Embedded Systems Reverse Engineering

// WEEK 04

Variables in Embedded Systems:
Debugging and Hacking Variables
w/ GPIO Output Basics

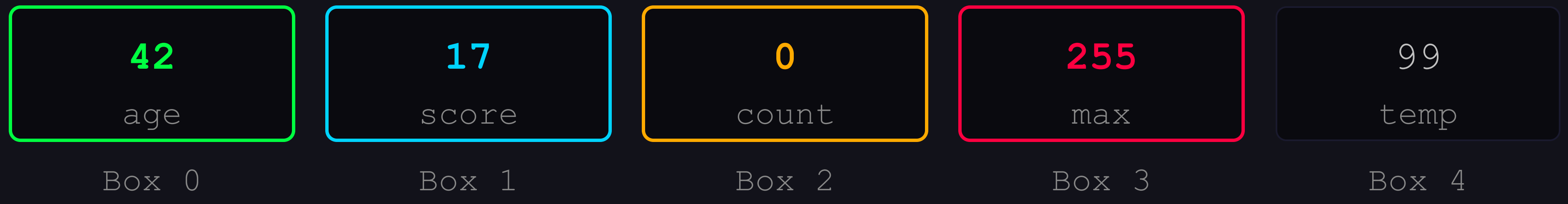
George Mason University

RP2350 // ARM Cortex-M33

What is a Variable?

Labeled Boxes in Memory (SRAM)

Memory — A Row of Numbered Boxes



42	17	0	255	99
age	score	count	max	temp
Box 0	Box 1	Box 2	Box 3	Box 4

Anatomy of a Declaration

```
uint8_t age = 42;
```

uint8_t	Data type (1 byte)	= 42	Initial value
age	Variable name (label)	;	End of statement

Key Concepts

Declaration	name + type
Definition	allocates memory
Initialization	assigns value

Important Rule

You MUST declare a variable BEFORE you use it!

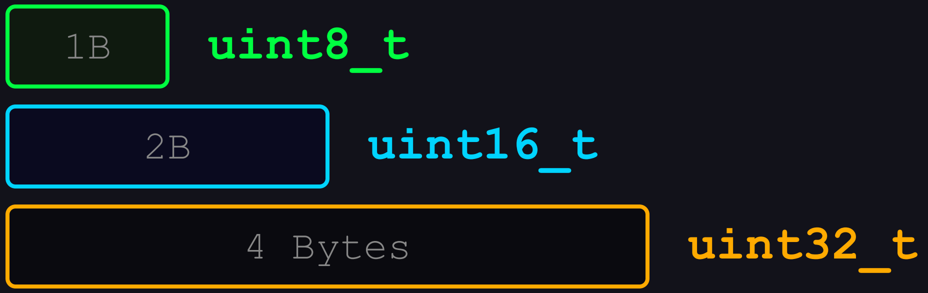
Compiler needs to know the type

Data Types & Sizes

How Much Memory Each Type Uses

Type	Size	Range	Description
uint8_t	1 byte	0 — 255	Unsigned 8-bit
int8_t	1 byte	-128 — 127	Signed 8-bit
uint16_t	2 bytes	0 — 65,535	Unsigned 16-bit
int16_t	2 bytes	-32,768 — 32,767	Signed 16-bit
uint32_t	4 bytes	0 — 4,294,967,295	Unsigned 32-bit
int32_t	4 bytes	-2.1B — 2.1B	Signed 32-bit

Size Comparison



Memory Sections

Where Variables Live After Compilation

.data Flash -> copied to RAM at startup

Contains: Initialized global/static variables

```
int counter = 42;
```

Initial value stored in flash, copied to SRAM by data_cpy

.bss RAM — zeroed at startup

Contains: Uninitialized global/static variables

```
int counter;
```

NOT stored in binary (saves space!) — memset to 0 at boot

.rodata Flash — read only

Contains: Constants and string literals

```
const int MAX = 100;
```

Lives in flash permanently — cannot be modified at runtime

.data	RAM	Writable	Initialized globals
.bss	RAM	Writable	Uninitialized globals (zeroed)
.rodata	Flash	Read-only	Constants & strings

GPIO Basics

General Purpose Input/Output on RP2350

Pico 2 GPIO Pins

GPIO 16	Red LED
GPIO 17	Green LED
GPIO 18	Blue LED
GPIO 25	Onboard LED

Software-controlled switches

Pico SDK Functions

gpio_init(pin)	Init pin
gpio_set_dir(pin,d)	I/O dir
gpio_put(pin,val)	Set H/L
sleep_ms(ms)	Delay

