SCC.131: Digital Systems
Memory layout (focus on nRF52833 for micro:bit)

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Summary of the last lecture

The last lecture focused on the memory layout of the x86-64 architecture and covered the following points:

- The memory management unit, the translation lookaside buffer and the relationship between physical and virtual addresses.
- The main memory regions: Text, Data, BSS, Heap, Stack and OS Kernel.
- The stack layout: the base pointer, the instruction pointer, the stack pointer and the memory regions for function parameters and locally declared variables.
- GDB commands that can help you examine and visualise the stack of a running C program.

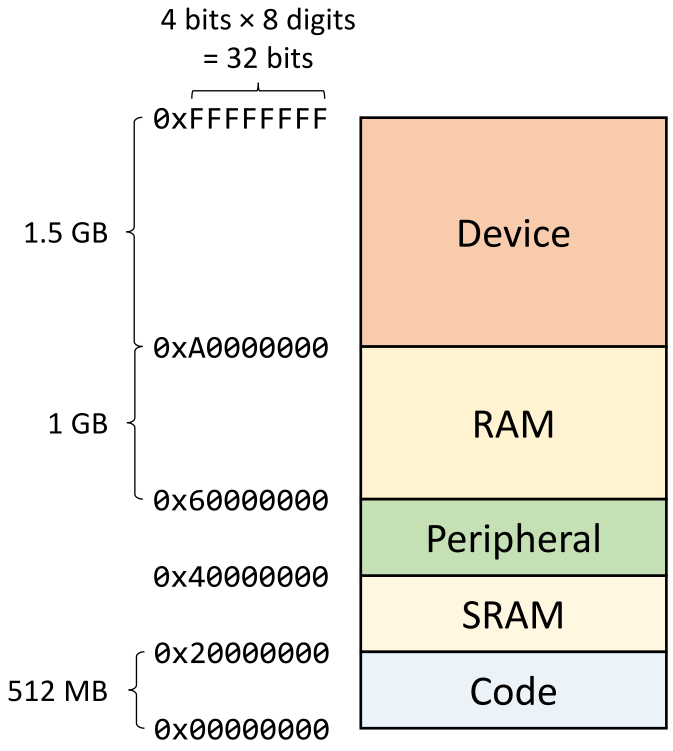
The nRF52833 System on Chip (SoC)

- Developed by Nordic Semiconductor (HQ in Trondheim, Norway).
- Built around a 64-MHz **32-bit** ARM Cortex-M4 processor with a Floating-Point Unit (FPU), referred to as Cortex-M4F.
- Equipped with **512 KB Flash** memory and **128 KB RAM** memory.
  - **Flash memory**: Non-volatile memory, i.e., it can retain information when power is off. Not as fast as RAM but faster than hard disks.
  - **Random access memory** (RAM): Volatile memory that can be static (SRAM – used for the cache of the CPU to store common instructions) or dynamic (DRAM – used as the main memory).
- Operates at temperatures between -40°C to 105°C.

Also supports:

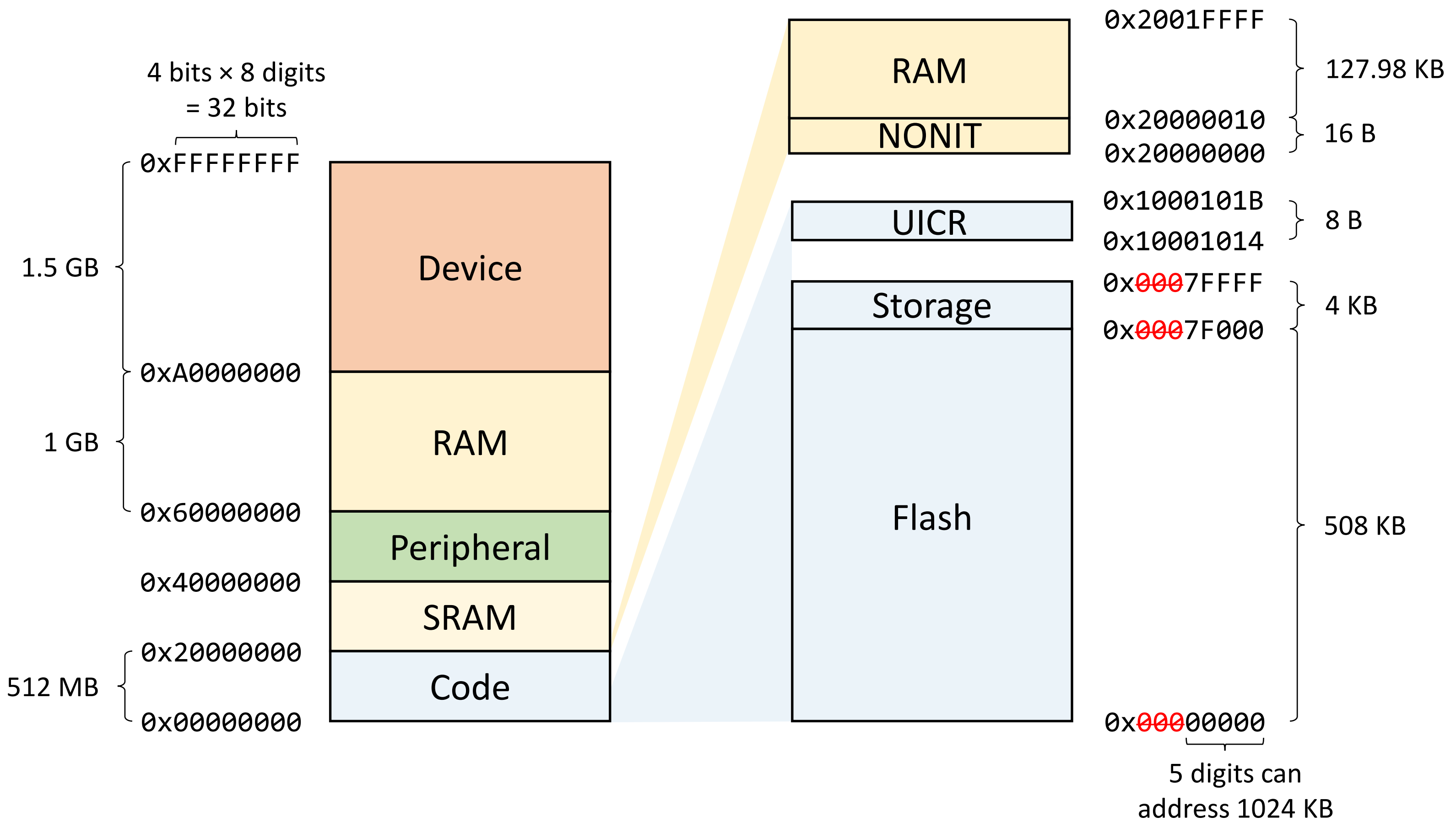
- Bluetooth
- ZigBee
- Proprietary 2.4 GHz

