

BIRZEIT UNIVERSITY

Department of Electrical & Computer Engineering
ENCS4110 – Computer Design Laboratory

Experiment 04

Microcontroller Architecture and GPIO Output

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4 Microcontroller Architecture and GPIO Output

Learning Objectives

After completing this experiment, you will be able to:

- Identify the main components and subsystems of the TM4C123 microcontroller and understand their roles within an embedded system.
- Recognize the organization of the ARM Cortex-M4 core, memory map, and peripheral buses.
- Understand the role of core peripherals including NVIC, SysTick, and System Control Block (SCB).
- Configure and control digital output pins using the General-Purpose Input/Output (GPIO) module.
- Write Assembly programs to drive on-board LEDs through direct register access.
- Relate register operations to physical hardware behavior and verify functionality through observation on the LaunchPad board.

Experiment Overview

This experiment introduces the TM4C123 microcontroller architecture and digital I/O interfacing through GPIO ports. You will explore the internal structure including the ARM Cortex-M4 core, memory regions, and peripheral interconnect, then write Assembly programs to control the on-board LEDs connected to PORTF. By the end of this lab, you will understand how peripheral registers are memory-mapped, be able to initialize and configure GPIO ports, and control external hardware through register manipulation—forming the foundation for subsequent experiments with interrupts, timers, and analog peripherals.

4.1 Theoretical Background

4.1.1 TM4C123 Microcontroller Architecture

The TM4C123GH6PM microcontroller is built around the ARM Cortex-M4F processor core, implementing the ARMv7-M architecture. It integrates the CPU core, memory, peripherals, and I/O interfaces on a single chip — a complete system-on-chip (SoC) solution for embedded applications.

4.1.1.1 Core Components

The TM4C123 contains the following major components:

- **ARM Cortex-M4F Processor Core:** 32-bit RISC processor with hardware Floating-Point Unit (FPU)
- **Memory:** 256 KB Flash, 32 KB SRAM, 2 KB EEPROM
- **System Buses:** Advanced High-Performance Bus (AHB) and Advanced Peripheral Bus (APB)
- **Core Peripherals:** NVIC, SysTick Timer, Memory Protection Unit (MPU), System Control Block (SCB)
- **General-Purpose Timers:** Six 16/32-bit and six 32/64-bit timers
- **Communication Interfaces:** UART, I²C, SSI (SPI), CAN
- **Analog Peripherals:** 12-bit ADC with 12 channels, analog comparators
- **GPIO Ports:** Six ports (A-F) with up to 43 programmable pins

4.1.2 ARM Cortex-M4 Core Peripherals

The ARM Cortex-M4 processor includes several **core peripherals** that are common across all Cortex-M4-based microcontrollers. They are tightly integrated with the CPU and provide essential system functions such as interrupt handling and timing.

4.1.2.1 Nested Vectored Interrupt Controller (NVIC)

The NVIC manages all interrupt and exception handling. It supports up to 240 interrupt sources (138 on the TM4C123), hardware priority levels, and automatic context saving for efficient servicing. Key features include nesting, tail-chaining, and late-arrival handling for minimal interrupt latency. Important NVIC registers (base address 0xE000E100):

- **NVIC_ENx** — Set-Enable
- **NVIC_DISx** — Clear-Enable
- **NVIC_PRIx** — Priority Configuration
- **NVIC_ACTIVEx** — Active Status

4.1.2.2 SysTick Timer

The SysTick timer is a simple 24-bit down-counter integrated in the core. It provides a consistent time base for system delays or periodic tasks. Many operating systems use it for time-keeping or scheduling.

SysTick registers (base address 0xE000E010):

- **STCTRL** — Control and Status
- **STRELOAD** — Reload Value
- **STCURRENT** — Current Counter Value

Other core peripherals such as the System Control Block (SCB) are present but not covered in this course.

4.1.3 Memory Map

The Cortex-M4 processor uses a unified 4 GB address space for all code, data, and peripherals. Every peripheral and memory region occupies a unique address range, allowing direct access through normal load and store instructions.

Region	Address Range	Description
Flash Memory	0x00000000 - 0x0003FFFF	Program storage (256 KB)
SRAM	0x20000000 - 0x20007FFF	On-chip data memory (32 KB)
Peripherals	0x40000000 - 0x400FFFFF	Peripheral registers
GPIO Ports	0x40004000 - 0x40025FFF	GPIO A-F registers
Core Peripherals	0xE0000000 - 0xE00FFFFF	NVIC, SysTick, SCB, etc.

