Lecture 03
Embedded Software

CE346 – Microprocessor System Design

Branden Ghena – Fall 2023

Some slides borrowed from:
Josiah Hester (Northwestern), Prabal Dutta (UC Berkeley)

Administrivia

- Office hours start today!
  - Four 1.5-hour slots per week to get help or lab checkoffs
  - Tried for a variety of times to meet everyone’s needs
- Make sure you have your personal lab setup working
  - Ask in office hours or on Piazza if you run into issues
- Labs will start this Friday!!!
  - You MUST come to your scheduled lab session
  - Not really enough room for students to swap sections
    - If there’s some known obligation and you give me a heads up, I could approve a few per week

Changes to schedule

- Unfortunately, I'm out-of-town on Wednesday and Thursday
  - In-class portion on Thursday is canceled
- Lecture for Thursday will be recorded and uploaded to Canvas
  - Necessary information for lab on Friday
  - Make sure you look through it
  - Ask questions on Piazza!
  - Lecture will be posted either late tonight or early tomorrow
- I will be back on Friday for labs!

Today's Goals

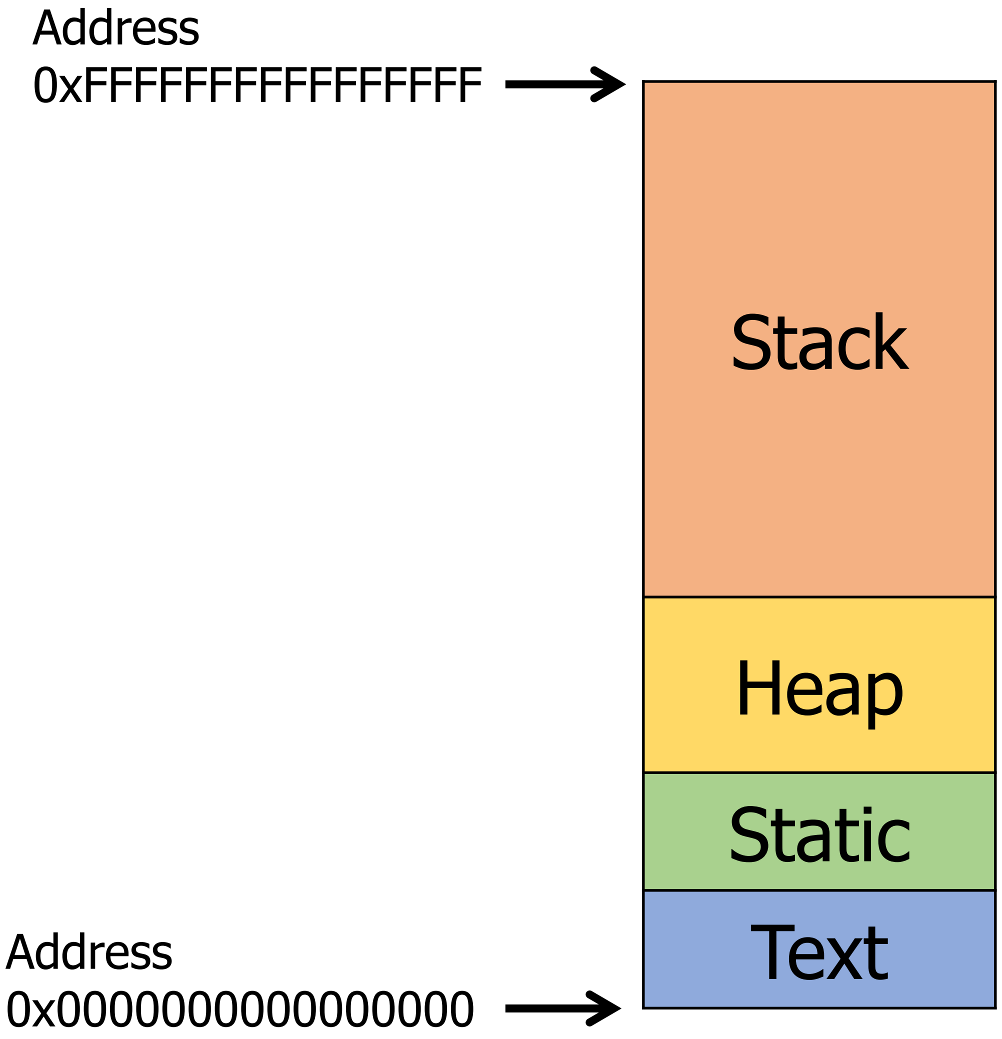
- Discuss challenges of embedded software
- Describe compilation and linking of embedded code
  - Actually applies to all code, but you probably never learned much about linking before
- Introduce new software pattern: interrupts
- Explore the microcontroller boot process