Memory map



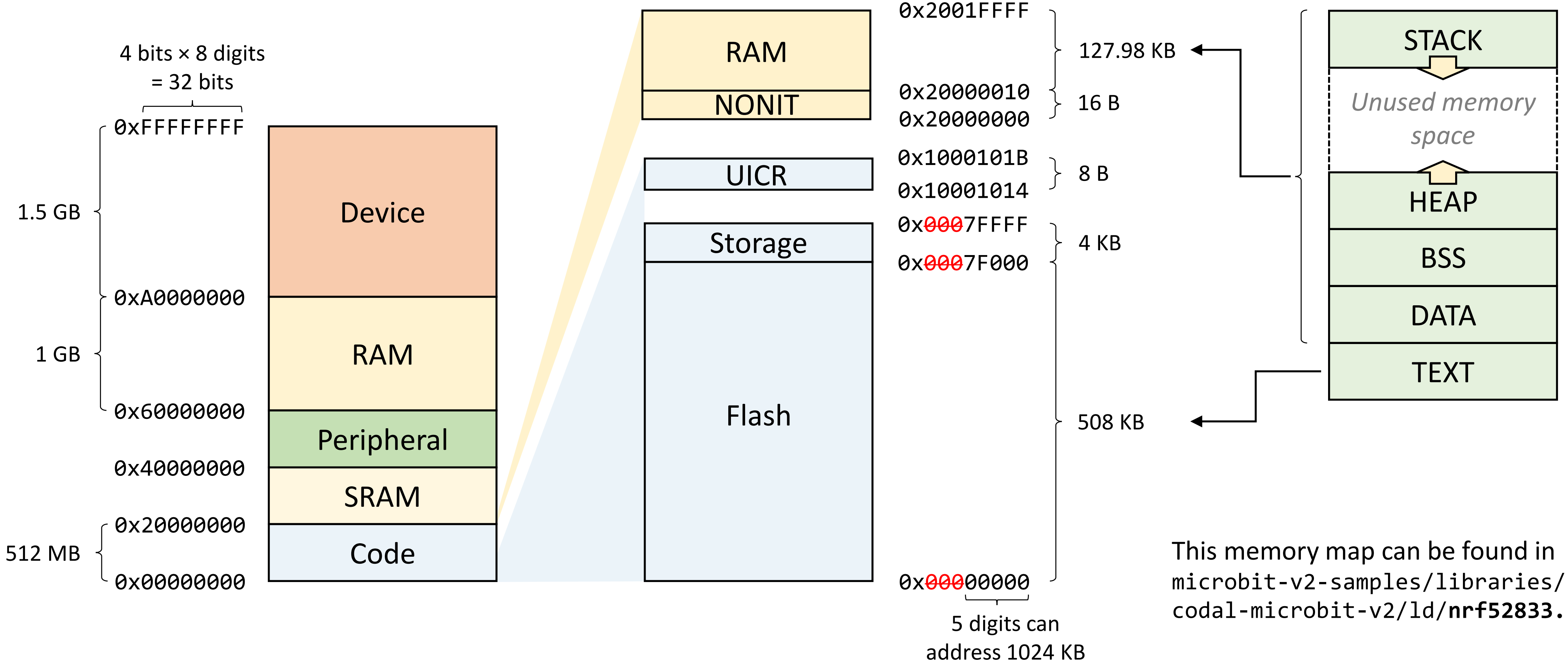
- Memory shared between the microcontroller and on-board **peripherals** (e.g., sensors) or external **devices** (e.g., phones).
- Peripherals and devices are often referred to as **General Purpose IO** (GPIOs).
- The process that allows the microcontroller to interact with other GPIOs by reading from and writing to predefined memory addresses is known as **memory mapped IO**.

Memory map when Bluetooth is disabled (1/2)



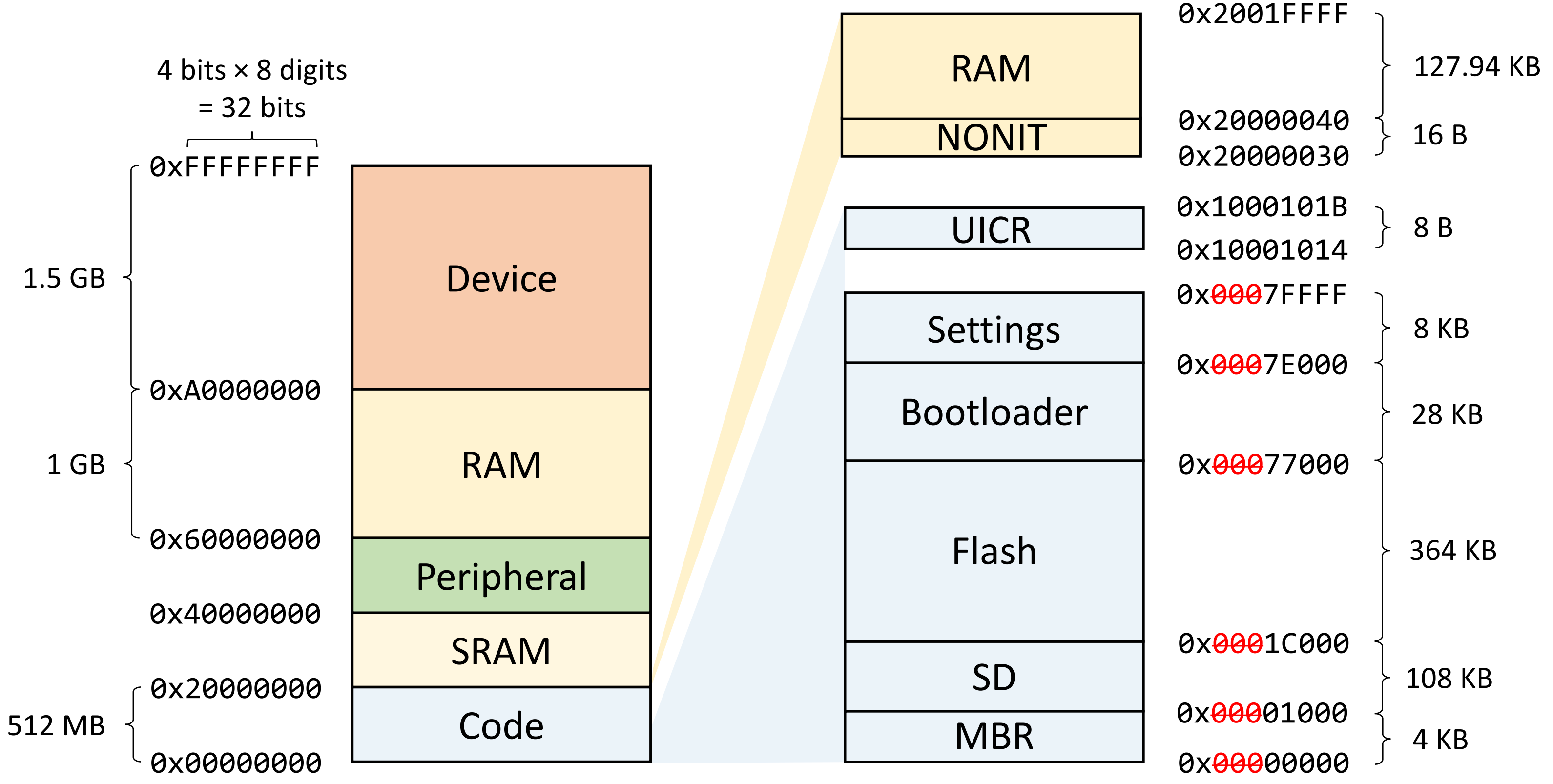
- **NOINIT**: Memory area that persists across micro:bit resets (e.g., to keep count of the number of times the reset button has been pressed so that the Bluetooth pairing mode can be activated).
- **UICR**: User Information Configuration Register (reserved).
- **Storage**: Long term non-volatile data (e.g., calibration data for the sensors).

