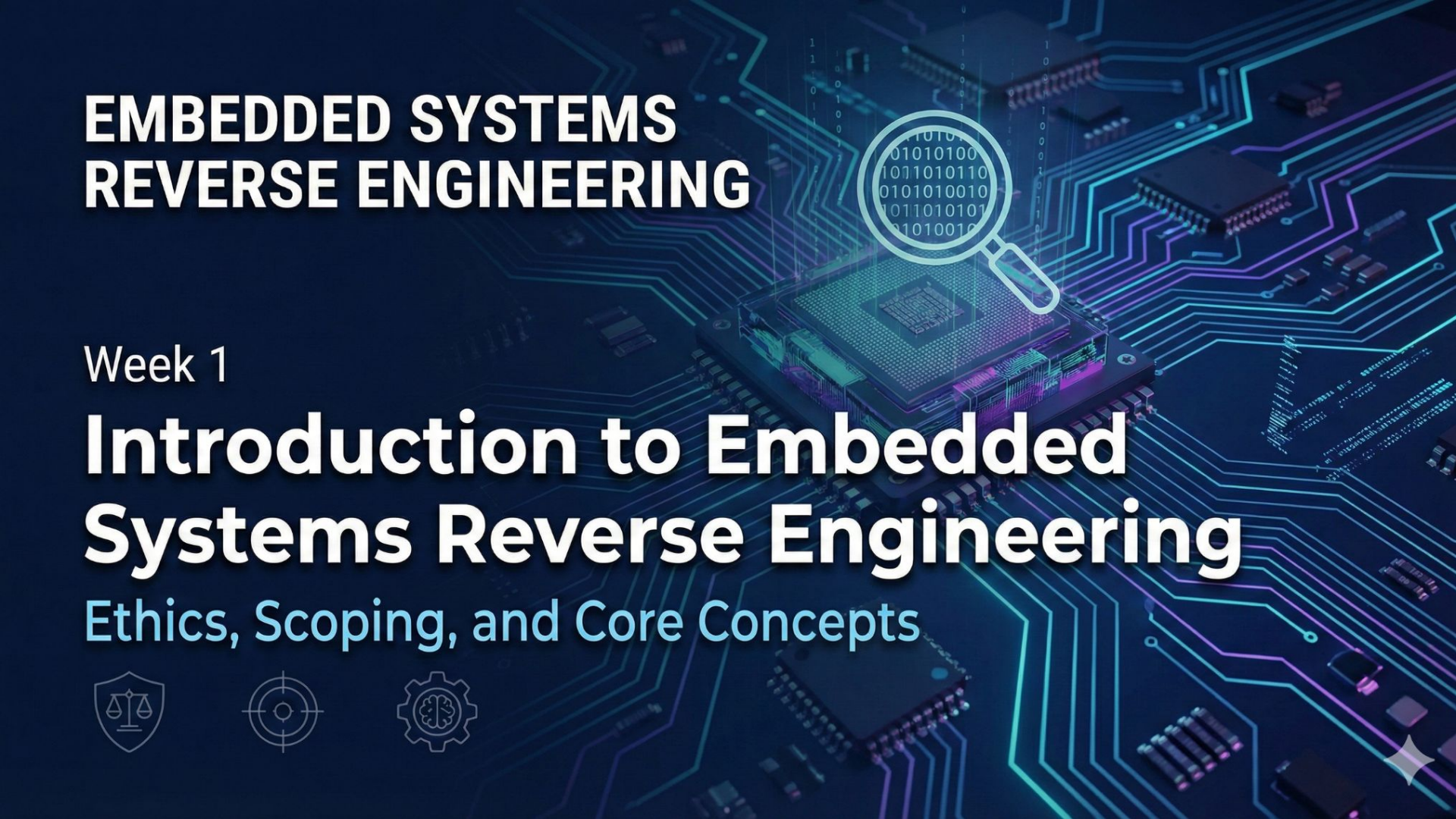

EMBEDDED SYSTEMS
REVERSE ENGINEERING
Week 1
Introduction to Embedded Systems Reverse Engineering
Ethics, Scoping, and Core Concepts

Course Goals & The Mindset

What Are We Doing?