Outline

- **Embedded Software**
- Embedded Toolchain
- Lab Software Environment
- Interrupts
- Boot Process

Review: C memory layout

- Stack Section
  - Local variables
  - Function arguments
- Heap Section
  - Memory granted through `malloc()`
- Static Section (a.k.a. Data Section)
  - Global variables
  - Static function variables
- Text Section (a.k.a Code Section)
  - Program code



Assumptions of embedded programs

- Expect limitations
  - Very little memory
  - Very little computational power
  - Very little energy

- Don’t expect a lot of support
  - Likely no operating system
  - Might not even have error reporting capabilities

- Moral: think differently about your programs

Ramifications of limited memory

- Stack and Data sections are limited
  - Be careful about too much recursion
  - Be careful about large local variables

  - Large data structures defined globally are preferred
    - Fail at compile time
    - In embedded, we often *encourage* global variables for large things

- Heap section is likely non-existent
  - **Why?**

Ramifications of limited memory

- Stack and Data sections are limited
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- Heap section is likely non-existent
  - **Why?**
    - Malloc could run out of memory at runtime

Avoiding dynamic memory

- Malloc is ***scary*** in an embedded context
- What if there’s no more memory available?
  - Traditional computer
    - Swap memory to disk
    - Worst case: wait for a process to end (or kill one)
  - Embedded computer
    - There’s likely only a single application
    - And it’s the one asking for more memory
    - So it’s not giving anything back anytime soon
- This is unlikely to happen at boot
  - Instead it’ll happen hours or days into running as memory is slowly exhausted…

Limitations on processing power

- Typically not all that important
  - Code still runs pretty fast
    - 10 MHz -> 100 ns per cycle (i.e. ~100 ns per instruction)
  - Controlling hardware usually doesn’t have a lot of code complexity
    - Quickly gets to the “waiting on hardware” part (apps are I/O bound)

- Problems
  - Machine learning
    - Learning on the device is neigh impossible
    - Memory limitations make it hard to fit weights anyways
  - Cryptography
    - Public key encryption takes seconds to minutes

Common programming languages for embedded

- C
  - For all the reasons that you assume
  - Easy to map variables to memory usage and code to instructions
- Assembly
  - Not entirely uncommon, but rarer than you might guess
  - C code optimized by a modern compiler is likely faster
  - Notable uses:
    - Cryptography to create deterministic algorithms
    - Operating Systems to handle process swaps
- C++
  - Similar to C but with better library support
  - Libraries take up a lot of code space though ~100 KB

Rarer programming languages for embedded

- Rust
  - Modern language with safety and reliability guarantees
  - Becoming relevant in the embedded space
    - But with a high learning curve

- Python, Javascript, etc.
  - Mostly toy languages
  - Fine for simple things but incapable of complex operations
    - Especially low-level things like managing memory

What's missing from programming languages?

- The embedded domain has several requirements that other domains do not
- What is missing from programming languages that it wants?
  - Sense of time
  - Sense of energy

Programming languages have no sense of time

- Imagine a system that needs to send messages to a motor every 10 milliseconds
  - Write a function that definitely completes within 10 milliseconds

- Accounting for timing when programming is very challenging
  - We can profile code and determine timing at runtime

  - If we know many details of hardware, instructions can give timing
    - Unless the code interacts with external devices

Determining energy use is rather complicated

- Software might
  - Start executing a loop
  - Turn on/off an LED
  - Send messages over a wired bus to another device

- Determining energy these operations take is really difficult
  - Even with many details of the hardware
  - Different choices of processor clocks can have a large impact

  - Often profiled at runtime after writing the code
    - Iterative write-test-modify cycle

Break + Say hi to your neighbors

- Things to share
  - Name

  - Major

  - One of the following
    - Favorite Candy
    - Favorite Pokemon
    - Favorite Emoji

Break + Say hi to your neighbors

- Things to share
  - Name -Branden
  - Major -Electrical and Computer Engineering, and Computer Science
  - One of the following
    - Favorite Candy - Twix
    - Favorite Pokemon - Eevee
    - Favorite Emoji - 🍢

Outline

- Embedded Software
- **Embedded Toolchain**
- Lab Software Environment
- Interrupts
- Boot Process

Embedded compilation steps

- Same first steps as any system

1. Compiler
    - Turn C code into assembly
    - Optimize code (often for code size instead of speed)

Cross compilers compile for different architectures

- The compiler we'll be using is a cross compiler
  - Run on one architecture but compile code for another
    - Example: runs on x86-64 but compiles armv7e-m

- GCC naming scheme: ARCH-VENDOR-(OS-)-ABI-gcc
  - arm-none-eabi-gcc
    - ARM architecture
    - No vendor
    - No OS
    - Embedded Application Binary Interface
  - Others: arm-none-linux-gnueabi-gcc, i686-pc-windows-msvc-gcc