Memory map when Bluetooth is disabled (2/2)



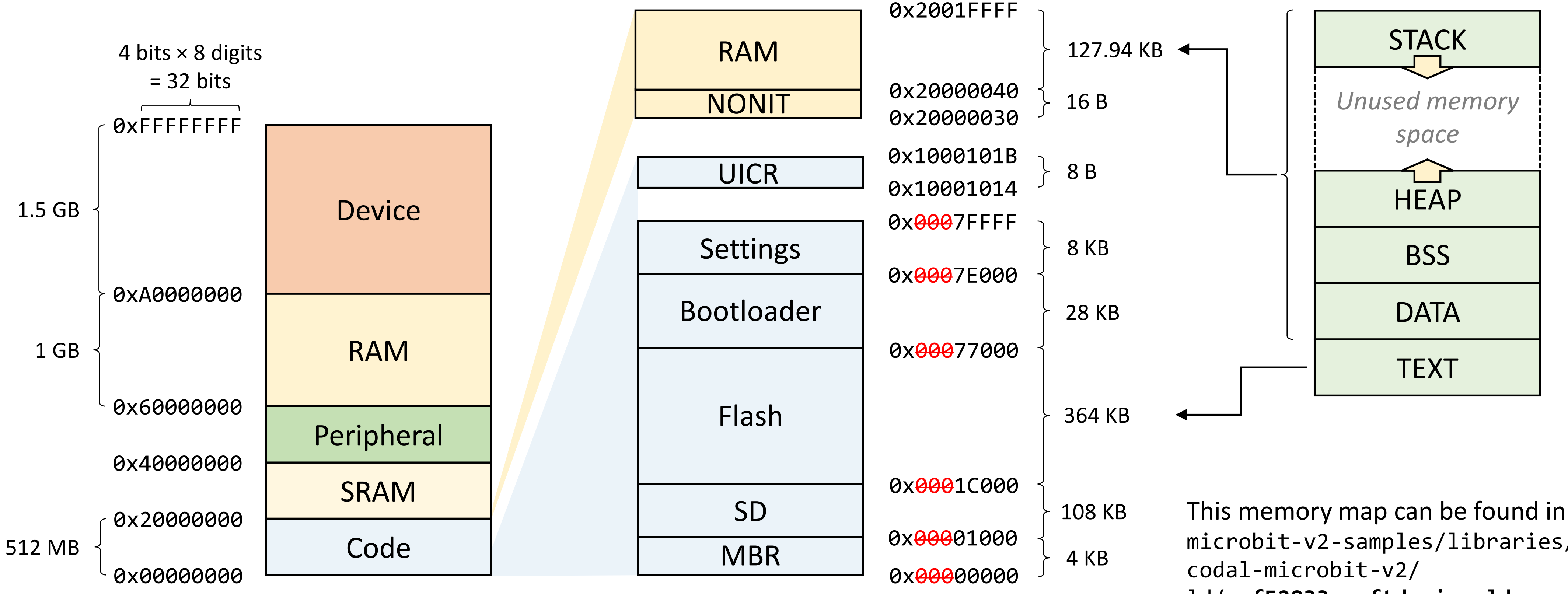
This memory map can be found in
`microbit-v2-samples/libraries/codal-microbit-v2/ld/`**`nrf52833.ld`**

Memory map when Bluetooth is enabled (1/2)



- **MBR**: Master Boot Record.
- **SD**: Soft Device. Memory area that holds information about the Bluetooth low energy (BLE) protocol.
- **Bootloader**: Memory area for over-the-air firmware updates.
- **Settings**: Holds similar information to 'Storage' as well as Bluetooth pairing keys and state.

Memory map when Bluetooth is enabled (2/2)



This memory map can be found in `microbit-v2-samples/libraries/codal-microbit-v2/ld/`**`nrf52833-softdevice.ld`**

Step-by-step demonstration

The demonstration presented in the following slides assumes that students have access to one of the **lab machines**, where the necessary software for micro:bit has been installed.

The steps presented in this demonstration **cannot be completed using MyLab** remotely, because the micro:bit board needs to be connected to a lab machine to debug the HEX file that has been transferred to it.

All addresses shown by the debugger of a process running on micro:bit are physical (remember: no OS Kernel, OS, or other running processes exist).

