Computer Programming

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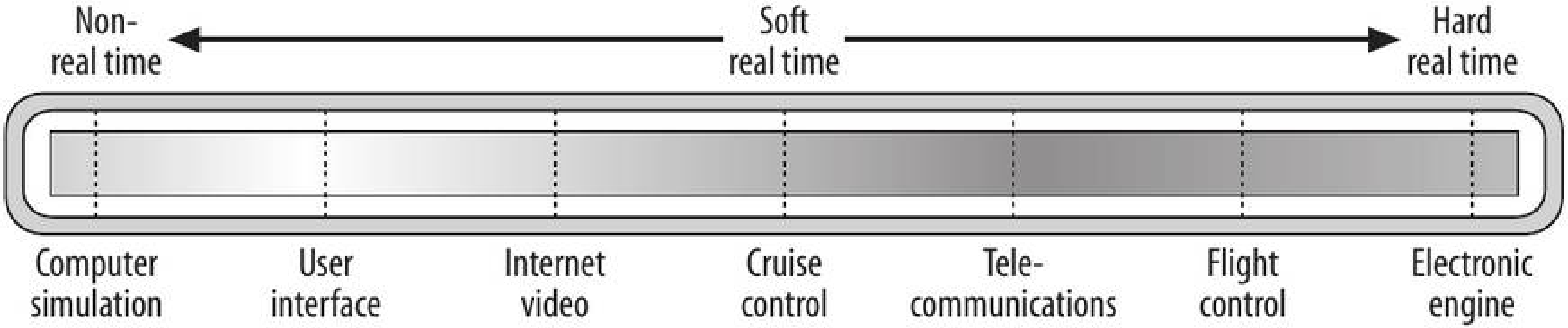
Collaborations:

Barcelona Supercomputing Center, Spain

European Network on High Performance and Embedded Architecture and Compilation

Pakistan Supercomputing Center

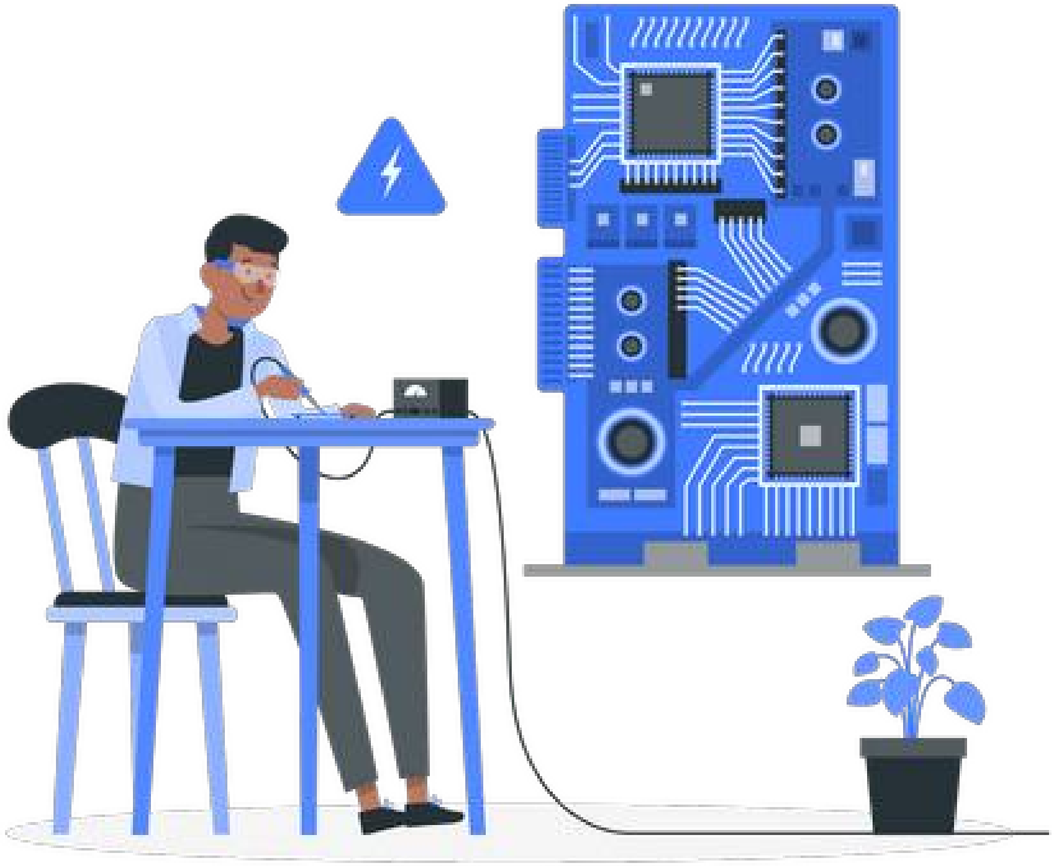
- Range of Applications



Introduction to C Programming

C

- Standard C (often just called "C") is a programming languages used to write software, but they differ in their target environments, constraints, and some aspects of functionality.
- Embedded C can be considered as the subset of C language. It uses same core syntax as C.
- Embedded C programs need cross-compliers to compile and generate HEX code
- Embedded C is designed for Computer Programming with specific constraints, hardware interaction requirements, and specialized development tools.



Introduction to Embedded C Programming

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Target Environment

A structural and programming language used by developers to create desktop-based applications

An extension of C primarily used to develop microcontroller based applications.

Memory Constraint

Typically used on systems with more resources.

Often used in environments with limited resources (memory, processing power).

Hardware Interaction

Hardware interactions are managed by operating system or libraries, unless used in system-level programming.

Interacts directly with hardware components, such as registers, I/O ports, and peripheral devices.

Libraries and Extensions

Uses standard libraries provided by the C standard library (e.g., stdio.h, stdlib.h) and other platform-specific or third-party libraries.