Embedded compilation steps

- Same first steps as any system

1. Compiler
   - Turn C code into assembly
   - Optimize code (often for size instead of speed)

2. Linker
   - Combine multiple C files together
   - Resolve dependencies
     - Point function calls at correct place
     - Connect creation and uses of global variables

Informing linker of system memory

- Linker actually places code and variables in memory
  - It needs to know where to place things

- **How do x86-64 compilers know which addresses to use?**

Informing linker of system memory

- Linker actually places code and variables in memory
  - It needs to know where to place things
- **How do x86-64 compilers know which addresses to use?**
  - Virtual memory allows all applications to use the same memory addresses
- Embedded solution
  - Only run a single application
  - Provide an LD file
    - Specifies memory layout for a certain system
    - Places sections of code in different places in memory

Anatomy of an LD file

- nRF52833: 512 KB Flash, 128 KB SRAM
- First, LD file defines memory regions

```
MEMORY {
  FLASH (rx) : ORIGIN = 0x00000000, LENGTH = 0x80000
  RAM (rwx) :  ORIGIN = 0x20000000, LENGTH = 0x20000
}
```

- A neat thing about microcontrollers: pointers have meaning
  - Just printing the value of a pointer can tell you if it’s in Flash or RAM

Anatomy of an LD file

- It then places sections of code into those memory regions

```
.text : {
    KEEP(*(.Vectors))
    *(.text*)
    *(.rodata*)
    . = ALIGN(4);
} > FLASH
__etext = .;
```

```
.data : AT (__etext) {
        __data_start__ = .;
        *(.data*)
        __data_end__ = .;
} > RAM

.bss :    {
        . = ALIGN(4);
        __bss_start__ = .;
        *(.bss*)
        . = ALIGN(4);
        __bss_end__ = .;
} > RAM
```

Sections of code

- Where do these sections come from?
- Most are generated by the compiler
  - .text, .rodata, .data, .bss
  - You need to be deep in the docs to figure out how the esoteric ones work

- Some are generated by the programmer
  - Allows you to place certain data items in a specific way

```
__attribute__((section(".foo")))
int test[10] = {0,0,0,0,0,0,0,0,0,0};
```

Embedded compilation steps

- Same first steps as any system

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- Output: a binary (or hex) file

Loading the hex file onto a board

- This is a use case for JTAG
  - You provide it a hex file which specifies addresses and values
  - It writes those into Flash on the microcontroller

- The LD file already specified addresses
  - So passing around hex files is enough to load an application

  - But a hex file for one microcontroller won’t work on another with a different memory layout

Example

- Demonstrated in the blink application in lab repo
  - https://github.com/nu-ce346/nu-microbit-base/tree/main/software/apps/blink

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Embedded environments

- There are a multitude of embedded software systems
  - Every microcontroller vendor has their own
  - Popular platforms like Arduino

- We’re using the Nordic software development libraries plus some extensions made by my research group
  - It’ll be a week until that matters for the most part
  - We’ll start off by writing low-level drivers ourselves without libraries

Software Development Kit (SDK)

- Libraries provided by Nordic for using their microcontrollers
  - Actually incredibly well documented! (relatively)
  - Various peripherals and library tools

- SDK documentation
  - https://infocenter.nordicsemi.com/topic/sdk_nrf5_v16.0.0/index.html
  - Warning: search doesn't really work

- Possibly more useful: the list of data structures
  - Search that page for whatever "thing" you're working with
  - https://infocenter.nordicsemi.com/topic/sdk_nrf5_v16.0.0/annotated.html

nRF52x-base

- Wrapper built around the SDK by Lab11
  - Branden Ghena, Brad Campbell (UVA), Neal Jackson, a few others
  - Allows everything to be used with Makefiles and command line
  - https://github.com/lab11/nrf52x-base

- We include it as a submodule
  - It has a copy of the SDK code and softdevice binaries
  - It has a whole Makefile system to include to proper C and H files
  - We include a Board file that specifies our specific board's needs and capabilities

- Go to repo to explain

Break

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- Embedded Software
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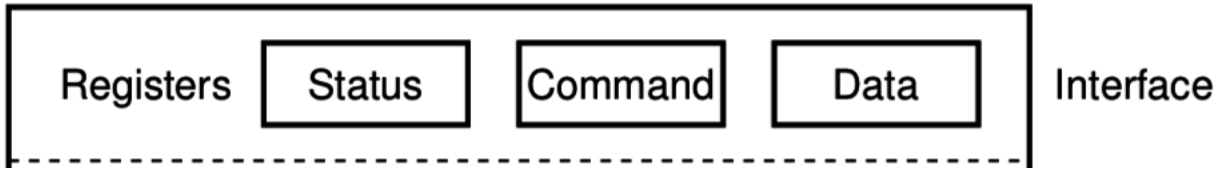
- **Interrupts**
- Boot Process

What do interactions with devices look like?