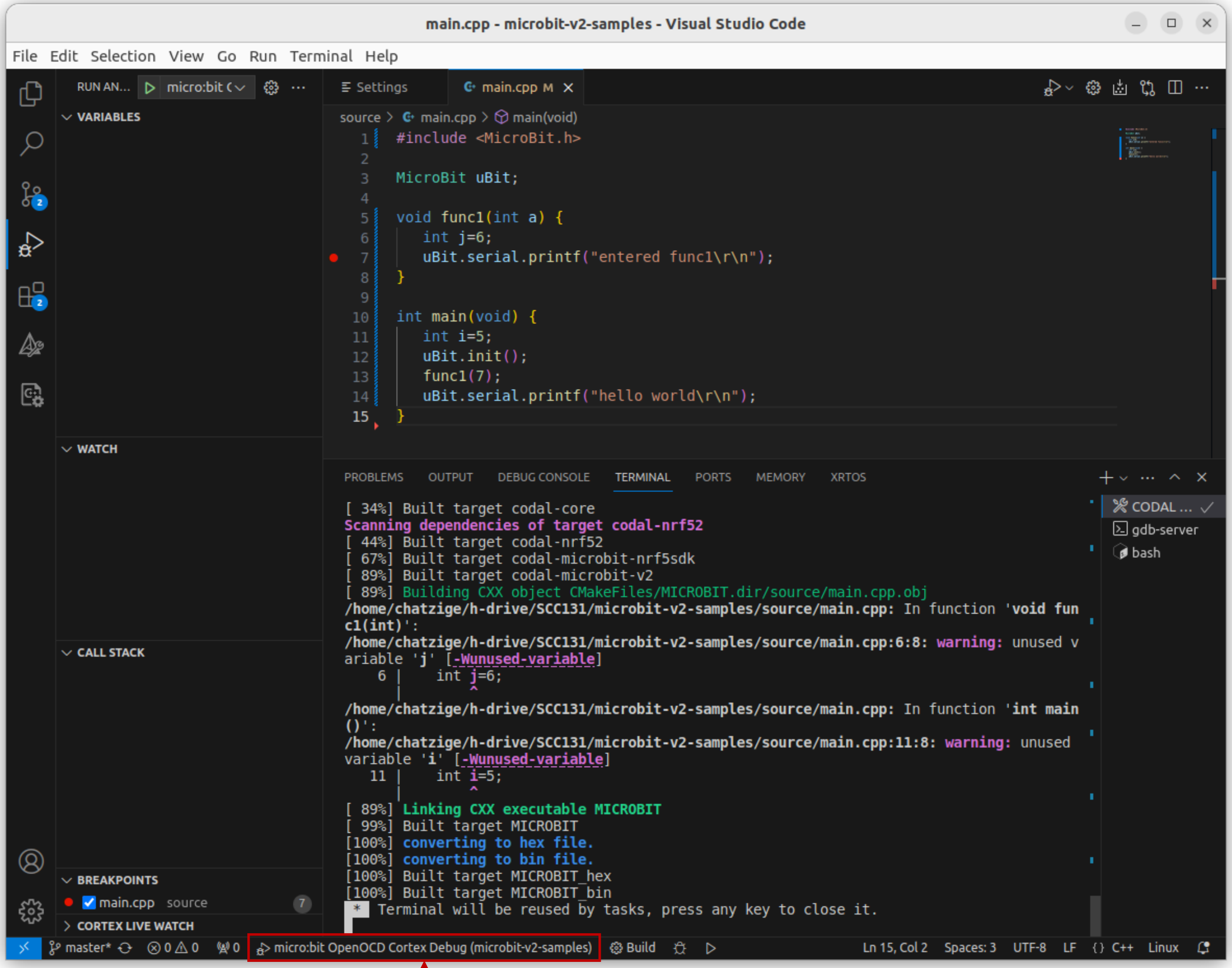
Step 1: Develop code to examine

main.cpp

```
#include <MicroBit.h>

MicroBit uBit;

void func1(int a) {
  int j=6;
  uBit.serial.printf("entered func1\r\n");
}

int main(void) {
  int i=5;
  uBit.init;
  func1(7);
  uBit.serial.printf("hello world\r\n");
}
```

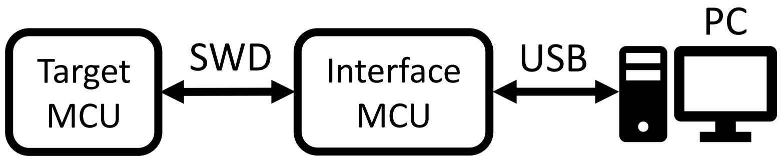
- This program will be examined using GDB **in Visual Studio Code**.
- As in the case of the previous lecture, `main()` is the caller and `func1()` is the callee.
- Notice that the **serial output** of micro:bit is used to display messages on an external monitor.
- Why do you think `\r` is used in addition to `\n` in `printf`?

Step 2: Compile and run code using GDB



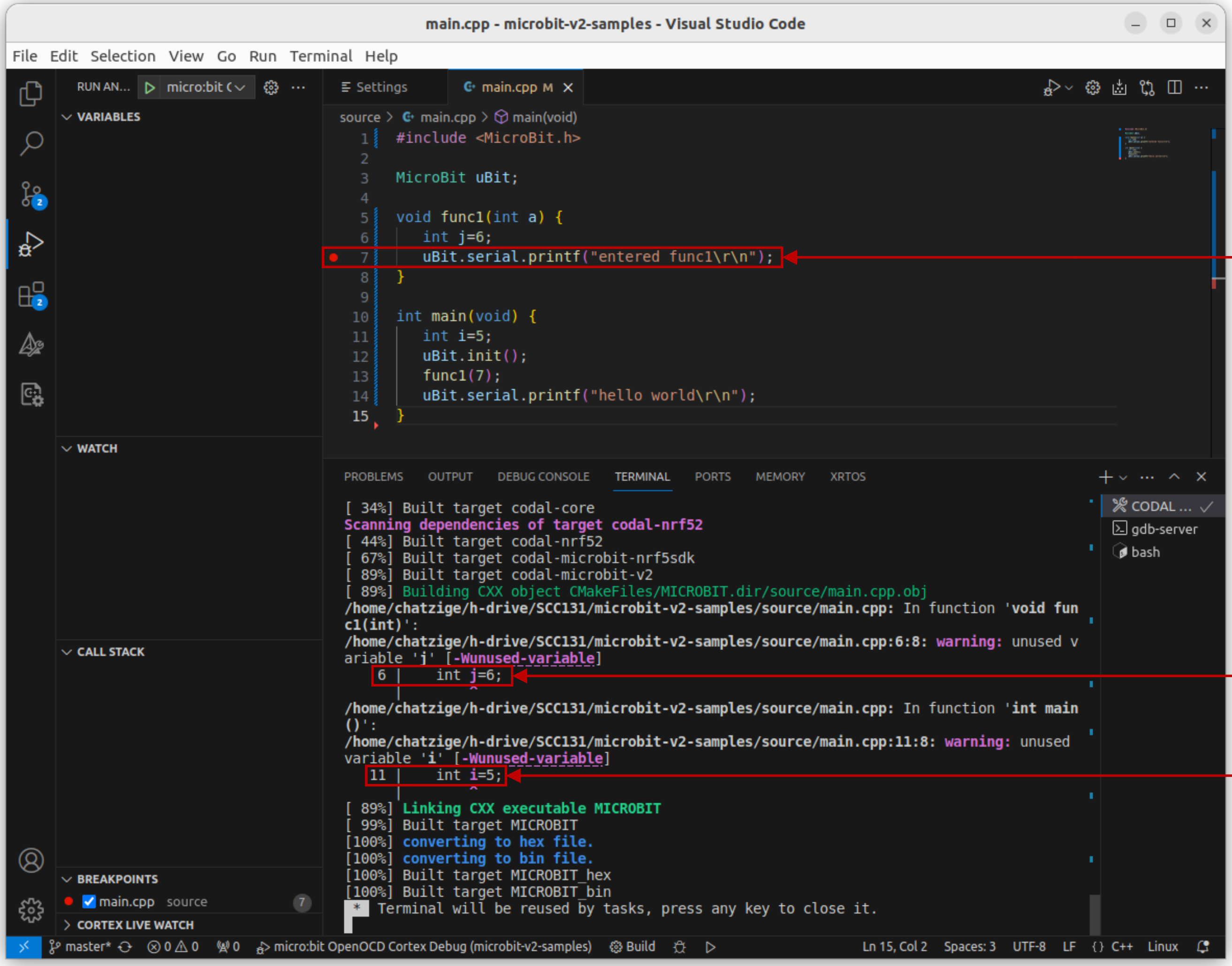
The **Open On-Chip Debugger** (OpenOCD) allows on-chip debugging via the SWD hardware interface of micro:bit.