Basic LED Blink Code

```
#define LED_PIN 16
int main(void) {
  gpio_init(LED_PIN);
  gpio_set_dir(LED_PIN, GPIO_OUT);
  while (true) {
    gpio_put(LED_PIN, 1);       // ON
    sleep_ms(500);
    gpio_put(LED_PIN, 0);       // OFF
    sleep_ms(500);
  }}
```

Ghidra Binary Analysis

Analyzing a Raw .bin Without Symbols

1. Import

File -> Import

Language:
ARM Cortex 32 LE

Block: **.text**

Base: **10000000**

XIP address for RP2350

2. Analyze

Auto-Analyze: Yes

Ghidra finds:

FUN_1000019a
FUN_10000210
FUN_10000234

Auto-generated names

3. Resolve

Edit Function Sig

Rename to:

data_cpy
frame_dummy
main

Fix signatures

Decompiled main() in Ghidra

Before Resolving:

```
void FUN_10000234(void){
  FUN_10002f54();
  do {
    FUN_100030e4(
      DAT_10000244,0x2b);
  } while(true);
}
```

After Resolving:

```
int main(void) {
  stdio_init_all();
  do {
    printf(
      "age: %d\r\n"
      , 0x2b);
  } while(true);
}
```

Compiler Optimization

Why Your Variable Disappeared

Source Code

```
int main(void) {
  uint8_t age = 42;
  age = 43;
  stdio_init_all();
  while (true)
    printf("age: %d", age);
```

Compiler Thinks...

age = 42 is NEVER read

Dead store -> REMOVED

age = 43 -> constant fold

Replaces variable with literal

Resulting Assembly

```
1000023a       2b 21       movs r1, #0x2b          ; 0x2b = 43
```

No age=42 instruction — compiler removed it

Key Takeaway

Source Code

age = 42
age = 43

->

Binary

movs r1, #0x2b

Compiler

Optimizes dead stores away!

Binary Patching

Changing Values in the Binary

Before Patch

```
1000023a   2b 21   movs r1,#0x2b
```

0x2b = 43 decimal

Output: **age: 43**

Compiler-optimized constant

After Patch

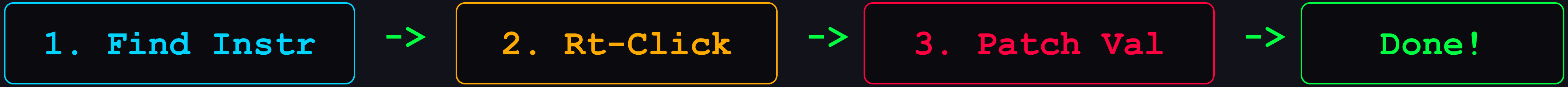
```
1000023a   46 21   movs r1,#0x46
```

0x46 = 70 decimal

Output: **age: 70**

Changed program behavior!

How to Patch in Ghidra



1. Find Instr -> **2. Rt-Click** -> **3. Patch Val** -> **Done!**

Patch Instruction: change operand

Export Patched Binary

File: Export

Format: Raw Bytes

Save as *-h.bin

Exported binary has your patches

GPIO Hacking

Patching GPIO 16 to GPIO 17

Original: GPIO 16

Red LED on pin 16

```
1000023a   10 20   movs r0,#0x10
10000244   10 23   movs r3,#0x10
10000252   10 24   movs r4,#0x10
```

0x10 = 16, three locations

Patched: GPIO 17

Green LED on pin 17

```
1000023a   11 20   movs r0,#0x11
10000244   11 23   movs r3,#0x11
10000252   11 24   movs r4,#0x11
```

0x11 = 17, all patched!

What Each Patch Controls

gpio_init r0

gpio_set_dir r3

gpio_put r4

ALL pin refs must be patched

Bonus: Change Print Value

```
00 21  movs r1,#0x0      age: 0
```

->

```
42 21   movs r1,#0x42     age: 66
```

Changed value: 0 to 66 (0x42)

GPIO Coprocessor

RP2350 Single-Cycle I/O via mcrr

mcrr Instruction Breakdown

```
mcrr p0, #4, r4, r5, c0
```

mcrr	Move to Coprocessor (2 regs)	r4	GPIO pin number
p0	Coprocessor 0 (GPIO)	r5	Value (0=LOW, 1=HIGH)