1. while STATUS==BUSY; Wait
   - (Need to make sure device is ready for a command)
2. Write value(s) to DATA
3. Write command(s) to COMMAND
4. while STATUS==BUSY; Wait
   - (Need to make sure device has completed the request)
5. Read value(s) from Data

This is the "polling" model of I/O.

"Poll" the peripheral in software repeatedly to see if it's ready yet.

Waiting can be a waste of CPU time

1. **while STATUS==BUSY; Wait**
   - **(Need to make sure device is ready for a command)**
2. Write value(s) to DATA
3. Write command(s) to COMMAND
4. **while STATUS==BUSY; Wait**
   - **(Need to make sure device has completed the request)**
5. Read value(s) from Data

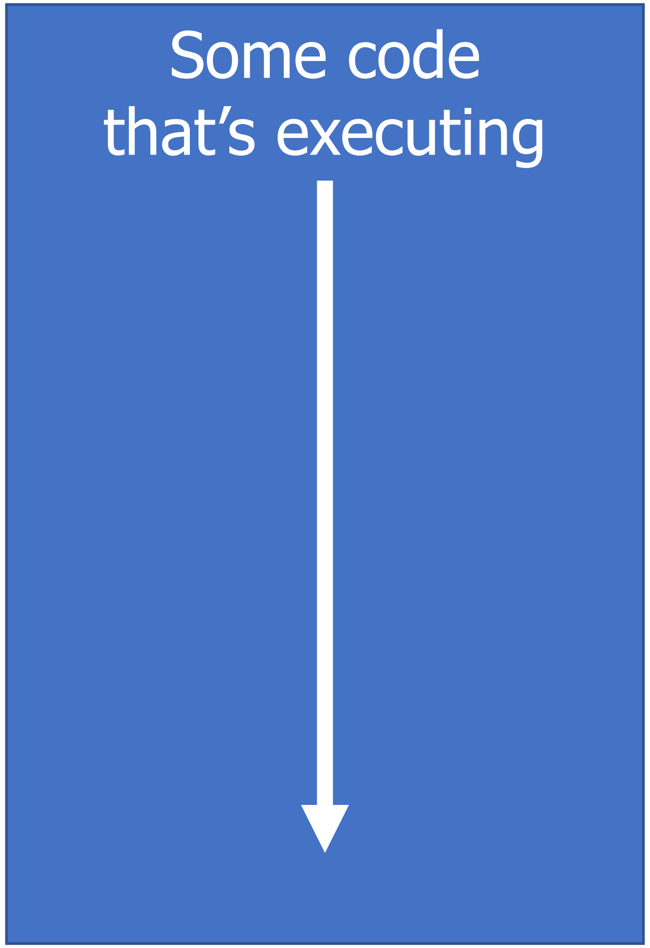
- Problem: imagine a keyboard device
  - CPU could be waiting for minutes before data arrives
  - Need a way to notify CPU when an event occurs
    - Interrupts!

Interrupts

- What is an interrupt?
  - Some event which causes the processor to stop normal execution
  - The processor instead jumps to a software "handler" for that event
    - Then returns back to what it was doing afterwards

- What causes interrupts?
  - Hardware exceptions
    - Divide by zero, Undefined Instruction, Memory bus error
  - Software
    - Syscall, Software Interrupt (SWI)
  - External hardware
    - Input pin, Timer, various "Data Ready"

Interrupts, visually



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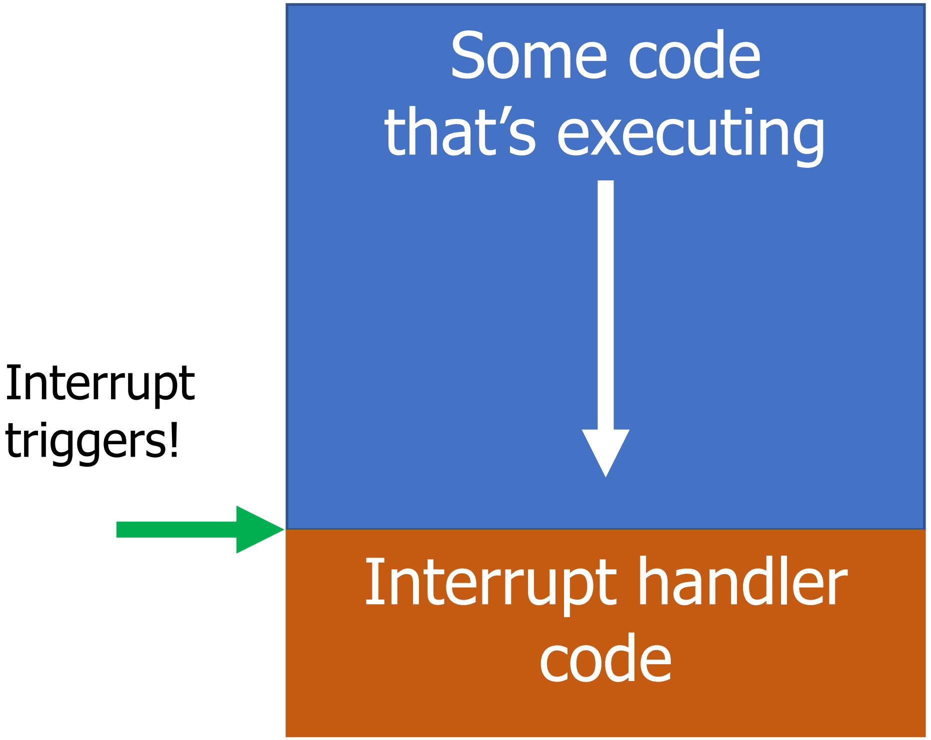