Uses specialized libraries and extensions for embedded systems (e.g., specific APIs for handling hardware interrupts, timers, and serial communication).

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Development Tools

Typically uses general-purpose IDEs (e.g., Visual Studio, Eclipse) and compilers (e.g., GCC, Clang).

Specific Integrated Development Environments (IDEs), compilers, and debuggers designed for embedded system development (e.g., Keil, IAR, MPLAB).

Real-Time Constraint

It can be used in real-time applications, but it is not inherently designed for real-time constraints and may rely on external real-time extensions or operating systems.

Often used in real-time systems where meeting timing constraints is crucial. It may include real-time operating systems (RTOS) or bare-metal programming.

Code Portability

Code is generally more portable across different platforms, adhering to the C standard.

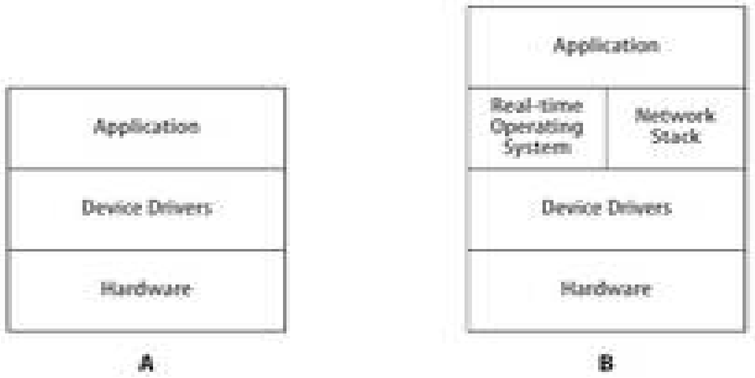
Code is often less portable due to hardware-specific dependencies and optimizations. Porting code between different embedded platforms can be challenging.

- Target Hardware Architecture:
  - Processor and Specifications:
  - Program Memory and Data Memory Size:
  - Peripherals and Components
- Memory Mapping
- Software Development
  - GCC Compiler: Compiler: riscv32-unknown-elf-gcc or riscv64-unknown-elf-gcc.
  - Debugger: GDB with RISC-V support.
  - ELF Loader: OpenOCD or RISC-V Proxy Kernel.

Stress Checking and Profiling Tools for RISC-V:

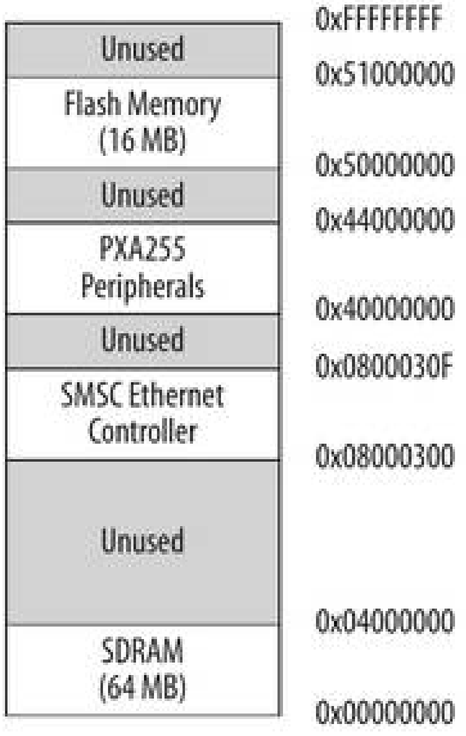
  - RISC-V Performance Monitor or Perf.