Cortex debug is a VS Code extension that offers debugging support for ARM Cortex-M MCUs.



SWD: Serial Wire Debug (Week 7, Lecture 2)

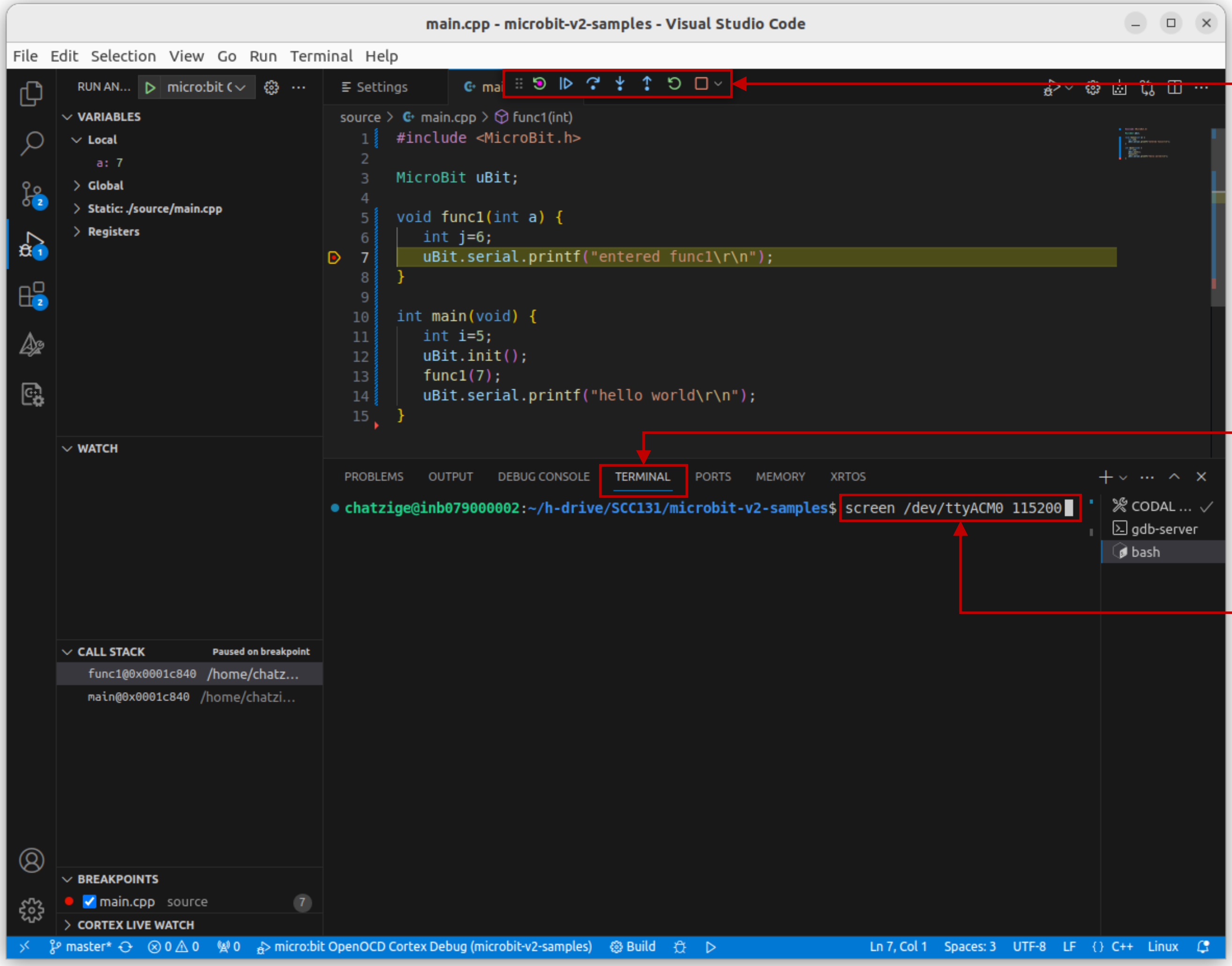
Step 2: Compile and run code using GDB



A breakpoint has been inserted in line 7.

Notice the warnings for local variables `i` and `j`.