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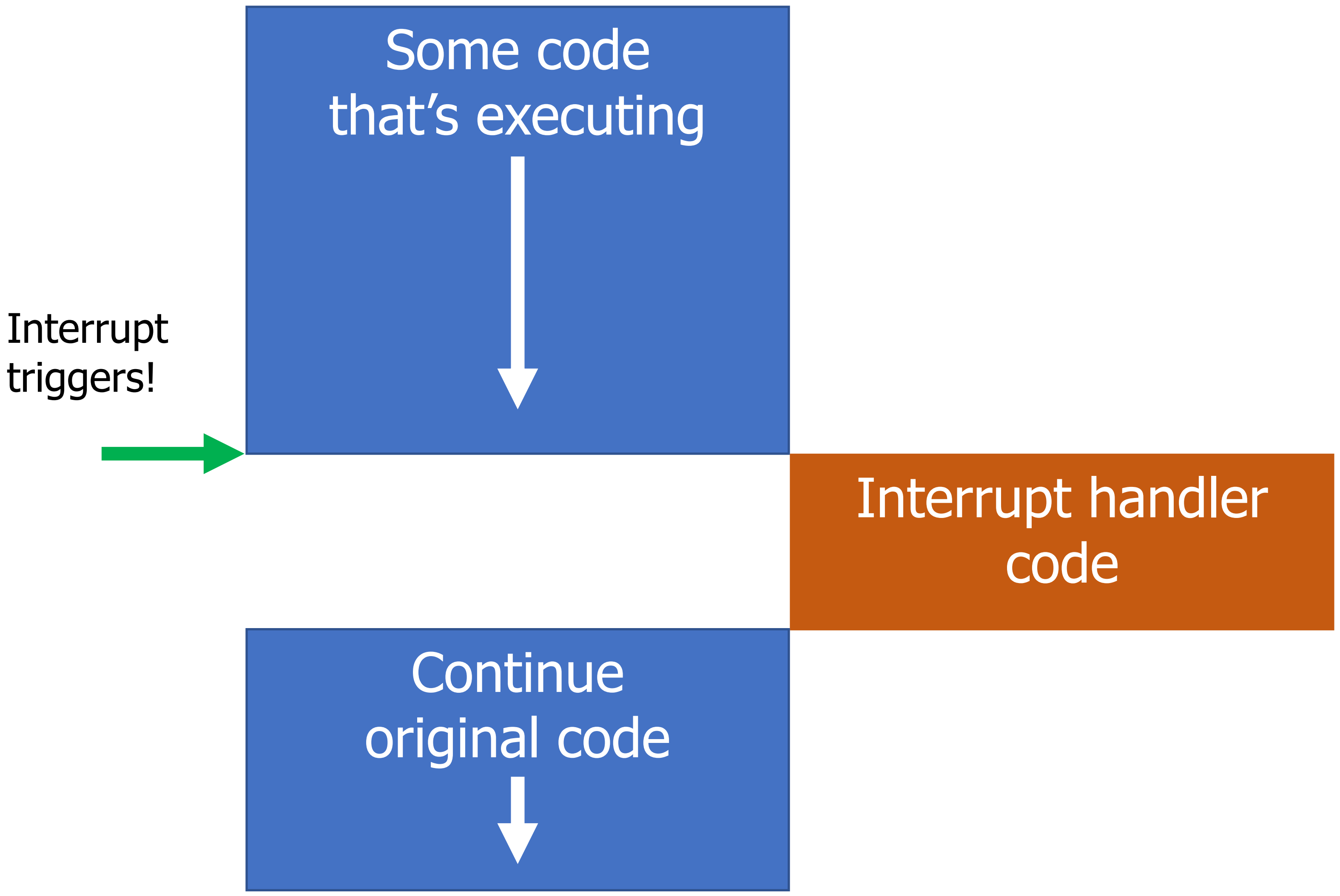


ARM Nested Vectored Interrupt Controller (NVIC)

Interrupts can preempt other interrupts!