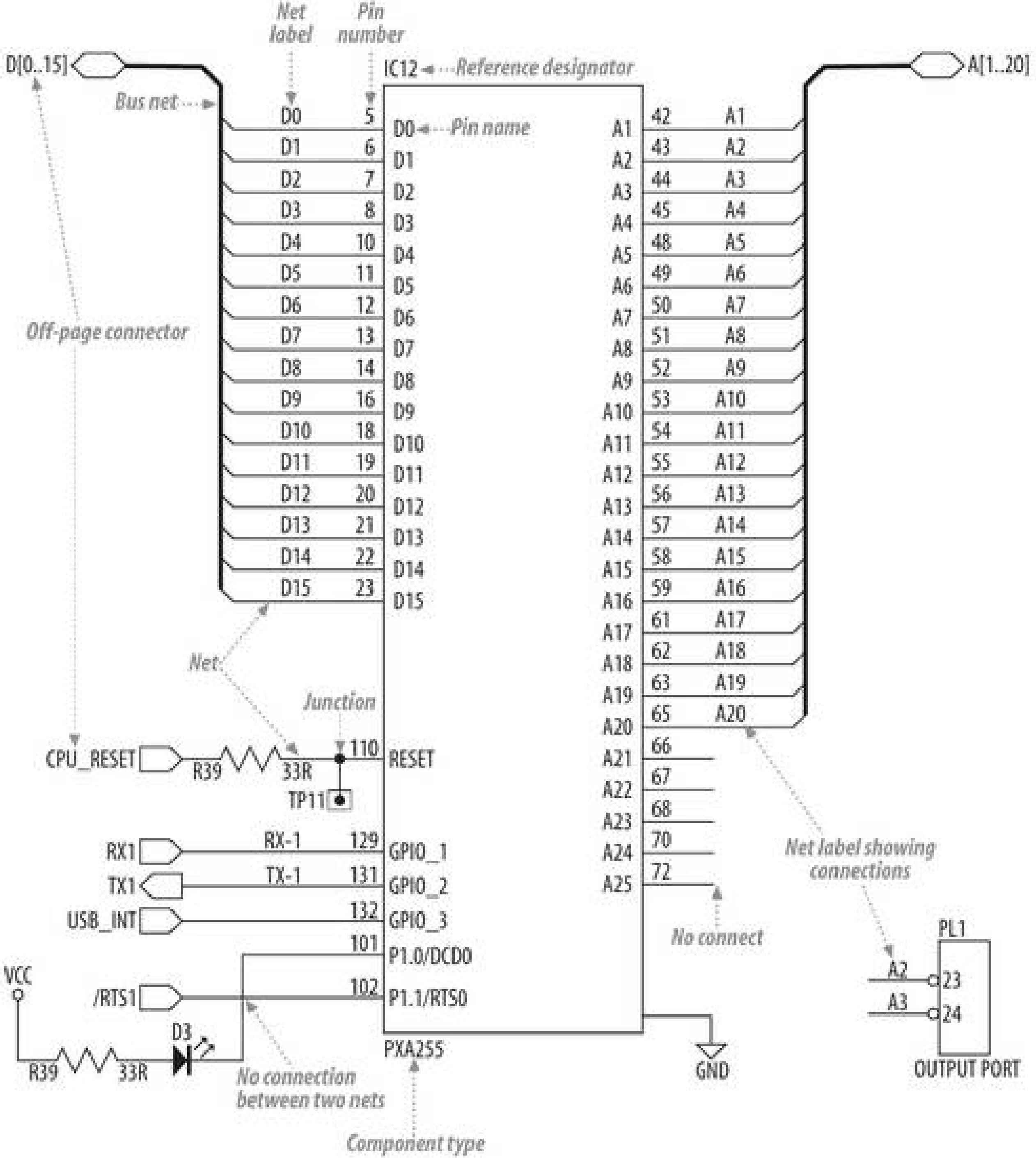
Requirements: Basic and Complex



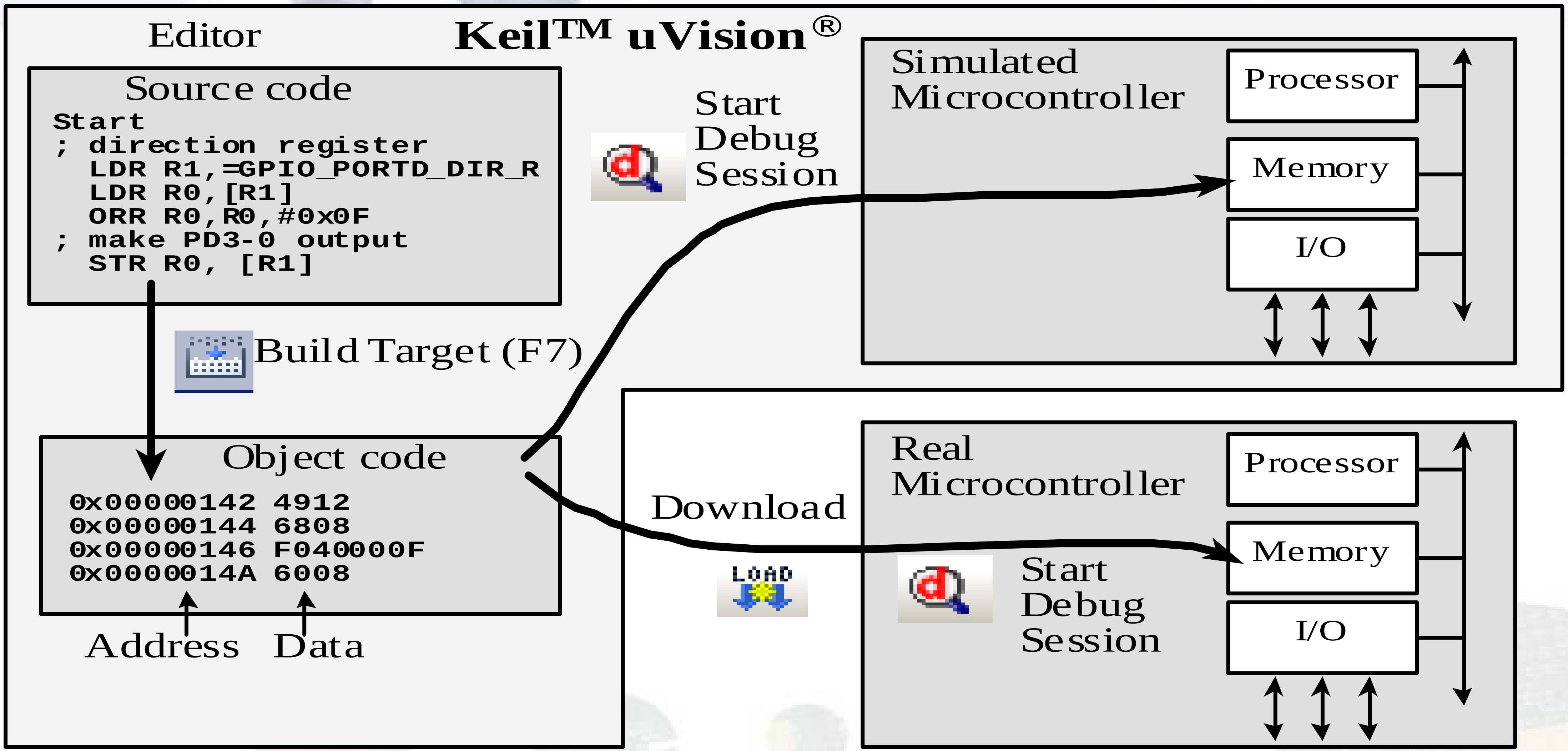
Criterion	Low	Medium	High
Processor	4- or 8-bit	16-bit	32- or 64-bit
Memory	< 64 KB	64 KB to 1 MB	> 1 MB
Development cost	< $100,000	$100,000 to $1,000,000	> $1,000,000
Production cost	< $10	$10 to $1,000	> $1,000
Number of units	< 100	100 to 10,000	> 10,000
Power consumption	> 10 mW/MIPS	1 to 10 mW/MIPS	< 1 mW/MIPS
Lifetime	Days, weeks, or months	Years	Decades
Reliability	May occasionally fail	Must work reliably	Must be fail-proof