Step 2: Compile and run code using GDB

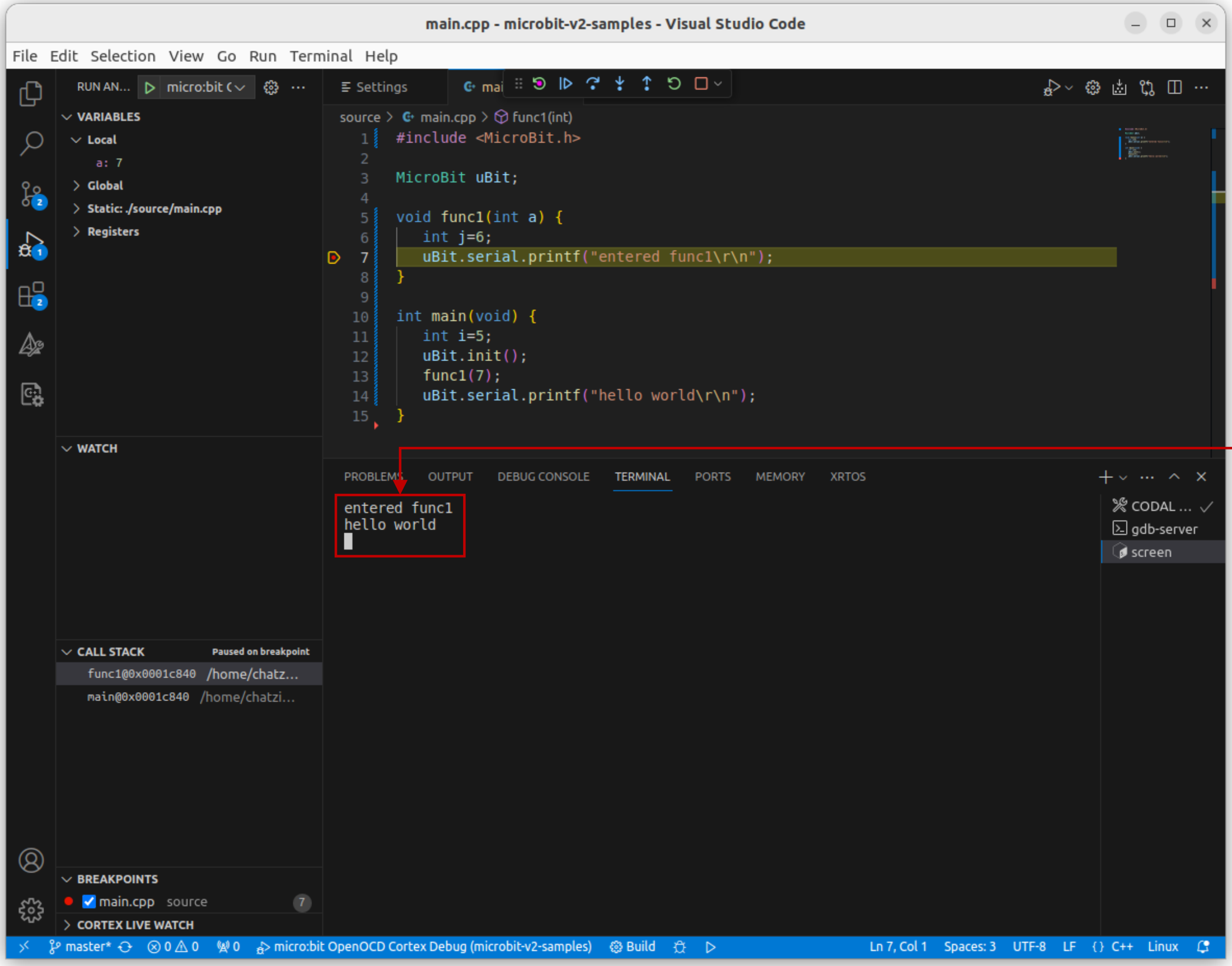


Control panel of Run and Debug.

The Terminal tab is used.

Display the output of the serial port of micro:bit on the screen (Week 10, Lecture 1).

Step 2: Compile and run code using GDB



The serial output of micro:bit has been displayed on the screen

Step 2: Compile and run code using GDB

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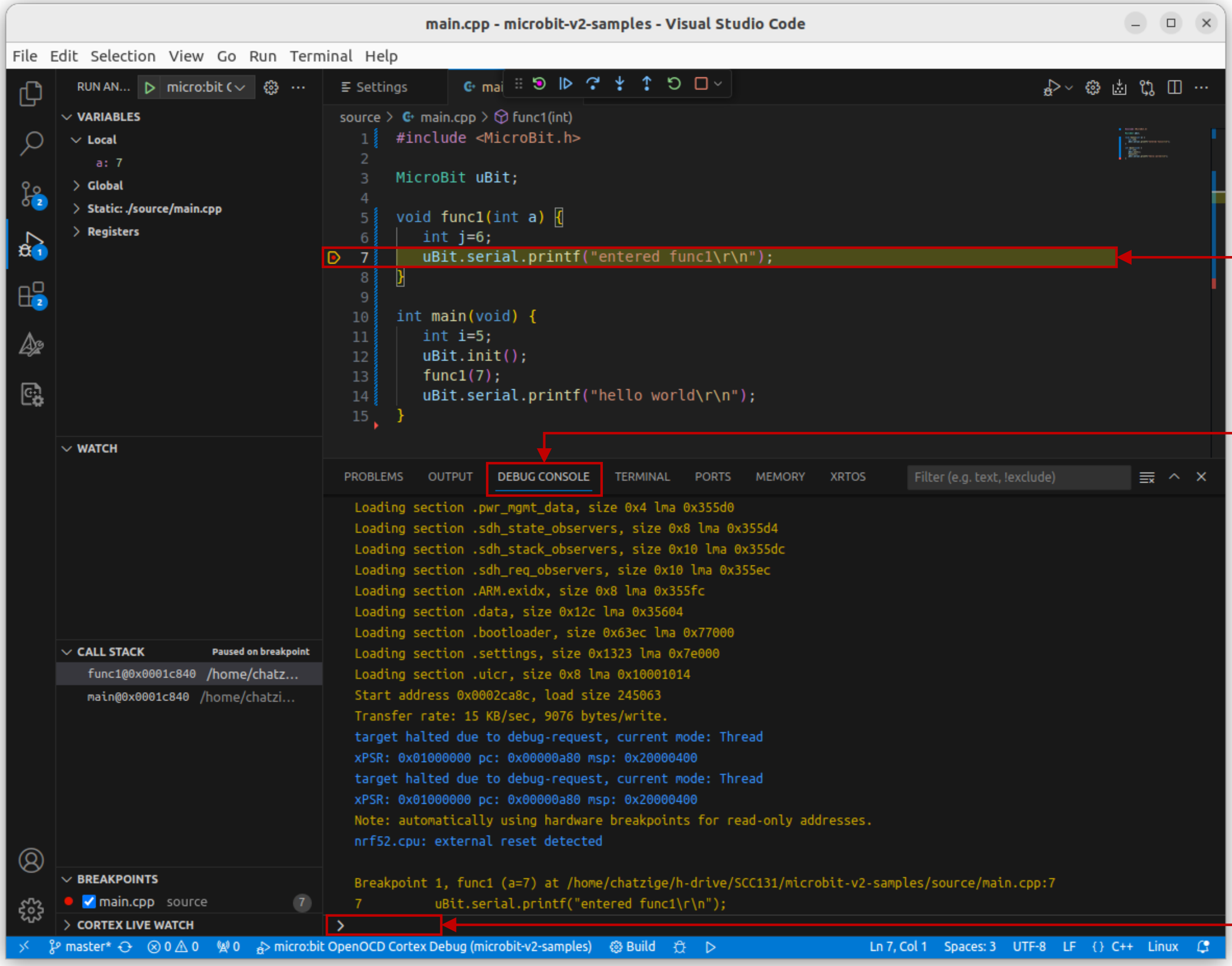

Breakpoint reached; execution paused.

We are now looking at the Debug Console.

GDB is waiting for our instructions.