Jump directly to the interrupt handler

Handles interrupt entry and exit
- Stacking
- Unstacking
- Priorities

- Manages interrupt requests (IRQ)
  - Stores all caller-saved registers on the stack
    - So the handler code doesn't overwrite them
  - Moves execution to proper handler, a.k.a. Interrupt Service Routine (ISR)
  - Restores registers after handler returns and moves execution back

ARM Vector table

- List of function pointers to handler for each interrupt/exception

- First 15 are architecture-specific exceptions

- After that are microcontroller interrupt signals

Table 7.1 List of System Exceptions

Exception Number	Exception Type	Priority	Description
1	Reset	–3 (Highest)	Reset
2	NMI	–2	Nonmaskable interrupt (external NMI input)
3	Hard fault	–1	All fault conditions if the corresponding fault handler is not enabled
4	MemManage fault	Programmable	Memory management fault; Memory Protection Unit (MPU) violation or access to illegal locations
5	Bus fault	Programmable	Bus error; occurs when Advanced High-Performance Bus (AHB) interface receives an error response from a bus slave (also called *prefetch abort* if it is an instruction fetch or *data abort* if it is a data access)
6	Usage fault	Programmable	Exceptions resulting from program error or trying to access coprocessor (the Cortex-M3 does not support a coprocessor)
7–10	Reserved	NA	—
11	SVC	Programmable	Supervisor Call
12	Debug monitor	Programmable	Debug monitor (breakpoints, watchpoints, or external debug requests)
13	Reserved	NA	—
14	PendSV	Programmable	Pendable Service Call
15	SYSTICK	Programmable	System Tick Timer

Table 7.2 List of External Interrupts

Exception Number	Exception Type	Priority
16	External Interrupt #0	Programmable
17	External Interrupt #1	Programmable
...	...	...
255	External Interrupt #239	Programmable

Vector table in software

- Placed in its own section
  - LD file puts it first in Flash
- Reset_Handler determines where software starts executing
- After that are all exception and interrupt handlers
  - All function pointers to some C code somewhere

```
    .section .isr_vector
    .align 2
    .globl __isr_vector
__isr_vector:
    .long   __StackTop                  /* Top of Stack */
    .long   Reset_Handler
    .long   NMI_Handler
    .long   HardFault_Handler
    .long   MemoryManagement_Handler
    .long   BusFault_Handler
    .long   UsageFault_Handler
    .long   0                           /*Reserved */
    .long   0                           /*Reserved */
    .long   0                           /*Reserved */
    .long   0                           /*Reserved */
    .long   SVC_Handler
    .long   DebugMon_Handler
    .long   0                           /*Reserved */
    .long   PendSV_Handler
    .long   SysTick_Handler

  /* External Interrupts */
    .long   POWER_CLOCK_IRQHandler
    .long   RADIO_IRQHandler
    .long   UARTE0_UART0_IRQHandler
    .long   SPIM0_SPIS0_TWIM0_TWIS0_SPI0_TWI0_IRQHandler
    .long   SPIM1_SPIS1_TWIM1_TWIS1_SPI1_TWI1_IRQHandler
    .long   NFCT_IRQHandler
    .long   GPIOTE_IRQHandler
    .long   SAADC_IRQHandler
```