Table 4.1: Simplified TM4C123 Memory Map

Each peripheral's registers are **memory-mapped**, meaning they are accessed just like variables in memory. For example, writing to address 0x400253FC directly updates the GPIO Port F data register.

4.1.4 General-Purpose Input/Output (GPIO)

GPIO (General-Purpose Input/Output) ports form the primary interface between the microcontroller and external devices such as LEDs, switches, and sensors. Each pin can be configured as either an input or an output.

When a pin is an **output**, software drives it high or low to control external hardware (e.g., turn an LED on/off). When a pin is an **input**, software reads its logic level (e.g., a button press).

4.1.4.1 GPIO Ports Overview

The TM4C123GH6PM provides six GPIO ports (A-F), each with up to eight programmable pins. Not all pins are available on the LaunchPad, and some are reserved for debugging or special functions.

Port	Pins Available	Notes
Port A	PA0-PA7	UART0 (PA0, PA1) shared with USB debug interface
Port B	PB0-PB7	I ² C0, SSI2, ADC channels
Port C	PC0-PC7	PC0-PC3 used for JTAG (avoid modification)
Port D	PD0-PD7	PD7 requires unlock for GPIO use
Port E	PE0-PE5	ADC and UART5 functionality available
Port F	PF0-PF4	On-board LEDs (PF1-PF3) and switches (PF0, PF4)

Table 4.2: GPIO Port Summary — TM4C123GH6PM

Each port exposes its own control and data registers, allowing independent configuration and operation.

4.1.4.2 Memory-Mapped GPIO Registers

GPIO modules are accessed via **memory-mapped registers**: fixed addresses that the CPU reads/writes with standard LDR/STR instructions.

Every port has a **base address**; key registers sit at fixed offsets from that base.

Port	Base Address
Port A	0x40004000
Port B	0x40005000
Port C	0x40006000
Port D	0x40007000
Port E	0x40024000
Port F	0x40025000

Table 4.3: GPIO Port Base Addresses (TM4C123GH6PM)

In this experiment we use Port F, so:

$$\text{GPIODIR} = 0x40025400, \quad \text{GPIODEN} = 0x4002551C, \quad \text{GPIODATA} = 0x400253FC.$$

4.1.4.3 Address Masking in GPIODATA

The GPIODATA register supports **address masking**: address bits [9:2] form a bit mask that selects which pins are affected.

- **Full access:** Base + 0x3FC — all 8 pins.
- **Masked access:** Base + (`mask` \ll 2) — only the pins in `mask`.

Example (PF1 only):

$$0x40025000 + (0x02 \ll 2) = 0x40025008.$$

This is **address masking** (often confused with “bit-banding”); it enables fast, selective reads/writes to individual pins.

4.1.4.4 Protected and Special-Function Pins

Some pins are locked or reserved at reset due to critical roles:

- **PF0** doubles as the Non-Maskable Interrupt (NMI) input and is locked. To use it as GPIO, write 0x4C4F434B to `GPIO_LOCK` and set the desired bits in `GPIO_CR`.
- **PC0-PC3** carry the JTAG debug interface and should not be reassigned in normal operation. Always confirm pin availability in the datasheet before repurposing special-function pins.

4.1.4.5 Port F on the LaunchPad

Port F connects to the on-board RGB LEDs and user push buttons:

Pin	Function	Connected Component	Active Level
PF1	Output	Red LED	Active High
PF2	Output	Blue LED	Active High
PF3	Output	Green LED	Active High
PF0	Input (locked)	SW2 (Push Button)	Active Low (enable pull-up)
PF4	Input	SW1 (Push Button)	Active Low (enable pull-up)

Table 4.4: GPIO Port F Pin Assignments — TM4C123 LaunchPad

LEDs are **active-high** (write 1 to turn on). Push buttons pull to ground when pressed, so inputs read **0 when pressed** and require internal pull-ups.

4.1.4.6 GPIO Configuration Workflow

In practice, GPIO usage has two phases:

- **Initialization (setup, runs once):** enable the port clock, unlock protected pins (if needed), set direction, and enable digital function.
- **Runtime (operation, repeats):** read inputs or write outputs by accessing `GPIO DATA` in the main loop or in interrupt service routines (ISRs).

