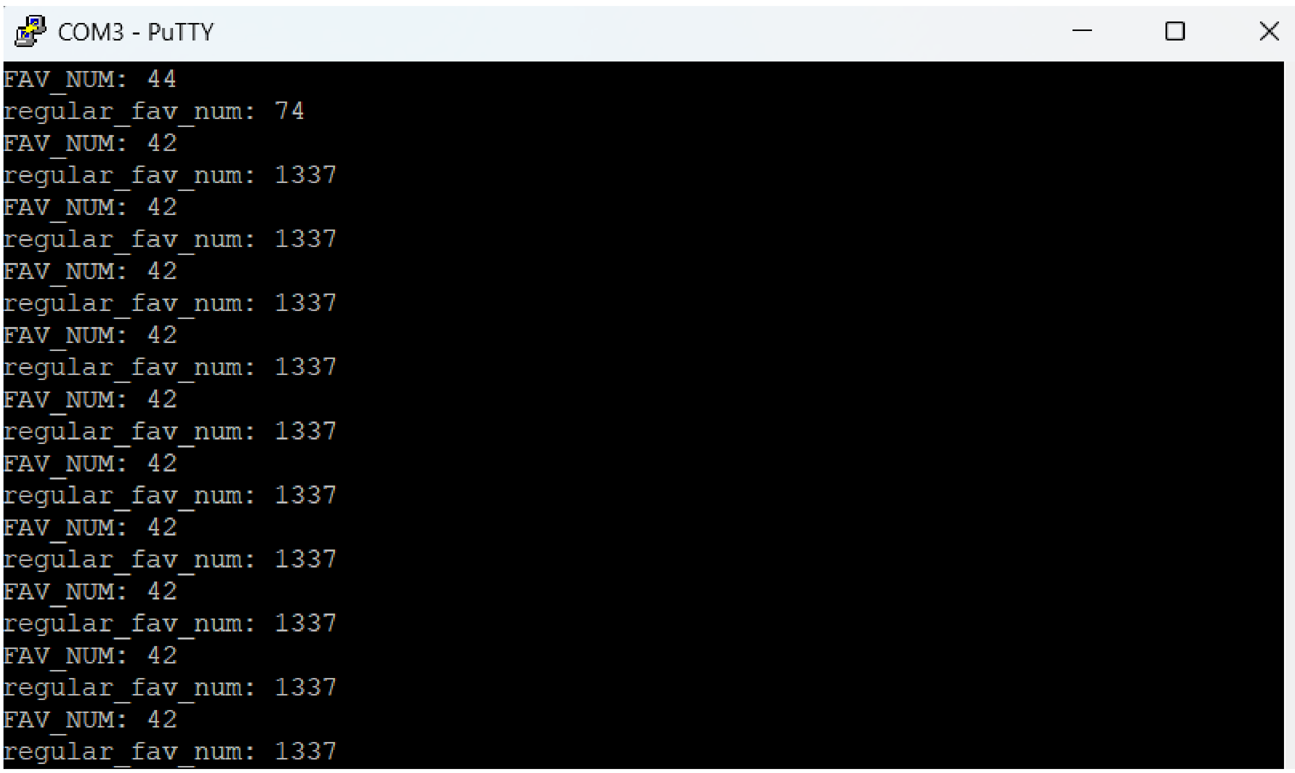
Let's step into once and set R1 to 44 instead of 42.

```
(gdb) si
0x1000030c in ?? ()
(gdb) set $r1 = 44
```

Let's continue and set R1 to 74 and continue.

```
(gdb) set $r1 = 74
```

We see that when we continue we see 44 and 74 hacked successfully! When we continue the loop iteration everything is back to normal as expected.



In our next lesson we will cover operators.

Chapter 26: Operators

In this chapter we are going to discuss operators.

Let’s open up our folder **0x001a_operators**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    stdio_init_all();

    int x = 5;
    int y = 10;
    int arithmetic_operator = (x * y);
    int increment_operator = x++;
    bool relational_operator = (x > y);
    bool logical_operator = (x > y) && (y > x);
    int bitwise_operator = (x<<1);  // x is now 6 because of x++ or 0b00000110 and (x<<1) is
0b00001100 or 12
    int assignment_operator = (x += 5);

    while (true) {
        printf("arithmetic_operator: %d\r\n", arithmetic_operator);
        printf("increment_operator: %d\r\n", increment_operator);
        printf("relational_operator: %d\r\n", relational_operator);
        printf("logical_operator: %d\r\n", logical_operator);
        printf("bitwise_operator: %d\r\n", bitwise_operator);
        printf("assignment_operator: %d\r\n", assignment_operator);
    }
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

Arithmetic Operator (*):
int arithmetic_operator = (x * y); multiplies the values of x and y together, storing the result in arithmetic_operator.

Increment Operator (++):
int increment_operator = x++; post-increments the value of x, meaning the current value of x is used in the expression, and then x is incremented by 1.

Relational Operator (>):

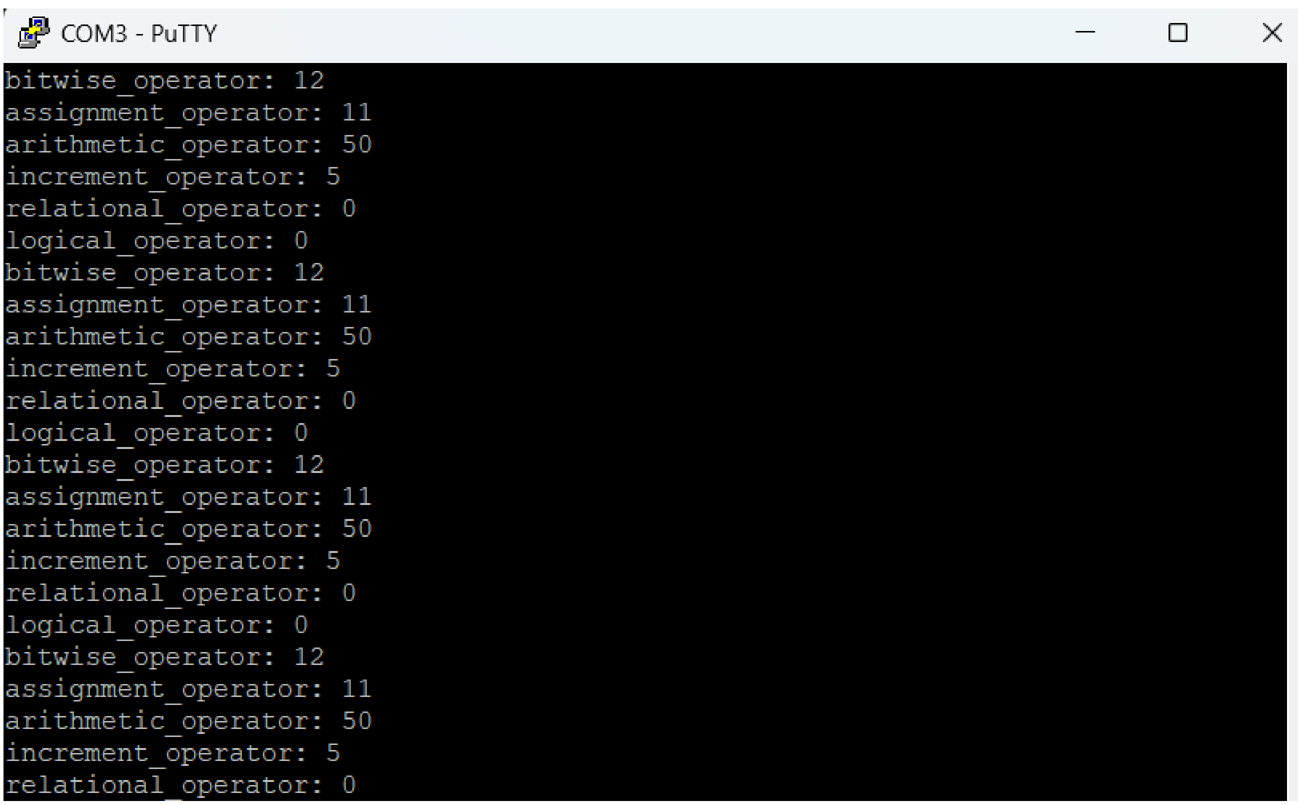
bool relational_operator = (x > y); checks if the value of x is greater than the value of y and stores the result in the boolean variable relational_operator.