Step 3: Examine the stack using GDB

```
info stack
#0  func1 (a=7) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:7
#1  main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:13
```

```
1   #include <MicroBit.h>
2
3   MicroBit uBit;
4
5   void func1(int a) {
6     int j=6;
7     uBit.serial.printf("entered func1\r\n");
8   }
9
10  int main(void) {
11    int i=5;
12    uBit.init;
13    func1(7);
14    uBit.serial.printf("hello world\r\n");
15  }
```

Step 3: Examine the stack using GDB

```
info stack
#0  func1 (a=7) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:7
#1  main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:13
```

No address has been given for when `func1` is completed and control returns to `main()`, i.e., immediately *after* the call of `func1` in line 13 (e.g., `#1 0x0001c868 in main () at ...`).

```
1   #include <MicroBit.h>
2
3   MicroBit uBit;
4
5   void func1(int a) {
6     int j=6;
7     uBit.serial.printf("entered func1\r\n");
8   }
9
10  int main(void) {
11    int i=5;
12    uBit.init;
13    func1(7);
14    uBit.serial.printf("hello world\r\n");
15  }
```

Step 3: Examine the stack using GDB

```
info stack
#0  func1 (a=7) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:7
#1  main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:13
```

```
info frame 0
Stack frame at 0x20020000:
 pc = 0x1c840 in func1 (/home/chatzige/h-drive/SCC131/microbit-v2-
samples/source/main.cpp:7); saved pc = 0x1c7c0
 inlined into frame 1
 source language c++.
 Arglist at unknown address.
 Locals at unknown address, Previous frame's sp in sp
```

Step 3: Examine the stack using GDB

```
info stack
#0  func1 (a=7) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:7
#1  main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:13

info frame 0
Stack frame at 0x20020000:
 pc = 0x1c840 in func1 (/home/chatzige/h-drive/SCC131/microbit-v2-
samples/source/main.cpp:7); saved pc = 0x1c7c0
 inlined into frame 1
 source language c++.
 Arglist at unknown address.
 Locals at unknown address, Previous frame's sp in sp
```

Beginning of frame 0 ('ceiling' of the RAM area). If frame 0 is 'touching' the ceiling, where is frame 1 located?

Step 3: Examine the stack using GDB

```
info stack
#0  func1 (a=7) at /home/chatzige/h-drive/SCC131/microbit-v2-samples/source/main.cpp:7
#1  main () at /home/chatzige/h-drive/SCC131/microbit-v2-samples/source/main.cpp:13
```

```
info frame 0
Stack frame at 0x20020000:
 pc = 0x1c840 in func1 (/home/chatzige/h-drive/SCC131/microbit-v2-samples/source/main.cpp:7); saved pc = 0x1c7c0
 inlined into frame 1
 source language c++.
 Arglist at unknown address.
 Locals at unknown address, Previous frame's sp in sp
```

Program counter (pc): Address that points to the next instruction, i.e., the address that the frame will return to when operation of `func1` resumes (equivalent to the instruction pointer).

Step 3: Examine the stack using GDB

```
info stack
#0  func1 (a=7) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:7
#1  main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:13

info frame 0
Stack frame at 0x20020000:
 pc = 0x1c840 in func1 (/home/chatzige/h-drive/SCC131/microbit-v2-
samples/source/main.cpp:7); saved pc = 0x1c7c0
 inlined into frame 1
 source language c++.
 Arglist at unknown address.
 Locals at unknown address, Previous frame's sp in sp
```

Why "`inlined into frame`" and not "`called by frame`" as expected?

Step 3: Examine the stack using GDB

```
info stack
#0  func1 (a=7) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:7
#1  main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:13

info frame 1
Stack frame at 0x20020000:
 pc = 0x1c840 in main (/home/chatzige/h-drive/SCC131/microbit-v2-
samples/source/main.cpp:13); saved pc = 0x1c7c0
 caller of frame at 0x20020000
 source language c++.
 Arglist at 0x2001fff8, args:
 Locals at 0x2001fff8, Previous frame's sp is 0x20020000
```

Frame 1 contains more details but most of them are identical to those of frame 0. Why is that?

Step 4: Disassemble the code (main)

```
disass main
Dump of assembler code for function main():
   0x0001c834 <+0>:   push       {r4, lr}
   0x0001c836 <+2>:   ldr        r0, [pc, #28]        ; (0x1c854 <main()+32>)
   0x0001c838 <+4>:   addw       r4, r0, #1652        ; 0x674
   0x0001c83c <+8>:   bl         0x21768 <codal::MicroBit::init()>
=> 0x0001c840 <+12>:  mov        r0, r4
   0x0001c842 <+14>:  ldr        r1, [pc, #20]        ; (0x1c858 <main()+36>)
   0x0001c844 <+16>:  bl         0x24a20 <codal::Serial::printf(char const*, ...)>
   0x0001c848 <+20>:  mov        r0, r4
   0x0001c84a <+22>:  ldr        r1, [pc, #16]        ; (0x1c85c <main()+40>)
   0x0001c84c <+24>:  bl         0x24a20 <codal::Serial::printf(char const*, ...)>
   0x0001c850 <+28>:  movs       r0, #0
   0x0001c852 <+30>:  pop        {r4, pc}
   0x0001c854 <+32>:  movs       r3, #0
   0x0001c856 <+34>:  movs       r0, #0
   0x0001c858 <+36>:  adds       r6, #124   ; 0x7c
   0x0001c85a <+38>:  movs       r3, r0
   0x0001c85c <+40>:  adds       r6, #140   ; 0x8c
   0x0001c85e <+42>:  movs       r3, r0
End of assembler dump.
```

Step 4: Disassemble the code (main)

```
disass main
Dump of assembler code for function main():
   0x0001c834 <+0>:   push      {r4, lr}
   0x0001c836 <+2>:   ldr       r0, [pc, #28]        ; (0x1c854 <main()+32>)
   0x0001c838 <+4>:   addw      r4, r0, #1652        ; 0x674
   0x0001c83c <+8>:   bl        0x21768 <codal::MicroBit::init()>
=> 0x0001c840 <+12>:  mov       r0, r4
   0x0001c842 <+14>:  ldr       r1, [pc, #20]        ; (0x1c858 <main()+36>)
   0x0001c844 <+16>:  bl        0x24a20 <codal::Serial::printf(char const*, ...)>
   0x0001c848 <+20>:  mov       r0, r4
   0x0001c84a <+22>:  ldr       r1, [pc, #16]        ; (0x1c85c <main()+40>)
   0x0001c84c <+24>:  bl        0x24a20 <codal::Serial::printf(char const*, ...)>
   0x0001c850 <+28>:  movs      r0, #0
   0x0001c852 <+30>:  pop       {r4, pc}
   0x0001c854 <+32>:  movs      r3, #0
   0x0001c856 <+34>:  movs      r0, #0
   0x0001c858 <+36>:  adds      r6, #124   ; 0x7c
   0x0001c85a <+38>:  movs      r3, r0
   0x0001c85c <+40>:  adds      r6, #140   ; 0x8c
   0x0001c85e <+42>:  movs      r3, r0
End of assembler dump.
```

Recall:

```
info frame 0
Stack frame at 0x20020000:
 pc = 0x1c840 in func1
```

When frame 0, i.e., `func1()`, resumes operation, why is the next instruction in `main()`?