Compiled Code
("The Answer")

↓

Reverse Engineering

↓

Source Logic
("The Question")

Working backward from compiled, running code to understand the original source logic.

Why do we do it?

Understanding: Learning complex hardware/software interactions without documentation.

Security Auditing: Finding vulnerabilities before bad actors do.

Interoperability: Figuring out how to make new software talk to old hardware.

The Ethical Hacker's Mindset

Stay within scope: Only analyze targets you have permission to touch.

Do no harm: Avoid bricking hardware or disrupting live systems.

Curiosity driven: It is a detective game of digital clues.

The Target: What is a Microcontroller (MCU)?

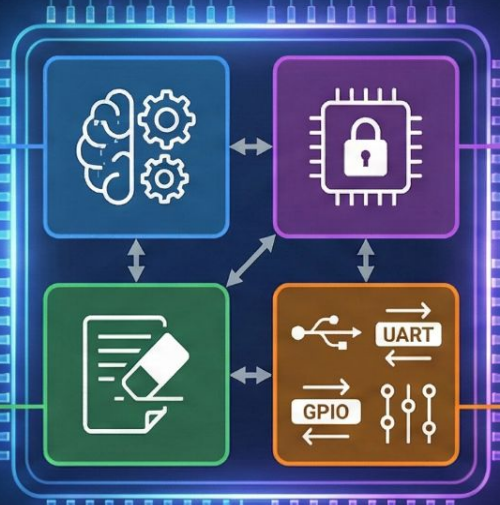
A Computer on a Single Chip

1. The Core (CPU)

The brain executing instructions (e.g., ARM Cortex-M, RISC-V, AVR).

2. Non-Volatile Memory (Flash/ROM)

Where the program code lives permanently. It survives a reboot.



3. Volatile Memory (SRAM)

Fast “scratchpad” memory for temporary data. Wiped on reboot.

4. Peripherals (I/O)

Hardware to talk to the outside world (UART, USB, GPIO pins).

Unlike a desktop, an MCU integrates everything.

ⓘ Note: In this course, our example hardware is the RP2350, which uses ARM Cortex-M33 cores.

The Two Paths of Analysis

RE is rarely done using just one method. We combine two approaches:

1. Static Analysis ("Dead" Code)

Analogy: Reading a blueprint of a building.

Action: Examining the binary file without running it.

Tools: Ghidra, IDA Pro, Binary Ninja.

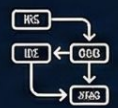
Goal: To see the "big picture," understand program structure, find strings, and identify key functions.

2. Dynamic Analysis ("Live" Code)

Analogy: Walking through the building, opening doors, and testing light switches.

Action: Running the code on actual hardware while attached to a debugger.

Tools: GDB (GNU Debugger), JTAG/SWD hardware probes (like OpenOCD).



Goal: To watch register values change, see exactly which path execution takes, and examine memory at a specific moment in time.

The CPU's Perspective: Registers

Registers are the fastest storage locations in a computer, located directly **inside the CPU core**. The CPU cannot do math directly on memory; it must load data into registers first.

General Purpose Registers

- Used for holding temporary data during calculations, passing arguments to functions, and holding return values.
- ***ARM Cortex-M example: r0 through r12.***

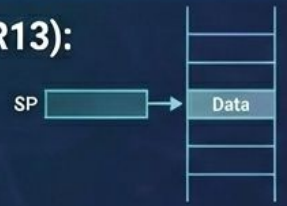
R0	Data
R1	Data
R2	0
R3	Data
R4	Data
R5	Data
R6	Data
R7	Data
R8	Data
R9	Data
R9	Data
R10	Data
R11	Data
R12	Data

The Special Registers
(The "State" of the Machine)

Program Counter (PC) (R15):

Link Register (LR) (R14):
Stores the return address for function calls.

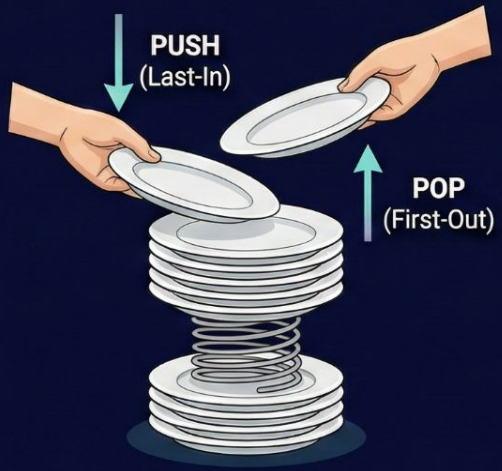
Stack Pointer (SP) (R13):
Points to the current "top" location of the temporary stack memory.