Logical Operator (&&):
bool logical_operator = (x > y) && (y > x); uses the logical AND operator to check if both conditions are true and stores the result in the boolean variable logical_operator.

Bitwise Left Shift Operator (<<):
int bitwise_operator = (x << 1); left-shifts the bits of x by 1 position. In this case, it effectively multiplies x by 2 because it shifts the bits to the left by 1 position.

Assignment Operator (+=):
int assignment_operator = (x += 5); adds 5 to the value of x and assigns the result back to x. The result is then stored in assignment_operator.

Let’s look at the compilation.



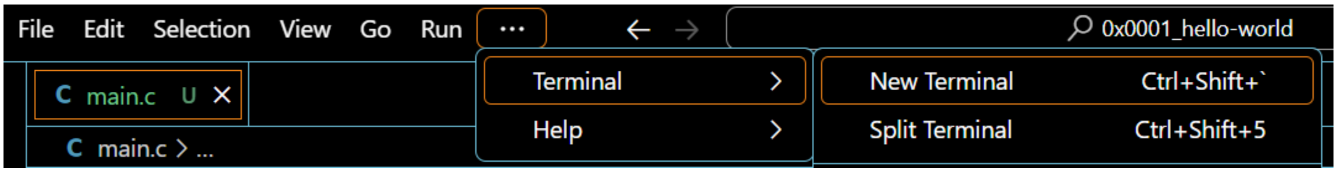
In our next chapter we will debug this.

Chapter 27: Debugging Operators

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x001a_operators.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let's examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003c14
   0x1000030a:  movs    r1, #50 ; 0x32
   0x1000030c:  ldr     r0, [pc, #44]   ; (0x1000033c)
   0x1000030e:  bl      0x10003bfc
   0x10000312:  movs    r1, #5
   0x10000314:  ldr     r0, [pc, #40]   ; (0x10000340)
   0x10000316:  bl      0x10003bfc
```

```
0x1000031a:  movs    r1, #0
0x1000031c:  ldr     r0, [pc, #36]   ; (0x10000344)
0x1000031e:  bl      0x10003bfc
0x10000322:  movs    r1, #0
0x10000324:  ldr     r0, [pc, #32]   ; (0x10000348)
0x10000326:  bl      0x10003bfc
0x1000032a:  movs    r1, #12
0x1000032c:  ldr     r0, [pc, #28]   ; (0x1000034c)
0x1000032e:  bl      0x10003bfc
0x10000332:  movs    r1, #11
0x10000334:  ldr     r0, [pc, #24]   ; (0x10000350)
0x10000336:  bl      0x10003bfc
0x1000033a:  b.n     0x1000030a
```

We see 50 loaded into r1 as that is our arithmetic_operator.

After that *bl* to *printf*, we see 5 being loaded into r1 which is our *increment_operator*.

After the next *bl* to *printf*, we see 0 being loaded in to r1 for our *relation_operator* which is false.

After the next *bl* to *printf*, we see 0 being loaded into r1 for our *logical_operator* which is false.

After the next *bl* to *printf*, we see 12 being loaded into r1 for our *bitwise_operator* as we need to recall earlier we had x++ so x originally was 5 but is now 6 and when we use the << bitwise operator with 1 that literally doubles the value and if we used >> 1 that would floor divide the value by 2.

Finally we see the *assignment_operator* which adds 5 to the current x which is 6 so we get 11.

In our next lesson we will hack some of these values.

Chapter 28: Hacking Operators

Let’s examine 21 instructions.

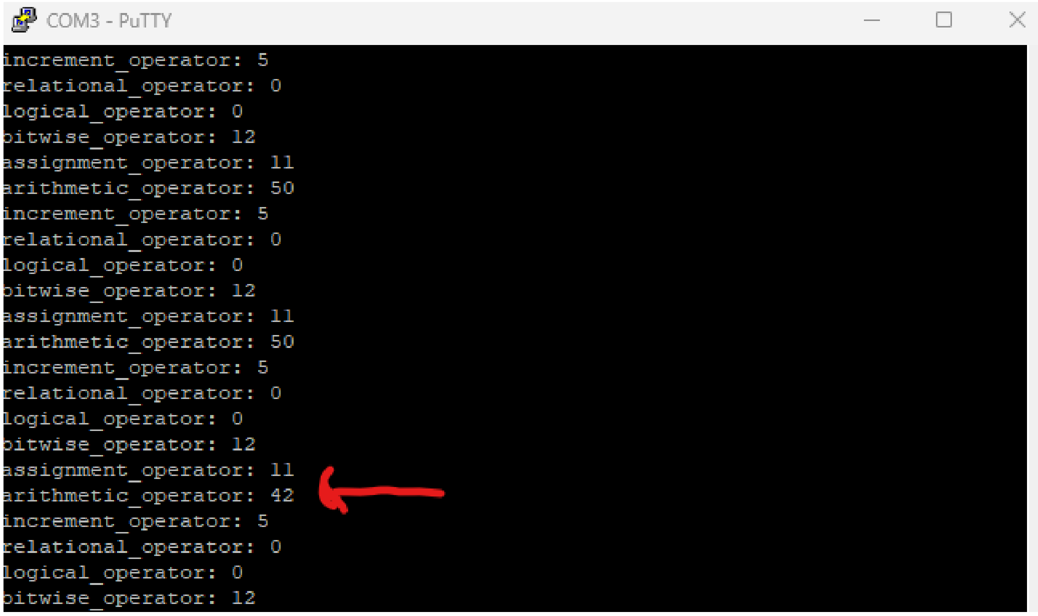
```
(gdb) x/21i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  bl      0x10003c14
   0x1000030a:  movs    r1, #50 ; 0x32
   0x1000030c:  ldr     r0, [pc, #44]   ; (0x1000033c)
   0x1000030e:  bl      0x10003bfc
   0x10000312:  movs    r1, #5
   0x10000314:  ldr     r0, [pc, #40]   ; (0x10000340)
   0x10000316:  bl      0x10003bfc
   0x1000031a:  movs    r1, #0
   0x1000031c:  ldr     r0, [pc, #36]   ; (0x10000344)
   0x1000031e:  bl      0x10003bfc
   0x10000322:  movs    r1, #0
   0x10000324:  ldr     r0, [pc, #32]   ; (0x10000348)
   0x10000326:  bl      0x10003bfc
   0x1000032a:  movs    r1, #12
   0x1000032c:  ldr     r0, [pc, #28]   ; (0x1000034c)
   0x1000032e:  bl      0x10003bfc
   0x10000332:  movs    r1, #11
   0x10000334:  ldr     r0, [pc, #24]   ; (0x10000350)
   0x10000336:  bl      0x10003bfc
   0x1000033a:  b.n     0x1000030a
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

Let’s hack the first 50 going into R1.

```
(gdb) b *0x1000030c
(gdb) c
(gdb) set $r1 = 42
(gdb) c
```

We now see arithemetic_operator is 42! Now that you have enough experience with this go ahead and set breakpoints after the value you want to hack and set it like we did above and continue and see the values update!