Embedded System Schematic and Memory Mapping





SW Development Environment



Compiler Options

- riscv32-unknown-elf-gcc //
  -march=rv32imac // Architecture and ISA Extensions:
  -mabi=ilp32 // ABI (Application Binary Interface: Int, long, pointer):
  -O2 // Optimization Levels:
  -mtune=sifive-e31 // Code Genartion for specific RISCV core
  -g // Debugging and Profiling -pg
  mhard-float // Floating Point Options: Hard/Soft Floting point:
- -T linker_script.ld // -T: Specify a linker script.
  -I/path/to/include // Include Paths and Libraries
  -L/path/to/li //
  -o output.elf // Output file
  source.c // source file
  -lm // -lm (math library)
- -funroll-loops // Loop Unrolling option

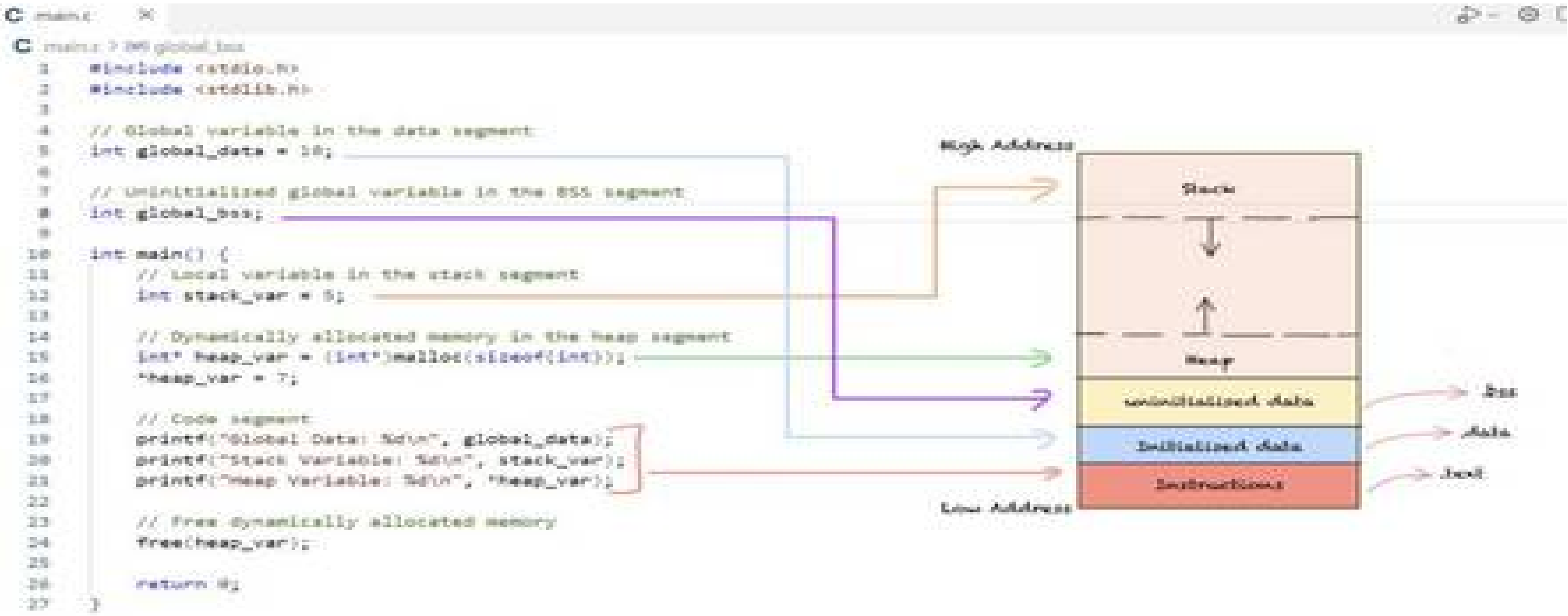
Define Memory Address

```
/* Timer Registers */
#define TIMER_0_MATCH_REG          (*((uint32_t volatile *)0x40A00000))
#define TIMER_1_MATCH_REG          (*((uint32_t volatile *)0x40A00004))
#define TIMER_2_MATCH_REG          (*((uint32_t volatile *)0x40A00008))
#define TIMER_3_MATCH_REG          (*((uint32_t volatile *)0x40A0000C))
#define TIMER_COUNT_REG            (*((uint32_t volatile *)0x40A00010))
#define TIMER_STATUS_REG           (*((uint32_t volatile *)0x40A00014))
#define TIMER_INT_ENABLE_REG       (*((uint32_t volatile *)0x40A0001C))

/* Timer Interrupt Enable Register Bit Descriptions */
#define TIMER_0_INTEN              (0x01)
#define TIMER_1_INTEN              (0x02)
#define TIMER_2_INTEN              (0x04)
#define TIMER_3_INTEN              (0x08)

/* Timer Status Register Bit Descriptions */
#define TIMER_0_MATCH              (0x01)
#define TIMER_1_MATCH              (0x02)
#define TIMER_2_MATCH              (0x04)
#define TIMER_3_MATCH              (0x08)

/* Interrupt Controller Registers */
#define INTERRUPT_PENDING_REG      (*((uint32_t volatile *)0x40D00000))
#define INTERRUPT_ENABLE_REG       (*((uint32_t volatile *)0x40D00004))
#define INTERRUPT_TYPE_REG         (*((uint32_t volatile *)0x40D00008))

/* Interrupt Enable Register Bit Descriptions */
#define GPIO_0_ENABLE              (0x00000100)
#define UART_ENABLE                (0x00400000)
#define TIMER_0_ENABLE             (0x04000000)
#define TIMER_1_ENABLE             (0x08000000)
#define TIMER_2_ENABLE             (0x10000000)
#define TIMER_3_ENABLE             (0x20000000)
```

```
/* General Purpose I/O (GPIO) Registers */
#define GPIO_0_LEVEL_REG           (*((uint32_t volatile *)0x40E00000))
#define GPIO_1_LEVEL_REG           (*((uint32_t volatile *)0x40E00004))
#define GPIO_2_LEVEL_REG           (*((uint32_t volatile *)0x40E00008))
#define GPIO_0_DIRECTION_REG       (*((uint32_t volatile *)0x40E0000C))
#define GPIO_1_DIRECTION_REG       (*((uint32_t volatile *)0x40E00010))
#define GPIO_2_DIRECTION_REG       (*((uint32_t volatile *)0x40E00014))
#define GPIO_0_SET_REG             (*((uint32_t volatile *)0x40E00018))
#define GPIO_1_SET_REG             (*((uint32_t volatile *)0x40E0001C))
#define GPIO_2_SET_REG             (*((uint32_t volatile *)0x40E00020))
#define GPIO_0_CLEAR_REG           (*((uint32_t volatile *)0x40E00024))
#define GPIO_1_CLEAR_REG           (*((uint32_t volatile *)0x40E00028))
#define GPIO_2_CLEAR_REG           (*((uint32_t volatile *)0x40E0002C))
#define GPIO_0_FUNC_LO_REG         (*((uint32_t volatile *)0x40E00054))
#define GPIO_0_FUNC_HI_REG         (*((uint32_t volatile *)0x40E00058))
```