Output Value (c0)

```
mcrr p0,#4,r4,r5,c0
```

r4 = pin number
r5 = 0 or 1

Controls GPIO output state

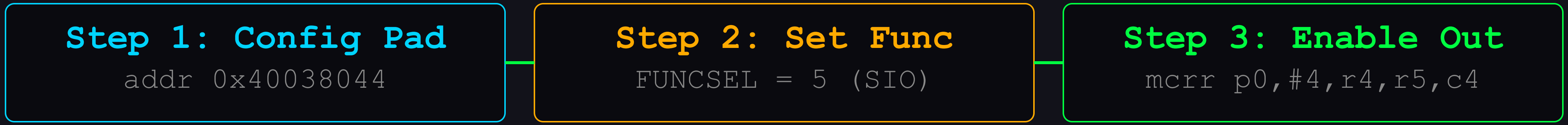
Output Enable (c4)

```
mcrr p0,#4,r4,r5,c4
```

r4 = pin number
r5 = 1 (enable output)

Sets pin direction to OUTPUT

gpio_init(16) Sequence



Step 1: Config Pad
addr 0x40038044

Step 2: Set Func
FUNCSEL = 5 (SIO)

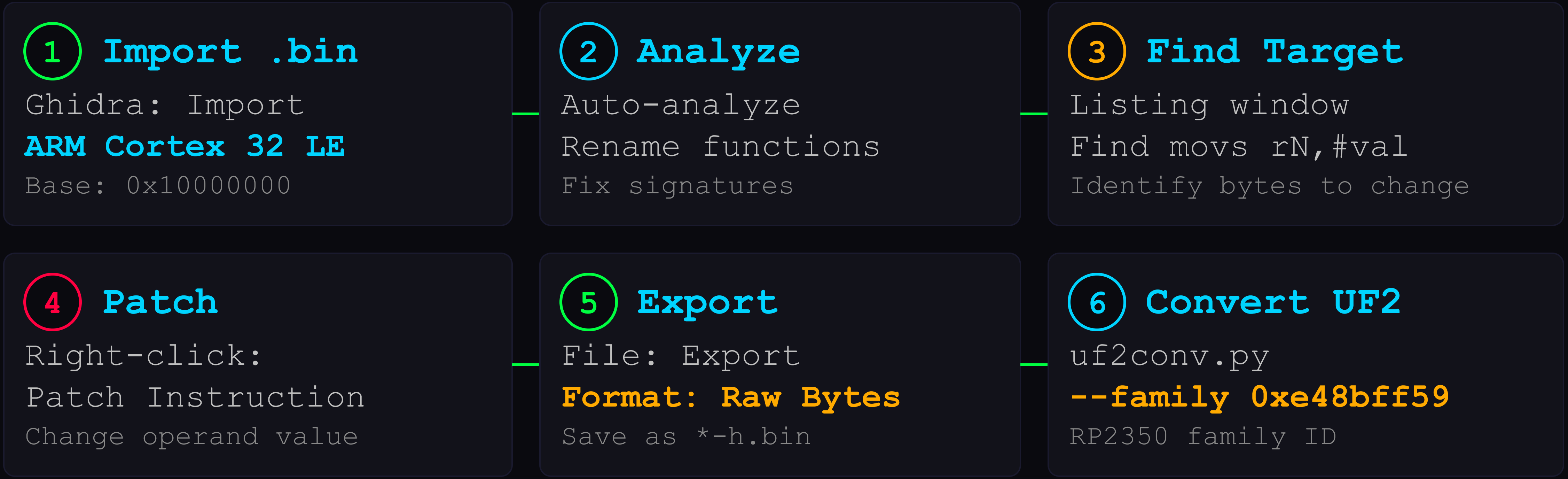
Step 3: Enable Out
mcrr p0,#4,r4,r5,c4

Pad: clear OD, set IE, clear ISO

SIO = fast single-cycle GPIO access

Full Patching Pipeline

End-to-End Binary Hacking Workflow



1 Import .bin

Ghidra: Import

ARM Cortex 32 LE

Base: 0x10000000

2 Analyze

Auto-analyze

Rename functions

Fix signatures

3 Find Target

Listing window

Find movs rN,#val

Identify bytes to change

4 Patch

Right-click:

Patch Instruction

Change operand value

5 Export

File: Export

Format: Raw Bytes

Save as *-h.bin

6 Convert UF2

uf2conv.py

--family 0xe48bff59

RP2350 family ID

UF2 Command

```
python uf2conv.py file.bin --base 0x10000000 -o hacked.uf2
```

Flash to Pico 2

1. Hold BOOTSEL + USB
2. Drop hacked.uf2
3. Pico reboots hacked

RPI-RP2 drive in BOOTSEL

Key Sections

.text	Flash	Code
.rodata	Flash	Constants
.data	RAM	Init globals
.bss	RAM	Zeroed globals