In our next lesson we will cover static conditionals.

Chapter 29: Static Conditionals

In this chapter we are going to discuss static conditionals.

Let’s open up our folder **0x001d_static-conditionals**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

int main(void) {
    stdio_init_all();

    int choice = 1;

    while (true) {
        if (choice == 1) {
            printf("1\r\n");
        } else if (choice == 2) {
            printf("2\r\n");
        } else {
            printf("?\r\n");
        }

        switch (choice) {
            case 1:
                printf("one\r\n");
                break;
            case 2:
                printf("two\r\n");
                break;
            default:
                printf("??\r\n");
        }
    }
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

We start with an int of *choice* assigned to *1* and then we check to see if *choice == 1* and if so follow that branch and if it satisfies that it will ignore the else if and else and go to the switch.
When we go to the switch it will parse the list to find the correct item, in our case 1 and exit otherwise it will follow the default.

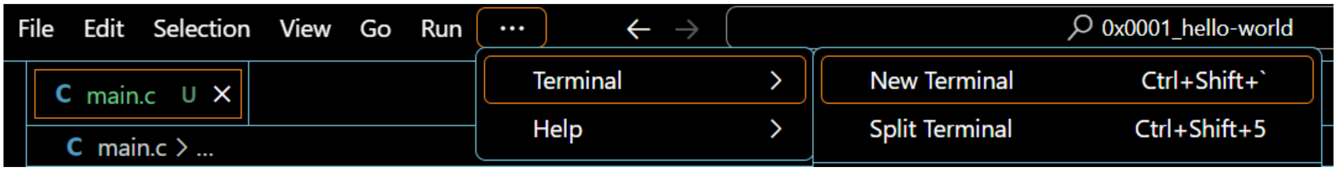
In our next lesson we will debug this.

Chapter 30: Debugging Static Conditionals

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x001d_static-conditionals.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
   0x10000308:  push    {r4, lr}
   0x1000030a:  bl      0x10003b80
   0x1000030e:  ldr     r0, [pc, #12]   ; (0x1000031c)
   0x10000310:  bl      0x10003b08
   0x10000314:  ldr     r0, [pc, #8]    ; (0x10000320)
   0x10000316:  bl      0x10003b08
   0x1000031a:  b.n     0x1000030e
```

We see the compiler optimized away our conditionals. This is why we will have different chapters so you understand that values are static likely the compiler will simply optimize away.

```
(gdb) x/s *0x1000031c
0x10003e60:     "1\r"
(gdb) x/s *0x10000320
0x10003e64:     "one\r"
```

In our next lesson we will hack this.

Chapter 31: Hacking Static Conditionals

Let's examine 7 instructions.

```
(gdb) x/7i 0x10000308
   0x10000308:  push    {r4, lr}
   0x1000030a:  bl      0x10003b80
   0x1000030e:  ldr     r0, [pc, #12]   ; (0x1000031c)
   0x10000310:  bl      0x10003b08
   0x10000314:  ldr     r0, [pc, #8]    ; (0x10000320)
   0x10000316:  bl      0x10003b08
   0x1000031a:  b.n     0x1000030e
```

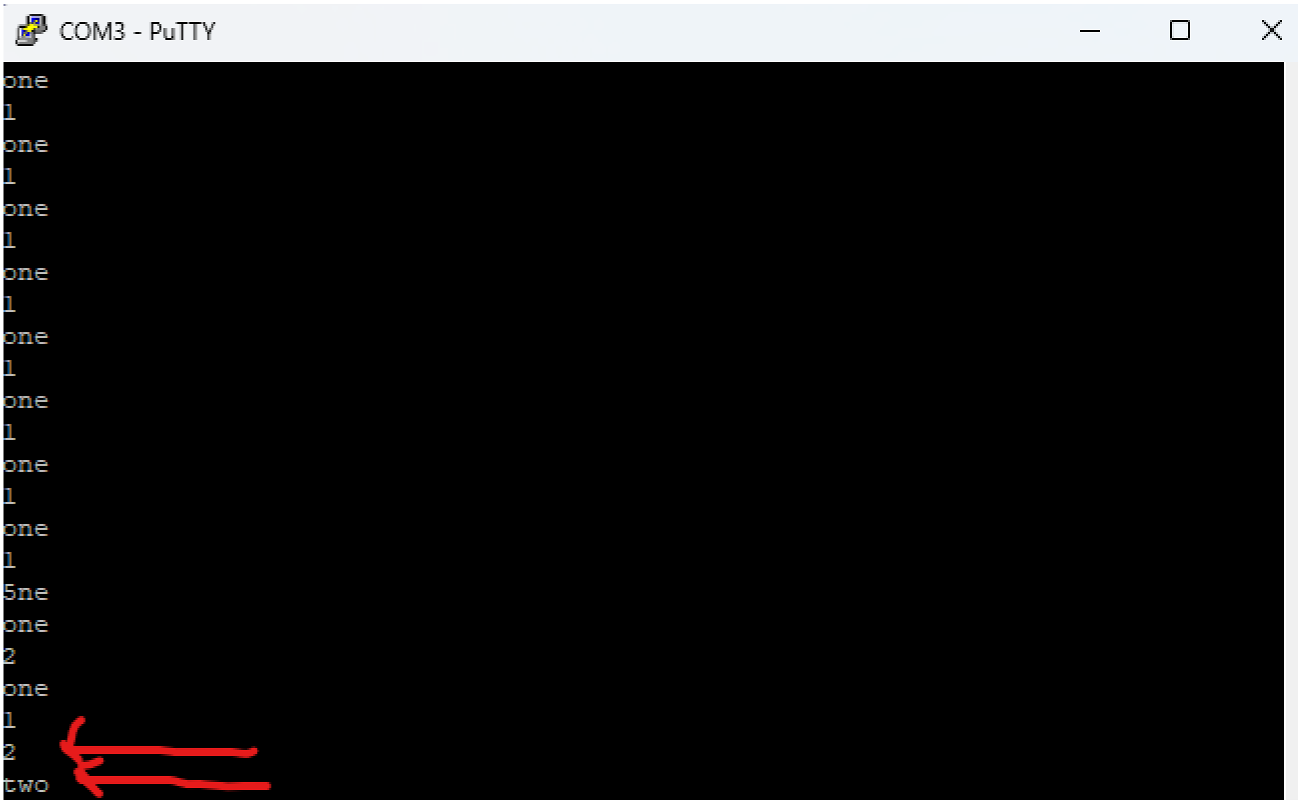
NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We are dealing with a string literal so we will have to hijack our address pointer in R0 with RAM.

Let's break and hack.