A typical structure is:

```
InitGPIO();           // RCGCGPIO, optional LOCK/CR, DIR, DEN
while (1) {           // Runtime phase
    // Read buttons (inputs) and/or drive LEDs (outputs)
    // Optionally, some I/O is handled inside ISRs
}
```

Listing 4.1: Typical GPIO program structure (setup vs. runtime)

The detailed register-level steps (clock enable, unlock, direction, digital enable, and data access) are demonstrated in the following subsections.

Step 1 — Enable the GPIO Port Clock

Register: RCGCGPIO — Run Mode Clock Gating Control for GPIO (0x400FE608)

Before accessing any GPIO port, its clock must be enabled. The RCGCGPIO register controls the clock to all GPIO modules. Each bit corresponds to a single port (A-F). Writing a '1' to a bit enables the clock to that port, while '0' disables it.

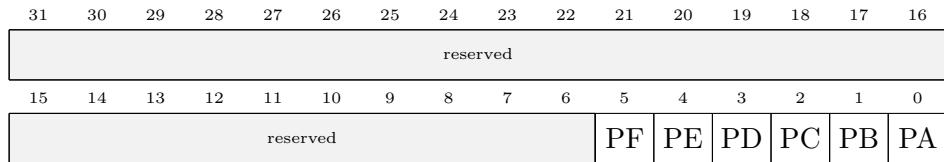


Figure 4.1: RCGCGPIO Register (0x400FE608) — GPIO Clock Control

To activate Port F, bit 5 must be set to 1 as shown below.

```
LDR    R1, =0x400FE608      ; RCGCGPIO register
LDR    R0, [R1]
ORR    R0, R0, #0x20        ; Set bit 5 (Port F)
STR    R0, [R1]
```

Listing 4.2: Enable clock for Port F

Once the clock is enabled, a short delay or status polling ensures the peripheral is ready before further configuration.

Step 2 — Unlock Protected Pins

Registers: GPIO_LOCK (0x40025520), GPIO_CR (0x40025524)

Certain pins such as PF0 are protected because they share critical alternate functions (e.g., the NMI input). To modify these pins, the port must be unlocked by writing the key value 0x4C4F434B (“LOCK”) into the GPIO_LOCK register. The GPIO_CR register (Commit Register) then determines which pins can be altered.

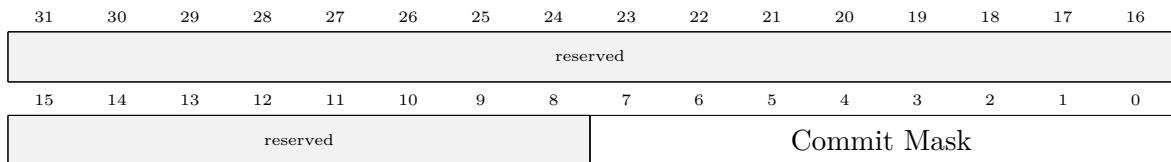


Figure 4.2: GPIO_CR Register — Commit Control

The following code unlocks Port F and enables modification of all pins.

```
LDR    R1, =0x40025520      ; GPIO_LOCK
LDR    R0, =0x4C4F434B      ; Unlock key
STR    R0, [R1]
LDR    R1, =0x40025524      ; GPIO_CR
MOV    R0, #0xFF            ; Allow changes to all pins
STR    R0, [R1]
```

Listing 4.3: Unlock Port F

In this experiment, PF0 is not used, so unlocking is optional. After unlocking, configuration registers such as direction and digital enable can be safely modified.

Step 3 — Configure Pin Direction

Register: GPIODIR (0x40025400) — GPIO Direction Control (Port F)

The GPIODIR register determines whether each GPIO pin functions as an input or an output. Writing '0' configures the pin as an input, while '1' configures it as an output.