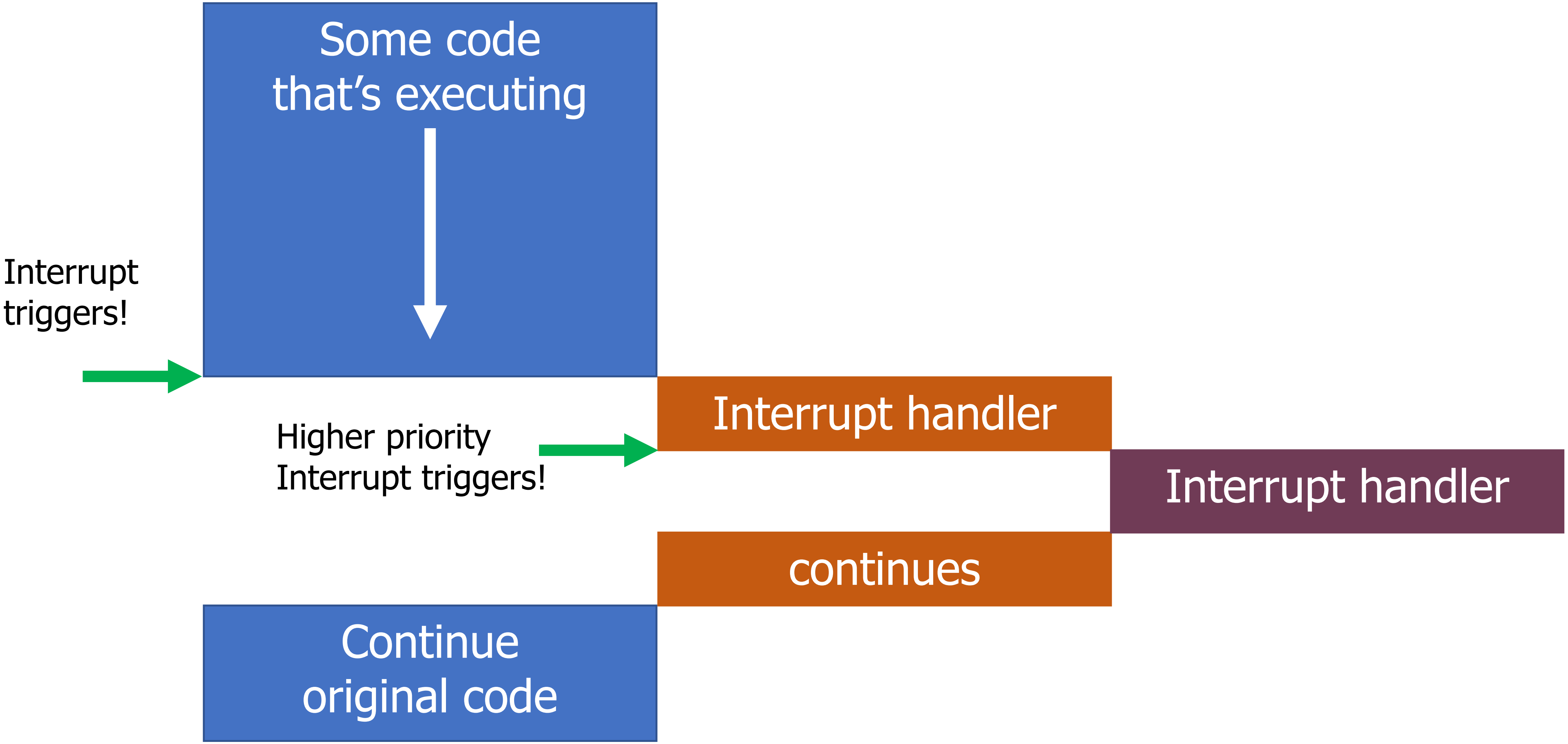
NVIC functionality

- NVIC functions
  - `NVIC_EnableIRQ(number)`
  - `NVIC_DisableIRQ(number)`
  - `NVIC_SetPriority(number, priority)`
    - Technically 256 priorities
    - Only 8 are implemented

- Must enable interrupts in two places!
  - Enabling interrupt in the peripheral will generate the signal
  - Enabling interrupt in the NVIC will cause signal to jump to handler

- Priority determines which interrupt goes first
  - And determines how interrupts are nested

Nested interrupts, visually



Break + Open Question

- When should a system use polling versus interrupts?

Break + Open Question

- When should a system use polling versus interrupts?

- Polling
  - Great if the device is going to respond immediately (like 1 cycle)
  - Important if we need to respond very quick (less than a microsecond)

- Interrupts
  - Great if we'll need to wait a long time for status to change
  - Still responds pretty quickly, but not *immediately*
    - Needs to context switch from running code to interrupt handler

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How does a microcontroller *start* running code?

- Power comes on
- Microcontroller needs to start executing assembly code

- You expect your main() function to run
  - But a few things need to happen first

Step 0: set a stack pointer

- Assembly code might need to write data to the stack
  - Might call functions that need to stack registers
- ARM: Valid address for the stack pointer is at address 0 in Flash
  - Needs to point to somewhere in RAM
  - Hardware loads it into the Stack Pointer when it powers on

Step 1: set the program counter (PC)

- a.k.a. the Instruction Pointer (IP) in x86 land

- 32-bit ARM: valid instruction pointer is at address 4 in Flash
  - Could point to RAM, usually to Flash though
  - In interrupt terms: this is the “Reset Handler”!