```
(gdb) b *0x10000310
(gdb) x/x $r0
0x10003e60:     0x31
(gdb) set {char[3]} 0x20000000 = { '2', '\r', '\0' }
(gdb) set $r0 = 0x20000000
(gdb) x/s $r0
0x20000000:     "2\r"
(gdb) b *0x10000316
(gdb) c
Continuing.
(gdb) set {char[5]} 0x20000000 = { 't', 'w', 'o', '\r', '\0' }
(gdb) set $r0 = 0x20000000
(gdb) x/s $r0
0x20000000:     "two\r"
(gdb) c
```

Let’s look at our output!



Isn’t hacking fun! In our next lesson we will cover dynamic conditionals.

Chapter 32: Dynamic Conditionals

In this chapter we are going to discuss dynamic conditionals.

Let’s open up our folder **0x0020_dynamic-conditionals**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"
#include "input.h"

#define ONE 0x31
#define TWO 0x32

int main(void) {
    stdio_init_all();
    uart0_init();

    uint8_t choice = 0;

    while (true) {
        choice = on_uart_rx();

        if (choice == ONE) {
            printf("1\r\n");
        } else if (choice == TWO) {
            printf("2\r\n");
        } else {
            printf("??\r\n");
        }

        switch (choice) {
            case '1':
                printf("one\r\n");
                break;
            case '2':
                printf("two\r\n");
                break;
            default:
                printf("??\r\n");
        }
    }
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

In order to properly handle input, I created a driver that is abstracted away at this time as I do not want to cover functions and drivers at this early stage so you can focus on the basics first.

Here when we press *1* in the terminal we will get the *1* printed along with the word *one*.

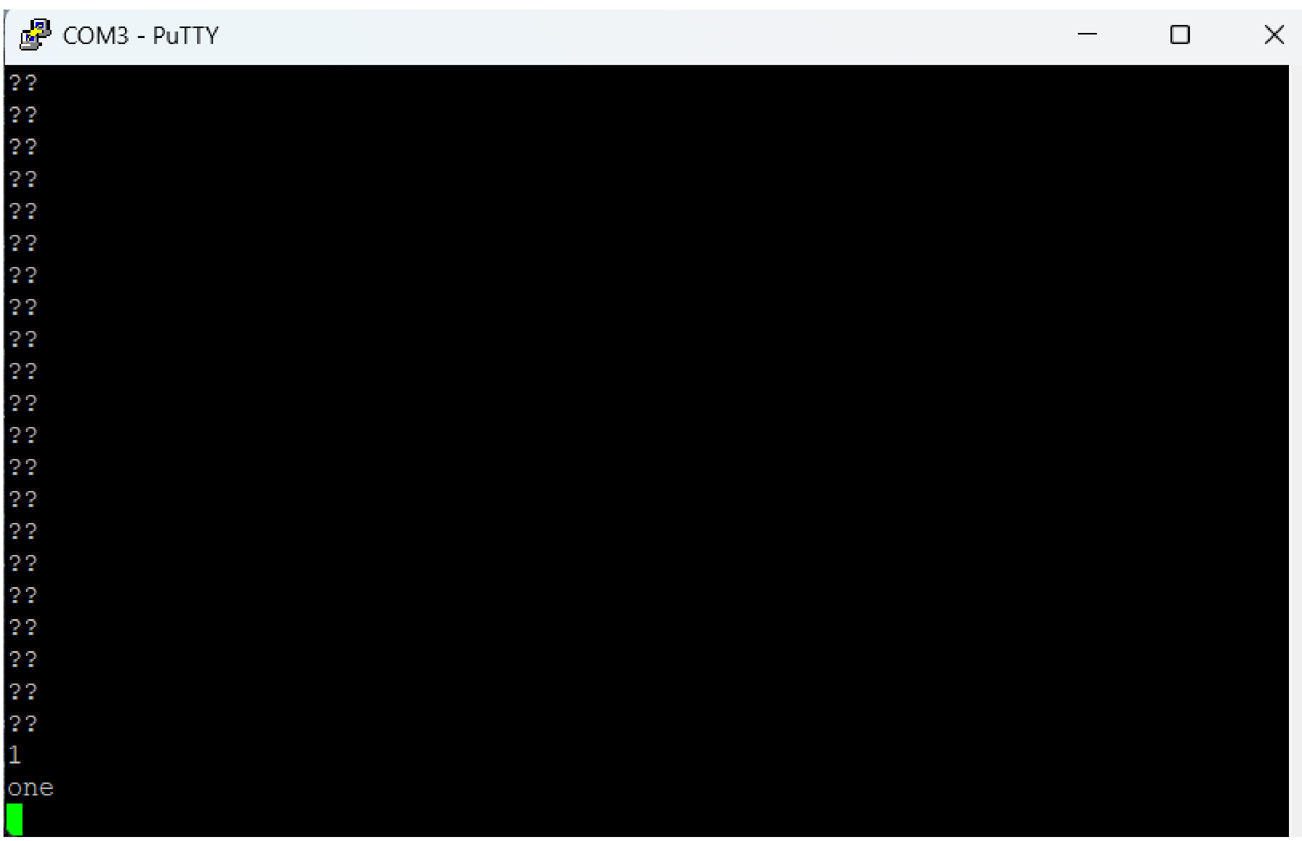
When we press *2* in the terminal we get the *2* printed along with the word *two*.

If we press anything else, we will get *??*.

We then check to see if *choice == 1* and if so follow that branch and if it satisfies that it will ignore the else if and else and go to the switch.

If it is not *choice == 1*, we then check to see if *choice == 2* and if so follow that branch else will print *??.*

When we go to the switch it will parse the list to find the correct item if a *1* or *2* is selected otherwise it will follow the default.



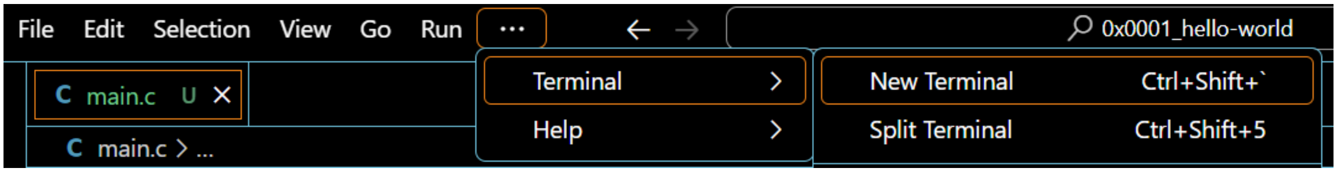
In our next lesson we will debug this.

Chapter 33: Debugging Dynamic Conditionals

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0020_dynamic-conditionals.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
   0x10000304:  push    {r4, lr}
   0x10000306:  movs    r1, #225        ; 0xe1
   0x10000308:  lsls    r1, r1, #9
   0x1000030a:  ldr     r0, [pc, #24]   ; (0x10000324)
   0x1000030c:  bl      0x10001e50
   0x10000310:  movs    r1, #2
```

```
   0x10000312:  movs    r0, #0
   0x10000314:  bl      0x10000734
   0x10000318:  movs    r1, #2
   0x1000031a:  movs    r0, #1
   0x1000031c:  bl      0x10000734
   0x10000320:  pop     {r4, pc}
   0x10000322:  nop                     ; (mov r8, r8)
   0x10000324:  ands    r0, r0
   0x10000326:  ands    r3, r0
   0x10000328:  sub     sp, #8
   0x1000032a:  ldr     r3, [pc, #48]   ; (0x1000035c)
   0x1000032c:  ldr     r3, [r3, #24]
   0x1000032e:  lsls    r3, r3, #27
   0x10000330:  bmi.n   0x10000336
   0x10000332:  add     sp, #8
   0x10000334:  bx      lr
   0x10000336:  movs    r2, #0
   0x10000338:  mov     r3, sp
   0x1000033a:  adds    r1, r3, #7
   0x1000033c:  cmp     r2, #0
   0x1000033e:  bne.n   0x10000354
   0x10000340:  ldr     r3, [pc, #24]   ; (0x1000035c)
   0x10000342:  ldr     r3, [r3, #24]
=> 0x10000344:  lsls    r3, r3, #27
   0x10000346:  bmi.n   0x10000340
   0x10000348:  ldr     r3, [pc, #16]   ; (0x1000035c)
   0x1000034a:  ldr     r3, [r3, #0]
   0x1000034c:  strb    r3, [r1, #0]
   0x1000034e:  adds    r2, #1
   0x10000350:  adds    r1, #1
   0x10000352:  b.n     0x1000033c
   0x10000354:  mov     r3, sp
   0x10000356:  ldrb    r0, [r3, #7]
   0x10000358:  b.n     0x10000332
```