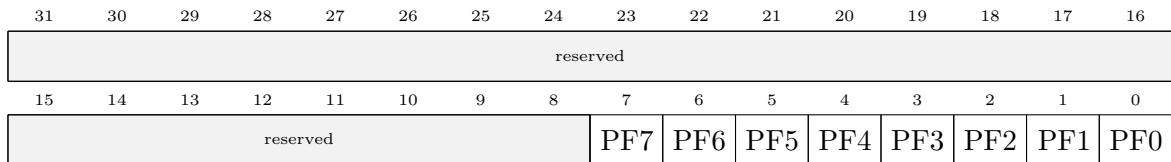


Figure 4.3: GPIODIR Register (Port F) — Direction Control

For the on-board RGB LED, PF1-PF3 must be configured as outputs. Bits 1-3 are therefore set to '1'.

```
LDR    R1, =0x40025400      ; GPIODIR register (Port F)
LDR    R0, [R1]
ORR    R0, R0, #0x0E        ; Set PF1, PF2, PF3 as outputs
STR    R0, [R1]
```

Listing 4.4: Set PF1, PF2, PF3 as outputs

Unmodified bits remain unchanged, allowing input pins (such as PF0 or PF4) to retain their default configuration.

Step 4 — Enable Digital Functionality

Register: GPIODEN (0x4002551C) — Digital Enable Register (Port F)

Each GPIO pin can serve analog or digital functions. The GPIODEN register enables the digital circuitry for selected pins. Pins configured as digital inputs or outputs must have their corresponding bits set to '1'.

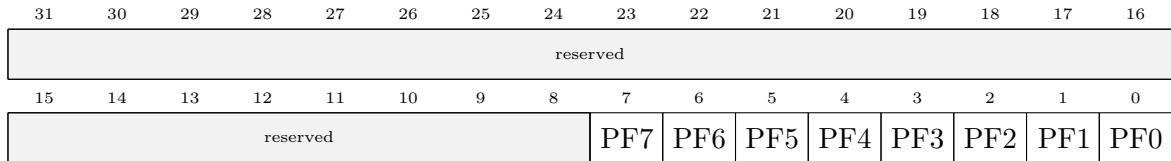


Figure 4.4: GPIODEN Register (Port F) — Digital Enable

Bits 1-3 are set to enable PF1-PF3 as digital outputs for the LED.

```
LDR    R1, =0x4002551C      ; GPIODEN register (Port F)
LDR    R0, [R1]
ORR    R0, R0, #0x0E        ; Enable PF1-PF3 as digital pins
STR    R0, [R1]
```

Listing 4.5: Enable digital function for PF1-PF3

Failing to enable GPIODEN leaves the pins electrically inactive even if their direction is set.

Step 5 — Write to the Data Register

Register: GPIO DATA (0x400253FC) — Data Input/Output Register (Port F)

The GPIO DATA register reflects the current logic levels on all GPIO pins. Writing to a bit drives the corresponding output high ('1') or low ('0'). Bits 1-3 correspond to the RGB LED pins on the LaunchPad: PF1 = Red, PF2 = Blue, PF3 = Green.

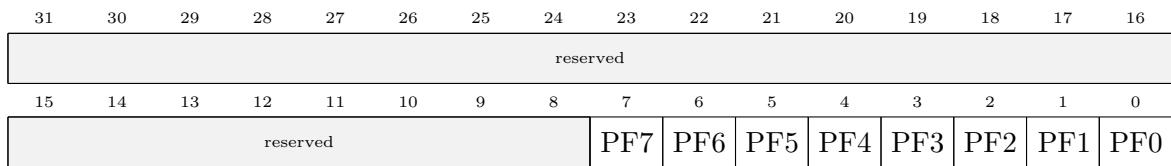


Figure 4.5: GPIO DATA Register (Port F) — Data Output/Input

The example below drives PF1 (Red) and PF3 (Green) simultaneously to produce a yellow color.

LDR	R1, =0x400253FC	; GPIO DATA register (Port F)
MOV	R0, #0xA	; Set PF1 (Red) and PF3 (Green) = Yellow
STR	R0, [R1]	

Listing 4.6: Turn on Yellow LED (Red + Green = PF1 + PF3)

By writing different bit combinations, various LED colors can be generated:

Color	Red (PF1)	Blue (PF2)	Green (PF3)	Hex	Combination
Red	●	○	○	0x02	Red only
Blue	○	●	○	0x04	Blue only
Green	○	○	●	0x08	Green only
Yellow	●	○	●	0x0A	Red + Green
Cyan	○	●	●	0x0C	Blue + Green
Magenta	●	●	○	0x06	Red + Blue
White	●	●	●	0x0E	All on

Table 4.5: LED Color Combinations on TM4C123 LaunchPad (PF1-PF3)

4.2 Procedure

4.2.1 Examples

The following examples illustrate the complete process of initializing Port F and controlling the on-board LEDs using Assembly language.