Step 4: Disassemble the code (main)

```
disass main
Dump of assembler code for function main():
   0x0001c834 <+0>:   push      {r4, lr}
   0x0001c836 <+2>:   ldr       r0, [pc, #28]        ; (0x1c854 <main()+32>)
   0x0001c838 <+4>:   addw      r4, r0, #1652        ; 0x674
   0x0001c83c <+8>:   bl        0x21768 <codal::MicroBit::init()>
=> 0x0001c840 <+12>:  mov       r0, r4
   0x0001c842 <+14>:  ldr       r1, [pc, #20]        ; (0x1c858 <main()+36>)
   0x0001c844 <+16>:  bl        0x24a20 <codal::Serial::printf(char const*, ...)>
   0x0001c848 <+20>:  mov       r0, r4
   0x0001c84a <+22>:  ldr       r1, [pc, #16]        ; (0x1c85c <main()+40>)
   0x0001c84c <+24>:  bl        0x24a20 <codal::Serial::printf(char const*, ...)>
   0x0001c850 <+28>:  movs      r0, #0
   0x0001c852 <+30>:  pop       {r4, pc}
   0x0001c854 <+32>:  movs      r3, #0
   0x0001c856 <+34>:  movs      r0, #0
   0x0001c858 <+36>:  adds      r6, #124   ; 0x7c
   0x0001c85a <+38>:  movs      r3, r0
   0x0001c85c <+40>:  adds      r6, #140   ; 0x8c
   0x0001c85e <+42>:  movs      r3, r0
End of assembler dump.
```

Recall:

```
info frame 0
Stack frame at 0x20020000:
 pc = 0x1c840 in func1
```

The 'culprit' is the compiler! Optimization flags instructed the compiler to make the code more compact. As a result, `func1()` has become part of `main()`, i.e., it is not a separate function but an *inline* function.

How can we alter the code?

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main.cpp

```
#include <MicroBit.h>

MicroBit uBit;
int k=1;

void func1(int a) {
  int j=6+a+k;
  uBit.serial.printf("entered func1: %d\r\n", j);
}

int main(void) {
  int i=5;
  uBit.init;
  func1(i+k);
  uBit.serial.printf("hello world\r\n");
}
```

In an effort to force the compiler to create separate functions:

- The local variables `i` and `j` are now used.
- Global variable `k` was declared and contributes to the values of the local variable `j` and the input parameter of `func1()`.

Impact of changes on the stack (1/3)

```
info stack
#0  func1 (a=6) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:8
#1  0x0001c868 in main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:14

info frame 0
Stack frame at 0x2001fff8:
 pc = 0x1c83c in func1 (/home/chatzige/h-drive/SCC131/microbit-v2-
samples/source/main.cpp:9); saved pc = 0x1c868
 called by frame at 0x20020000
 source language c++.
 Arglist at 0x2001fff8, args: a=6
 Locals at 0x2001fff8, Previous frame's sp is 0x2001fff8
```

Impact of changes on the stack (2/3)

```
info stack
#0  func1 (a=6) at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:8
#1  0x0001c868 in main () at /home/chatzige/h-drive/
SCC131/microbit-v2-samples/source/main.cpp:14
```

```
info frame 1
Stack frame at 0x20020000:
 pc = 0x1c868 in main (/home/chatzige/h-drive/SCC131/microbit-v2-
samples/source/main.cpp:15); saved pc = 0x1c7c0
 caller of frame at 0x2001fff8
 source language c++.
 Arglist at 0x2001fff8, args:
 Locals at 0x2001fff8, Previous frame's sp is 0x20020000
```

Impact of changes on the stack (3/3)

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```
disass main
Dump of assembler code for function main():
   0x0001c854 <+0>:     push    {r4, lr}
   0x0001c856 <+2>:     ldr     r4, [pc, #32]; (0x1c878 <main()+36>)
   0x0001c858 <+4>:     mov     r0, r4
   0x0001c85a <+6>:     bl      0x2178c <codal::MicroBit::init()>
   0x0001c85e <+10>:    ldr     r3, [pc, #28]; (0x1c87c <main()+40>)
   0x0001c860 <+12>:    ldr     r0, [r3, #0]
   0x0001c862 <+14>:    adds    r0, #5
   0x0001c864 <+16>:    bl      0x1c834 <func1(int)>
   0x0001c868 <+20>:    addw    r0, r4, #1652; 0x674
   0x0001c86c <+24>:    ldr     r1, [pc, #16]; (0x1c880 <main()+44>)
   ...
End of assembler dump.
disass func1
Dump of assembler code for function func1(int):
   0x0001c834 <+0>:     ldr     r3, [pc, #16]; (0x1c848 <func1(int)+20>)
   0x0001c836 <+2>:     ldr     r1, [pc, #20]; (0x1c84c <func1(int)+24>)
   0x0001c838 <+4>:     ldr     r3, [r3, #0]
   0x0001c83a <+6>:     mov     r2, r0
=> 0x0001c83c <+8>:     adds    r3, #6
   0x0001c83e <+10>:    ldr     r0, [pc, #16]; (0x1c850 <func1(int)+28>)
   0x0001c840 <+12>:    add     r2, r3
   0x0001c842 <+14>:    b.w     0x24a44 <codal::Serial::printf(char const*, ...)>
   ...
End of assembler dump.
```

Recall:

```
info frame 0
Stack frame at 0x2001fff8:
 pc = 0x1c83c in func1; saved pc = 0x1c868

info frame 1
Stack frame at 0x20020000:
 pc = 0x1c868 in main; saved pc = 0x1c7c0
```

Summary

We looked at micro:bit, which uses the nRF52833 SoC that is built around the 32-bit ARM Cortex-M4F processor, and we discussed about:

- The different **types of memory** (flash, RAM, memory of external devices).
- The memory layout of **physical addresses**, when Bluetooth is disabled and when Bluetooth is enabled.
- The stack layout for the same **example** used in the previous lecture (but adapted for the micro:bit).
- GDB commands used within Visual Studio Code, which can help visualise the stack of the running program and reveal if functions are **inline** or not.

Resources

- General description of key features of nRF52833: https://www.nordicsemi.com/products/nrf52833
- nRF52833 Product Specification: https://infocenter.nordicsemi.com/topic/ps_nrf52833/keyfeatures_html5.html
- Linked editors:
  - https://github.com/lancaster-university/codal-microbit-v2/blob/master/ld/nrf52833.ld (Bluetooth disabled)
  - https://github.com/lancaster-university/codal-microbit-v2/blob/master/ld/nrf52833-softdevice.ld (Bluetooth enabled)