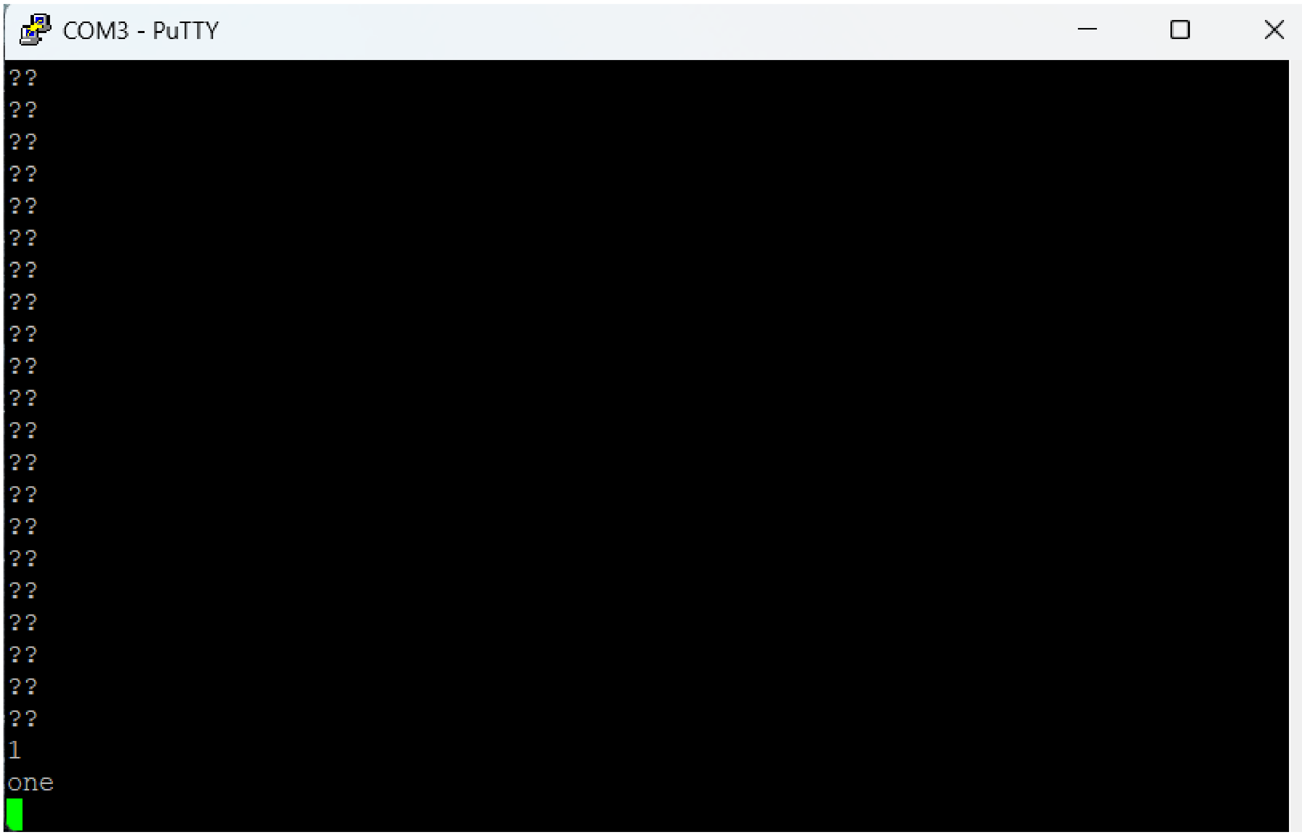
Let’s set a breakpoint on our first compare and continue.

```
(gdb) b *0x1000033c
(gdb) c
```

We see that if we press 1, and we do an info registers we will see 0x31.

```
(gdb) i r $r3
r3             0x31
```

If you continue it will print out 1 and one.



In our next lesson we will hack this.

Chapter 34: Hacking Dynamic Conditionals

Let’s examine 40 instructions.

```
(gdb) x/40i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  movs    r1, #225        ; 0xe1
   0x10000308:  lsls    r1, r1, #9
   0x1000030a:  ldr     r0, [pc, #24]   ; (0x10000324)
   0x1000030c:  bl      0x10001e50
   0x10000310:  movs    r1, #2
   0x10000312:  movs    r0, #0
   0x10000314:  bl      0x10000734
   0x10000318:  movs    r1, #2
   0x1000031a:  movs    r0, #1
   0x1000031c:  bl      0x10000734
   0x10000320:  pop     {r4, pc}
   0x10000322:  nop                     ; (mov r8, r8)
   0x10000324:  ands    r0, r0
   0x10000326:  ands    r3, r0
   0x10000328:  sub     sp, #8
   0x1000032a:  ldr     r3, [pc, #48]   ; (0x1000035c)
   0x1000032c:  ldr     r3, [r3, #24]
   0x1000032e:  lsls    r3, r3, #27
   0x10000330:  bmi.n   0x10000336
   0x10000332:  add     sp, #8
   0x10000334:  bx      lr
   0x10000336:  movs    r2, #0
   0x10000338:  mov     r3, sp
   0x1000033a:  adds    r1, r3, #7
   0x1000033c:  cmp     r2, #0
   0x1000033e:  bne.n   0x10000354
   0x10000340:  ldr     r3, [pc, #24]   ; (0x1000035c)
   0x10000342:  ldr     r3, [r3, #24]
=> 0x10000344:  lsls    r3, r3, #27
   0x10000346:  bmi.n   0x10000340
   0x10000348:  ldr     r3, [pc, #16]   ; (0x1000035c)
   0x1000034a:  ldr     r3, [r3, #0]
   0x1000034c:  strb    r3, [r1, #0]
   0x1000034e:  adds    r2, #1
   0x10000350:  adds    r1, #1
   0x10000352:  b.n     0x1000033c
   0x10000354:  mov     r3, sp
   0x10000356:  ldrb    r0, [r3, #7]
   0x10000358:  b.n     0x10000332
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

Let’s break and hack.