Computer Programming and Memory Layout

- Understanding C memory layout is crucial for debugging, optimizing performance, security and interfacing with low-level systems.
- **Text (Code) Segment**:
- **Data Segment**:
- **BSS Segment**:
- **Heap Segment**:
- **Stack Segment**:



Text (Code), Data and BSS Segment:

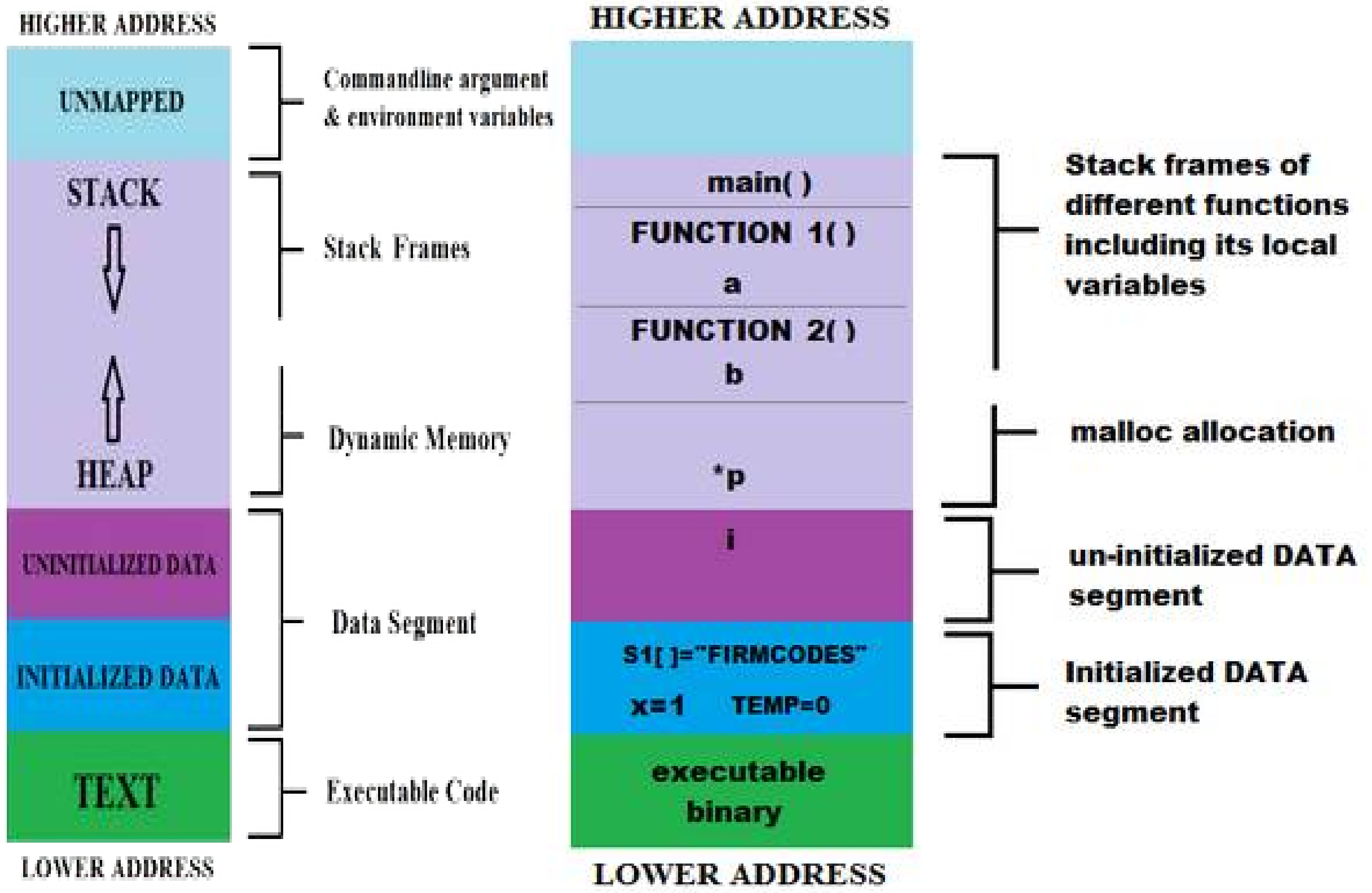
- The text segment contains the executable code of the program. It is read-only and holds the instructions for the program.
- The data segment contains initialized global and static variables. In the example code, global_data is an initialized global variable with value 10.
- The BSS (Block Started by Symbol) segment contains uninitialized global and static variables. The BSS segment is set to zero during program startup. In the example code, global_bss variable will be added to the bss section by linker.
- The Text, Data, and BSS segments collectively form the static part of the program that contains fixed-sized instructions and data that persists throughout its execution. These should be kept in a non-volatile memory to ensure successful execution of code following a power cycle.
- You can use the size utility that comes with the compiler to get the size of the executable. Below is the output for the example code:
  ----

text	data	bss	dec	hex	filename
1585	600	8	2193	891	main.out

Heap and Stack Segments

- **Heap Segment**:
- The heap segment is used for dynamic memory allocation during the program's runtime. In the example, we allocate memory for an integer using malloc(), and heap_var points to the newly allocated memory location.
- It's important to free the allocated memory after it is no longer needed.
- Over time, repeated memory allocation without freeing memory can cause the program's memory usage to grow unnecessarily leading to poor performance and runtime allocation failures.

- **Stack Segment**:
- The stack segment is used for managing function calls, local variables, and function call frames. In the example, stack_var is a local variable that will be allotted on the stack during the execution of the main() function.
- The stack and heap memory share the dynamic memory area of the program. The stack typically starts from the end address of the memory and grows downward, while the heap starts from the end of the BSS segment.