The Stack Concept

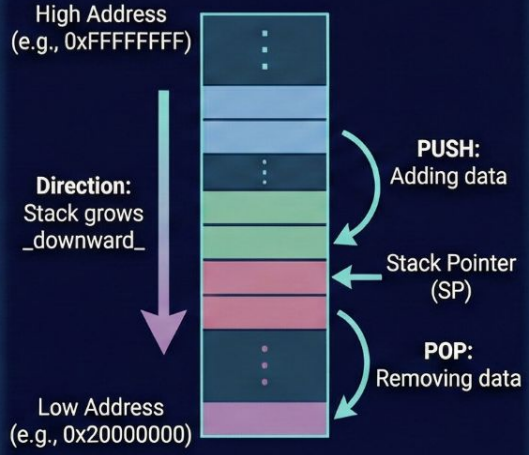
The Stack is a fundamental concept in almost all computer architectures used for managing function calls and temporary data.

LIFO (Last-In, First-Out)



Think of a stack of plates in a cafeteria. The last plate you put on top is the first one you take off.

How it works in Embedded Memory



PUSH: SP decreases, data saved.
POP: Data read, SP increases.

What is it used for?

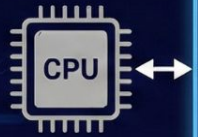
- Saving local variables inside a function.

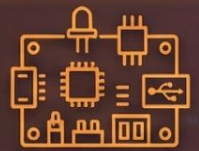
- Remembering where to return to after a function call finishes.

The Memory Map Landscape

In embedded systems, “Memory” doesn’t just mean RAM. Everything the CPU can talk to has a memory address. This is called a “Memory Map”.

CPU Address Space (0x00000000 to 0xFFFFFFFF)





Code Space

Typical Contents: The program instructions (Firmware)

Characteristics: Read-Only (usually), Non-Volatile (Flash)

ARM Cortex-M Example Addresses: Often starts at `0x00000000` or `0x10000000`

RAM Space

Typical Contents: Stack, Heap, Global Variables

Characteristics: Read/Write, Volatile (Fast SRAM)

ARM Cortex-M Example Addresses: Often starts at `0x20000000`

Peripheral Space (MMIO)

Typical Contents: Hardware control registers (e.g., turn on an LED, read USB data)

Characteristics: Read/Write, changing these affects physical hardware

ARM Cortex-M Example Addresses: Architecture dependent (e.g., `0x40000000` range)

Tip: In RE, knowing *where* data is tells you a lot about *what* it is.

From C to Machine Code (The Reverse Path)

As reverse engineers, we are walking backward through the compilation process.

Forward Process (Development):

1. C Source Code:

High-level logic
(`printf("hello");`)

2. Compiler:

3. Assembler:

Machine Code (Hex/ Binary):

```
0x1000023c: 01 f0 de f9...
0x1000023c: 01 f0 de f9...
...
```

Reverse Process (Our Job):

1. Machine Code (Binary):

We start with the raw
`0x1000023c: 01 f0 de f9`

2. Disassembler (Ghidra/GDB):

Turns hex back into readable Assembly
(`bl __wrap_puts`)

3. Decompiler (Ghidra):

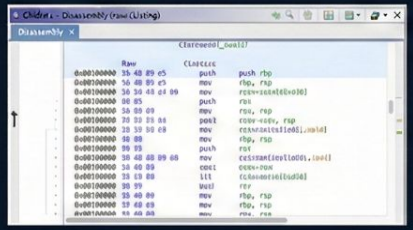
Attempts to turn Assembly back into C-like pseudocode.

Tool Theory: Static Analysis (Ghidra)

We use tools like Ghidra to perform static analysis on binary files (like .elf or .bin).