```
(gdb) b *10000386
(gdb) c
```

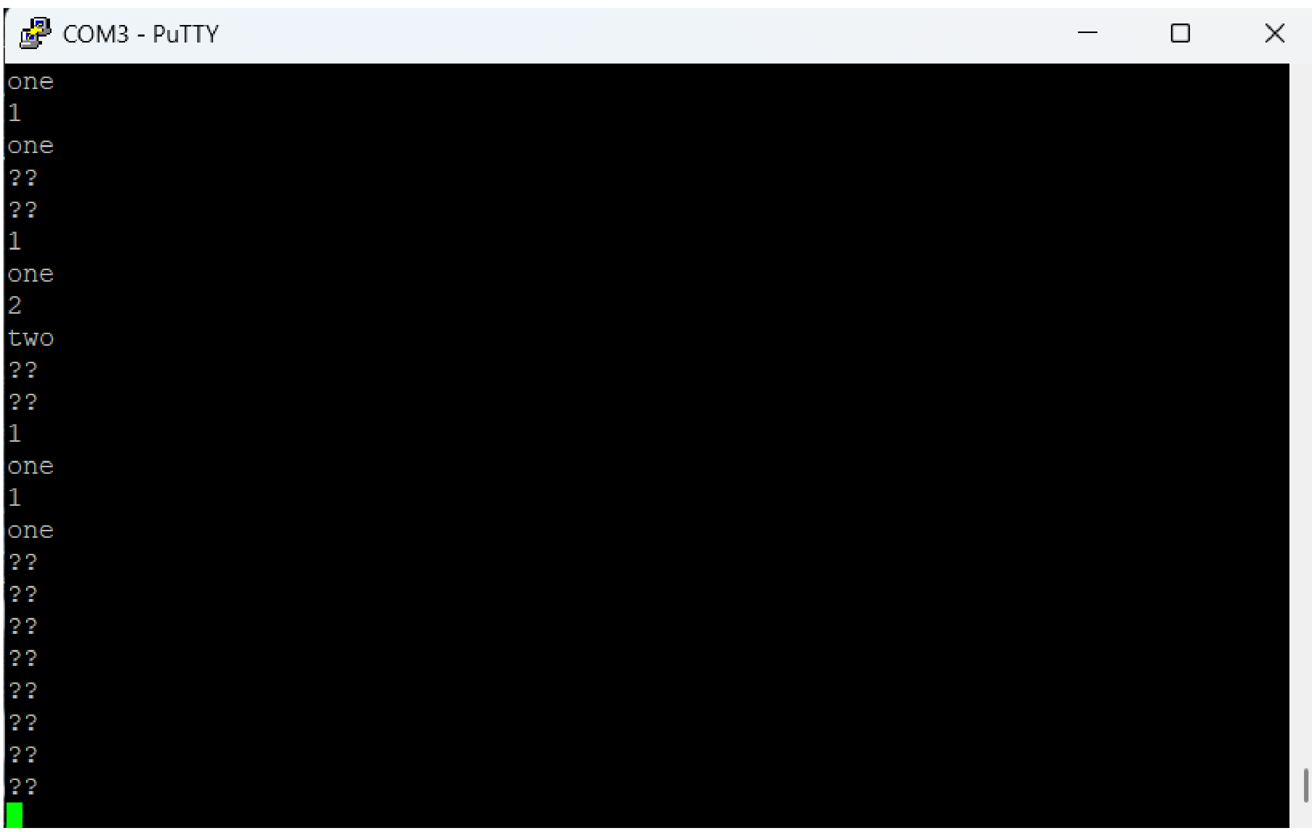
Press *1* in the terminal and lets look at R0!

```
(gdb) i r $r0
r0             0x31                49
```

Let’s hack R0 to 0x42!

```
(gdb) i r $r0
r0             0x31                49
(gdb) x/5i 0x10000386
=> 0x10000386:  movs    r4, r0
   0x10000388:  cmp     r0, #49 ; 0x31
   0x1000038a:  beq.n   0x1000036c
   0x1000038c:  cmp     r0, #50 ; 0x32
   0x1000038e:  beq.n   0x10000374
(gdb) set $r0 = 42
(gdb) c
```

BOOM! We entered in *1* and should have got *1 one* but we got *?? ??*!



In our next lesson we will cover functions, w/o param, w/o return.

Chapter 35: Functions, w/o Param, w/o Return

In this chapter we are going to discuss functions that do not have any params nor any return value.

Let’s open up our folder **0x0023_functions-wo-params-wo-return**.

Now let’s review our **main.c** file as this is located in the main folder.

```
#include <stdio.h>
#include "pico/stdlib.h"

#define FAV_NUM 42

void print_me(void);

int main(void) {
    stdio_init_all();

    while (true)
        print_me();
}

void print_me(void) {
    printf("FAV_NUM: %d\r\n", FAV_NUM);
}
```

Let’s flash the uf2 file onto the Pico. If you are unsure about this step please take a look at Chapter 1 to get re-familiar with this process.

This is our first use of working with our own custom functions.

When we write professional development code, each function prototype, will exist in it’s own header file or .h file and the functions will exist in their on .c file.

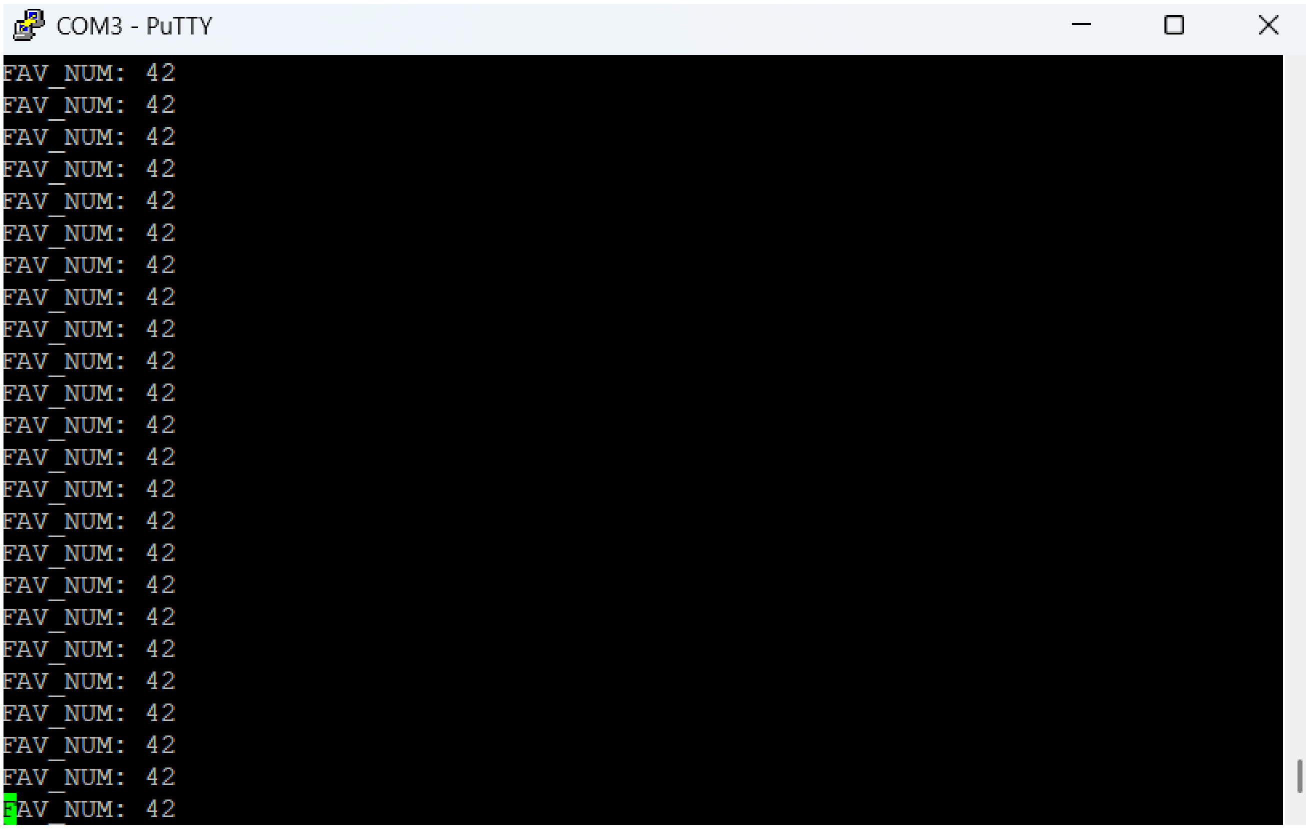
In our examples we start with the forward declaration which means this function will be visible everywhere within our module.