  - Automatically loaded into the PC after the SP is loaded
    - Again, hardware does this

Step 2: “reset handler” prepares memory

- Code that handles system resets
  - Either reset button or power-on reset
  - Address was loaded into PC in Step 1

- Reset handler code:
  - Loads initial values of .data section from Flash into RAM
  - Loads zeros as values of .bss section in RAM
  - Calls SystemInit
    - Starts correct clocks for the system
    - Handles various hardware configurations/errata
  - Calls _start

nu-microbit-base/software/nrf52x-base/sdk/nrf5_sdk_16.0.0/modules/nrfx/mdk/gcc_startup_nrf52833.S

nu-microbit-base/software/nrf52x-base/sdk/nrf5_sdk_16.0.0/modules/nrfx/mdk/system_nrf52.c

Step 3: set up C runtime

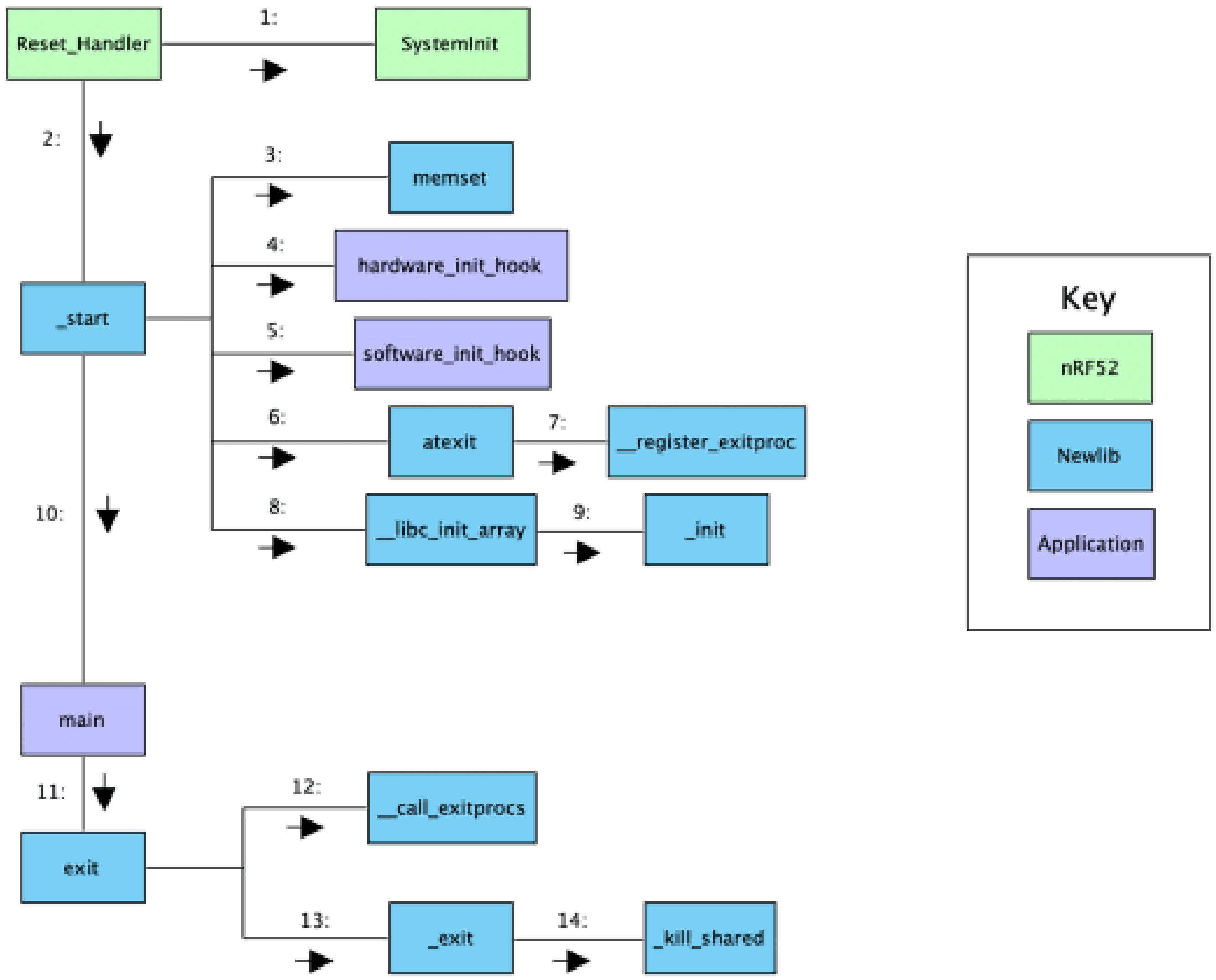
- _start is provided by newlib
  - An implementation of libc – the C standard library
  - Startup is a file usually named crt0

- Does more setup, almost none of which is relevant for our system
  - Probably is this code that actually zeros out .bss
  - Sets argc and argv to 0
  - Calls main() !!!

https://sourceware.org/git/gitweb.cgi?p=newlib-cygwin.git;a=blob_plain;f=libgloss/arm/crt0.S;hb=HEAD

Online writeup with way more details and a diagram

- Relevant guide!!
  - https://embeddedartistry.com/blog/2019/04/17/exploring-startup-implementations-newlib-arm/
  - Covers the nRF52!



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