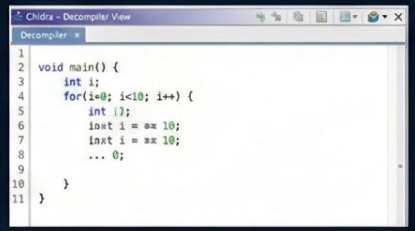
Key Views:

The Disassembly View (Listing):



Shows the exact assembly instructions exactly as they exist in the binary. This is the “truth,” but it’s hard to read quickly.

The Decompiler View:



A “best guess” reconstruction of C code. It is incredibly helpful for understanding high-level logic rapidly, but it can sometimes be wrong or misleading.

Symbols matter:

ELF Files:

Usually contain “symbols” (human readable names for functions like `main` or `stdio_init`). These are training wheels for RE.

Binary Files (.bin):

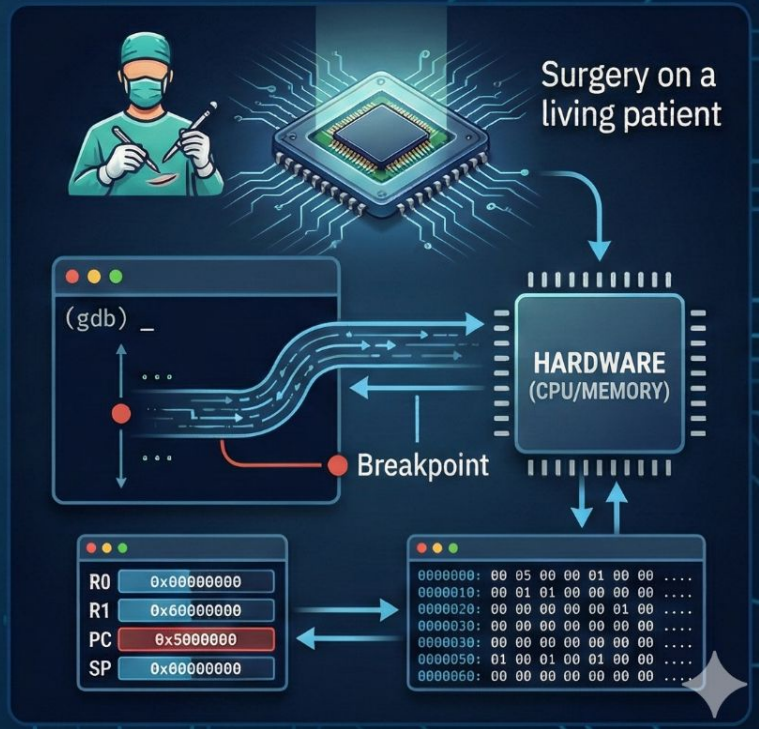
“Stripped” binaries with no symbols. Real-world embedded RE often looks like this, requiring you to recognize functions by their behavior, not their names.

Tool Theory: Dynamic Analysis (Debuggers/GDB)

We use debuggers like GDB to interact with the hardware while it runs.
This is surgery on a living patient.

The Essential Debugger Verbs:

- **Breakpoint** (**b**): “Stop execution immediately when the PC reaches this address.”
- **Continue** (**c**): “Run at full speed until you hit a breakpoint.”
- **Step** (**si** / **ni**): “Execute exactly one instruction and then pause again.”
- **Examine Registers** (**i r**): “Show me the current state of the CPU brain right now.”
- **Examine Memory** (**x/...**): “Show me what values are currently stored at this specific RAM or Flash address.”



Key Takeaways for Week 1

It's all just numbers:

Context determines meaning.

The PC is King:

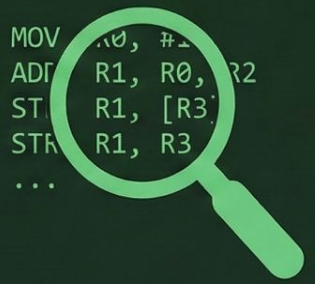
Knowing where the Program Counter is pointing tells you exactly what the machine is about to do.

Combine your tools:

Static Analysis (Ghidra) gives you the map; + dynamic analysis (GDB) lets you drive the car. =

You need both.

Assembly isn't magic:



It's just a series of very small, very simple steps. Don't get overwhelmed by the whole program; focus on one instruction at a time.