```
void print_me(void);
```

If we did not have the forward declaration, the function would not be seen under main.

Our function print_me takes no parameters nor does it return any value. We use void to preface the function name to indicate there is no return value and we put void within the param to indicate no parameters.

When we run we simply print the *FAV_NUM: 42* within the terminal infinitely.



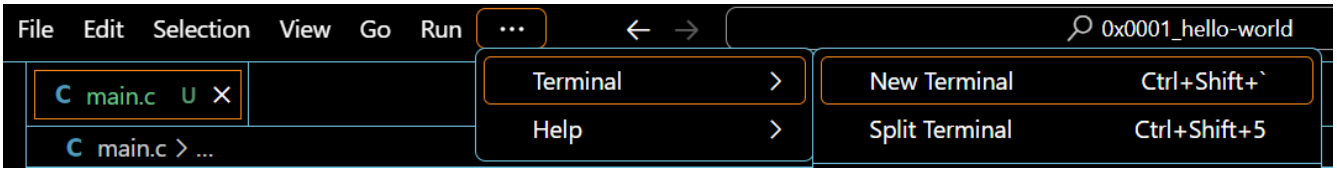
In our next lesson we will debug this.

Chapter 36: Debugging Functions, w/o Param, w/o Return

Today we debug!

Lets run OpenOCD to get our remote debug server going.

Open up a terminal within VSCode.




```
cd ..
.\openocd.ps1
```

If you are on MAC or Linux, simply run the below command.

```
openocd -f interface/cmsis-dap.cfg -f target/rp2040.cfg -c "adapter speed 5000"
```

Open up a new terminal and cd .\build\ dir and then run the following.

```
arm-none-eabi-gdb .\0x0023_functions-wo-params-wo-return.bin
```

Once it loads, we need to target our remote server.

```
target remote :3333
```

We need to halt the currently running binary.

```
monitor reset halt
```

Let’s examine instructions from the beginning of our vector table.

```
x/1000i 0x10000100
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

We see something interesting here.

```
   0x10000304:  push    {r4, lr}
   0x10000306:  movs    r1, #42 ; 0x2a
   0x10000308:  ldr     r0, [pc, #4]    ; (0x10000310)
   0x1000030a:  bl      0x10003bc8
   0x1000030e:  pop     {r4, pc}
   0x10000310:  subs    r6, #176        ; 0xb0
   0x10000312:  asrs    r0, r0, #32
   0x10000314:  push    {r4, lr}
   0x10000316:  bl      0x10003be0
   0x1000031a:  bl      0x10000304
   0x1000031e:  b.n     0x1000031a
```

We notice *42* being moved into r1 and then a branch and link to *0x10003bc8*. Let’s disassemble there.

```
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
```

Let’s set a breakpoint on our function.

```
(gdb) b *0x10003bc8
Breakpoint 1 at 0x10003bc8
Note: automatically using hardware breakpoints for read-only addresses.
(gdb) c
Continuing.
(gdb) x/11i $pc
=> 0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
```

Let’s set another breakpoint after the bl to printf. Then step.

```
(gdb) b *0x10003bd8
Breakpoint 2 at 0x10003bd8
(gdb) c
```

```
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 2, 0x10003bd8 in ?? ()
(gdb) x/4i $pc
=> 0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
(gdb) si
0x10003bda in ?? ()
(gdb) si
0x10003bdc in ?? ()
(gdb) si
0x10003bde in ?? ()
(gdb) si
0x1000030e in ?? ()
```

Now we can see we are back in main.

```
(gdb) x/11i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  movs    r1, #42 ; 0x2a
   0x10000308:  ldr     r0, [pc, #4]    ; (0x10000310)
   0x1000030a:  bl      0x10003bc8
=> 0x1000030e:  pop     {r4, pc}
   0x10000310:  subs    r6, #176        ; 0xb0
   0x10000312:  asrs    r0, r0, #32
   0x10000314:  push    {r4, lr}
   0x10000316:  bl      0x10003be0
   0x1000031a:  bl      0x10000304
   0x1000031e:  b.n     0x1000031a
```

Let’s better understand what happens when we enter into a function in Embedded C.

```
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
```

We see we are pushing the first 4 registers onto the stack in addition to the link register.

The first four registers are where params are utilized. In our case we do not have any params.

The R0 register is where the return value is sent back to the calling function. In our case we do not have any.

The LR is the link register which holds the address of where we need to return to in our main function.

We see a sub sp, #12 where we are setting up room on our stack, in our case 12 bytes, for local variables. Remember that the stack grows downward.

Let’s continue and re-examine our function.

```
(gdb) c
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 1, 0x10003bc8 in ?? ()
(gdb) x/11i $pc
=> 0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
(gdb) x/x $sp
0x20041ff0:     0x10000264
(gdb) si
0x10003bca in ?? ()
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
=> 0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
```

Here we see the stack pointer at 0x20041ff0.

```
(gdb) x/x $sp
0x20041fe0:     0x10003eb0
```

```
(gdb) si
0x10003bcc in ?? ()
```

We see the stack pointer is now at 0x20041fe0. This is a difference of 16 bytes.

```
(gdb) si
0x10003bcc in ?? ()
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
=> 0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
(gdb) x/x $sp
0x20041fdc:     0x1000030f
```

We see the stack pointer is now at 0x20041fdc. This is a difference of 4 bytes.

```
(gdb) si
0x10003bce in ?? ()
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
=> 0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
(gdb) x/x $sp
0x20041fd0:     0x18000000
```

We see the stack pointer is now at 0x20041fdc. This is a difference of 12 bytes.

Before we execute the add instruction, we know R1 is going to have 42 or 0x2a. Let’s verify

```
(gdb) x/x $r1
0x2a:   0x1c18d1f7
```

Let’s set a breakpoint to then understand how the stack will return from the function.

```
(gdb) b *0x10003bd8
Note: breakpoint 2 also set at pc 0x10003bd8.
Breakpoint 3 at 0x10003bd8
(gdb) c
Continuing.

Thread 1 "rp2040.core0" hit Breakpoint 2, 0x10003bd8 in ?? ()
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
=> 0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
```

We verify SP is still at 0x020041fd0.

```
(gdb) x/x $sp
0x20041fd0:     0x18000000
```

Let’s step once.

```
(gdb) si
0x10003bda in ?? ()
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
=> 0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
(gdb) x/x $sp
0x20041fdc:     0x1000030f
```

We see the stack pointer increased by 12 bytes. This is the difference between 0x20041fdc – 0x20041fd0.

Let’s step again.

```
(gdb) si
0x10003bdc in ?? ()
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
=> 0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
(gdb) x/x $sp
0x20041fe0:     0x10003eb0
```

We see the stack pointer increased by 4 bytes. This is the difference between 0x20041fe0 – 0x20041fdc.