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

void FUNCTION_1();
void FUNCTION_2();

char S1[]="FIRMCODES";  //initialized read-write area of DATA segment
int i;                  //uninitialized DATA segment
const int x=1;          //initialized read-only area of DATA segment

int main()
{
    static int TEMP=0;  //uninitialized DATA segment

    char *p=(char*)malloc(sizeof(char)); //Heap segment

    FUNCTION_1();       //FUNCTION_1 stack frame

    return 0;
}

void FUNCTION_1()
{
    int a;          //initialized in stack frame of FUNCTION_1

    FUNCTION_2();   //FUNCTION_2 stack frame
}

void FUNCTION_2()
{
    int b;          //initialized in stack frame of FUNCTION_2
}
```

Steps: Code Compilation to Execution

- riscv32-unknown-elf-gcc -march=rv32i -S -o riscv.s ./code.c
- riscv32-unknown-elf-as -march=rv32i -S -o riscv.o ./riscv.s
- riscv32-unknown-elf-as -march=rv32i -o riscv.o ./riscv.s
- riscv32-unknown-elf-ld -o riscv ./riscv.o
- riscv32-unknown-elf-objcopy -O binary --only-section=.text riscv instr.mem
- riscv32-unknown-elf-objcopy -O binary --only-section=.data riscv data.mem
- riscv32-unknown-elf-objdump -D -b binary -m riscv:rv32i instr.mem

Debugging

- # Compile with debugging information
- riscv64-unknown-elf-gcc -march=rv64gc -mabi=lp64d -g -o my_program ./for_loop.c

Start GDB and load program

- riscv64-unknown-elf-gdb my_program
- # Run program in GDB
- (gdb) target sim
  - (gdb) break linenumber
  - (gdb) print variable_name

Profiling

- **# Compile for performance analysis with perf**
- riscv32-unknown-elf-gcc -march=rv32i -o my_program ./code.c
- # Run program with QEMU and collect profiling data
- qemu-riscv32 -cpu rv32, my_program -perf my_program
- # Analyze profiling data with perf
- // Not yet configured in cluster

Stress Testing

- riscv32-unknown-elf-gcc -march=rv32i -o stress-ng stress-ng.c
- **# Run stress tests with stress-ng**
- qemu-riscv32 -L /path/to/riscv/rootfs ./stress-ng --cpu 4 --io 2 --vm 2 --vm-bytes 128M --timeout 60s
- **Custom Stress Checking**
- riscv32-unknown-elf-gcc -march=rv32i -o stress_test ./stress_test.c
- **# Run custom stress test program**
- qemu-riscv32 ./stress_test

Performance Analysis

- riscv32-unknown-elf-gcc -march=rv32i -o my_program ./code.c
- qemu-riscv32 -L /path/to/riscv/rootfs valgrind --tool=cachegrind ./my_program
- # Run program with QEMU for performance analysis
- qemu-riscv32 -d in_asm,cpu ./my_program > qemu_log.txt
- # Analyze QEMU log
- grep -E 'IN:|CPU:|Cycle:' qemu_log.txt

Testing Spike

```
/opt/riscv-gnu32/bin/spike --isa=RV32IMAC -d /opt/riscv/riscv32-unknown-elf/bin/pk ./heap32
until reg 0 pc 0x1000  # Stop execution when program counter of core 0 reaches 0x1000
mem 0 0x80000000  # View memory content at address 0x80000000 for core 0
freg 0 f0  # Display floating-point register f0 for core 0
run 1000  # Resume execution for 1000 instructions
reg 0  # View all registers for core 0
pc 0    # View the program counter of core 0
until pc 0 0x1000  # Stop execution when PC of core 0 reaches address 0x1000
while reg 0 sp 0x80000000  # Continue running while stack pointer (sp) of core 0 is 0x80000000
dump 0x80000000 0x80001000  # Dump memory from address 0x80000000 to 0x80001000
quit
mtime
mtimecmp 0
```

QEMU Debuging

- qemu-system-riscv32 -gdb tcp::1234 -S -kernel ./hello32.o
- riscv32-unknown-elf-gdb ./hello32.o #Sperate window open
- Debug Commands
- (gdb) target remote :1234   # Connect to the QEMU GDB server

```
(gdb) load                    # Load the binary into QEMU
(gdb) b main                  # Set a breakpoint at the main function
(gdb) c                       # Continue execution until the breakpoint is hit
(gdb) info reg                # Display registers
(gdb) step                    # Step through code line by line
(gdb) next                    # Step over functions
(gdb) continue                # Continue execution until the next breakpoint
(gdb) quit                    # Exit GDB
```

Profiling QEMU

- qemu-system-riscv32 -d exec,int -kernel ./hello32.o
- perf record -e cycles -a -- qemu-system-riscv32 -kernel ./hello32.o
- perf report

Hands-on Embedded C for RISCV