Let's step again.

```
(gdb) si
0x10003bde in ?? ()
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
=> 0x10003bde:  bx      r3
(gdb) x/x $sp
0x20041ff0:     0x10000264
```

We see the stack pointer increased by 16 bytes. This is the difference between 0x20041ff0 – 0x20041fe0.

Here we see the stack at it's original value 0x20041ff0.

```
Higher Memory Addresses
       |
       V
+-----------------+
|    0x10000264   |   <-- Original Stack Pointer (sp = 0x20041ff0)
+-----------------+
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
|                 |
+-----------------+
|   0x10003eb0     |   <-- Value at sp = 0x20041fe0
+-----------------+
|                 |
|                 |
|                 |
|                 |
+-----------------+
|   0x1000030f     |   <-- Value at sp = 0x20041fdc
+-----------------+
|   0x18000000     |   <-- Value at sp = 0x20041fd4
+-----------------+
|   0x10003eb0     |   <-- Value at sp = 0x20041fd0
+-----------------+
|                 |
|                 |
|                 |
|                 |
+-----------------+
|   0x1000030f     |   <-- Value at sp = 0x20041fe0
+-----------------+
```

Now you have the full picture of how a function works in Embedded C!

In our next lesson we will hack this!

Chapter 37: Hacking Functions, w/o Param, w/o Return

Let’s examine our main function.

```
(gdb) x/11i 0x10000304
   0x10000304:  push    {r4, lr}
   0x10000306:  movs    r1, #42 ; 0x2a
   0x10000308:  ldr     r0, [pc, #4]    ; (0x10000310)
   0x1000030a:  bl      0x10003bc8
   0x1000030e:  pop     {r4, pc}
   0x10000310:  subs    r6, #176        ; 0xb0
   0x10000312:  asrs    r0, r0, #32
   0x10000314:  push    {r4, lr}
   0x10000316:  bl      0x10003be0
   0x1000031a:  bl      0x10000304
   0x1000031e:  b.n     0x1000031a
```

Let’s examine our print_me function.

```
(gdb) x/11i 0x10003bc8
   0x10003bc8:  push    {r0, r1, r2, r3}
   0x10003bca:  push    {lr}
   0x10003bcc:  sub     sp, #12
   0x10003bce:  add     r1, sp, #16
   0x10003bd0:  ldmia   r1!, {r0}
   0x10003bd2:  str     r1, [sp, #4]
   0x10003bd4:  bl      0x10003b88
   0x10003bd8:  add     sp, #12
   0x10003bda:  pop     {r3}
   0x10003bdc:  add     sp, #16
   0x10003bde:  bx      r3
```

NOTE: ADDRESSES WILL VARY FROM MACHINE TO MACHINE

Here we can hack *R1* either in *main* or in *print_me*.

Let’s break and hack the one in main.

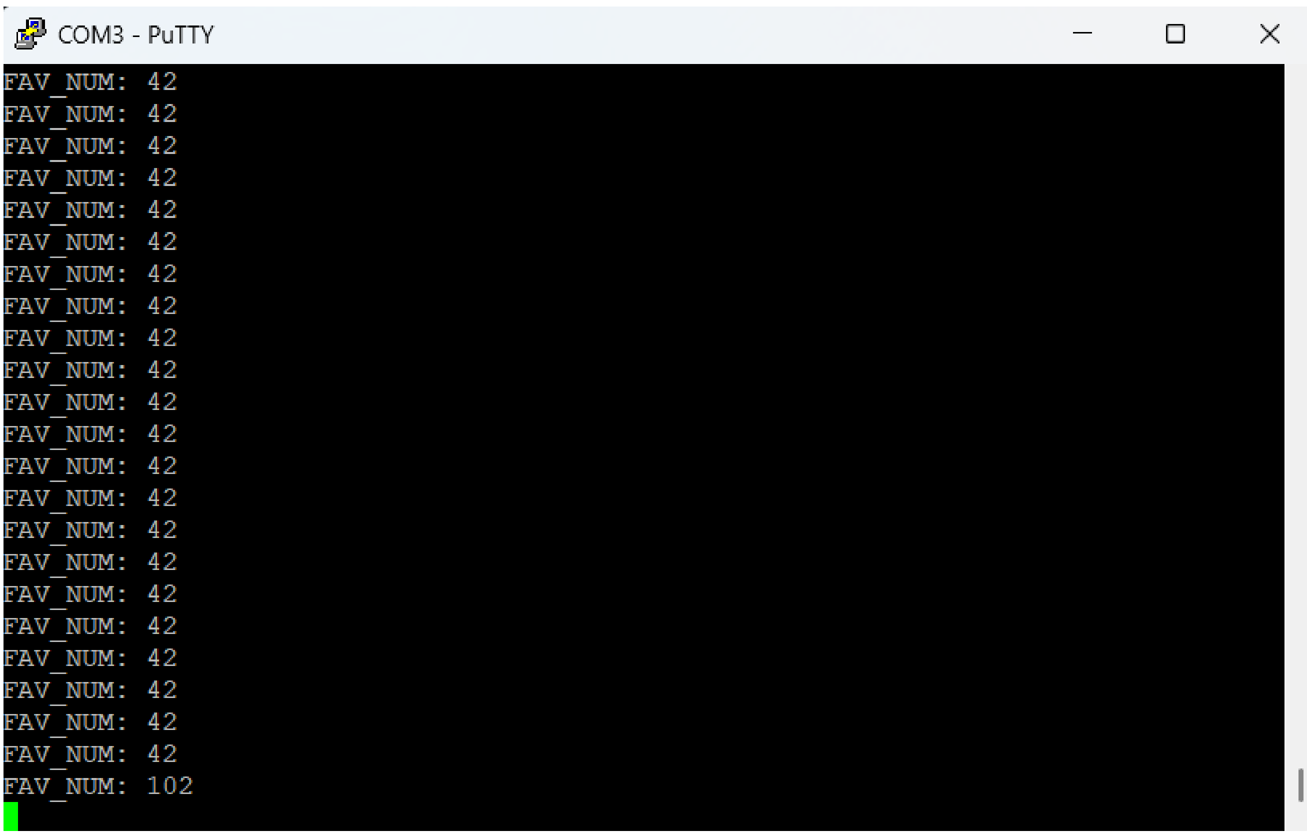
```
(gdb) b *10000304
(gdb) c
(gdb) x/11i $pc
=> 0x10000304:  push    {r4, lr}
   0x10000306:  movs    r1, #42 ; 0x2a
   0x10000308:  ldr     r0, [pc, #4]    ; (0x10000310)
   0x1000030a:  bl      0x10003bc8
   0x1000030e:  pop     {r4, pc}
   0x10000310:  subs    r6, #176        ; 0xb0
   0x10000312:  asrs    r0, r0, #32
   0x10000314:  push    {r4, lr}
   0x10000316:  bl      0x10003be0
   0x1000031a:  bl      0x10000304
```

```
   0x1000031e:  b.n     0x1000031a
(gdb) si
0x10000306 in ?? ()
(gdb) si
0x10000308 in ?? ()
```

Let’s hack R1 to be 0x66 and continue.

```
(gdb) set $r1 = 0x66
(gdb) c
Continuing.
```

BOOM!



In our next lesson we will cover functions, w param, w/o return.

This concludes our studies and I am hope you enjoyed diving deep into the ARM embedded architecture!

I can’t wait to see what you do next!