4.2.1.1 Example 1 — Simple LED Blink

This example initializes Port F and toggles the Red LED (PF1) on and off using address masking with a software delay. Address Masking for PF1:

$$0x40025000 + (0x02 \ll 2) = 0x40025008$$

```

AREA    RESET, CODE, READONLY      ; Code section
THUMB
EXPORT  __main                 ; Export symbol

__main PROC
    LDR    R1, =0x400FE608       ; RCGCGPIO address
    LDR    R0, [R1]                ; Read current value
    ORR    R0, R0, #0x20          ; Enable Port F clock
    STR    R0, [R1]                ; Write back
    NOP
    NOP

    LDR    R1, =0x40025400        ; GPIODIR address
    LDR    R0, [R1]                ; Read current value
    ORR    R0, R0, #0x02          ; Set PF1 as output
    STR    R0, [R1]                ; Write back

    LDR    R1, =0x4002551C        ; GPIODEN address
    LDR    R0, [R1]                ; Read current value
    ORR    R0, R0, #0x02          ; Enable digital function for PF1
    STR    R0, [R1]                ; Write back

loop   LDR    R1, =0x40025008        ; Masked DATA address for PF1
    MOV    R0, #0x02                ; Turn ON red LED (PF1)
    STR    R0, [R1]                ; Write to GPIODATA

    LDR    R0, =1000000            ; Load delay count
    BL     DELAY                  ; Call delay

    MOV    R0, #0x00                ; Turn OFF red LED (PF1)
    STR    R0, [R1]                ; Write to GPIODATA

    LDR    R0, =1000000            ; Load delay count
    BL     DELAY                  ; Call delay

    B     loop                   ; Repeat
ENDP

DELAY  PROC
    SUBS  R0, R0, #1              ; Decrement counter
    BNE   DELAY                  ; Loop until zero
    BX    LR                     ; Return
ENDP
END

```

Listing 4.7: Assembly code to blink the Red LED (PF1) on the TM4C123 LaunchPad

4.2.1.2 Example 2 — Cycle Through RGB Colors

This example extends the previous one by cycling through RGB LED colors (Red, Green, Blue) using a software delay. Address Masking for PF1, PF2, PF3:

$$0x40025000 + ((0x02 \mid 0x04 \mid 0x08) \ll 2) = 0x40025038$$

```

AREA    RESET, CODE, READONLY      ; Code section
THUMB
EXPORT  __main                 ; Export symbol
__main  PROC
        BL     PF_Init           ; Initialize Port F
loop
        LDR   R1, =0x40025038    ; Masked DATA address for PF1-PF3

        MOV   R0, #0x02            ; Turn ON red LED (PF1)
        STR   R0, [R1]              ; Write to GPIO DATA
        LDR   R0, =10000000          ; Load delay count
        BL    DELAY               ; Call delay

        MOV   R0, #0x04            ; Turn ON blue LED (PF2)
        STR   R0, [R1]
        LDR   R0, =10000000
        BL    DELAY

        MOV   R0, #0x08            ; Turn ON green LED (PF3)
        STR   R0, [R1]
        LDR   R0, =10000000
        BL    DELAY
        B     loop                ; Repeat
ENDP

DELAY   PROC
        SUBS  R0, R0, #1           ; Decrement counter
        BNE   DELAY               ; Loop until zero
        BX    LR                  ; Return
ENDP

PF_Init PROC
        LDR   R1, =0x400FE608     ; RCGCGPIO address
        LDR   R0, [R1]              ; Read current value
        ORR   R0, R0, #0x20         ; Enable Port F clock
        STR   R0, [R1]

        NOP
        NOP
        LDR   R1, =0x40025400     ; GPIO DIR address
        LDR   R0, [R1]
        ORR   R0, R0, #0x0E         ; Set PF1-PF3 as outputs
        STR   R0, [R1]

        LDR   R1, =0x4002551C     ; GPIO DEN address
        LDR   R0, [R1]
        ORR   R0, R0, #0x0E         ; Enable digital function for PF1-PF3
        STR   R0, [R1]
        BX    LR                  ; Return
ENDP
END

```

Listing 4.8: Assembly code to cycle through RGB colors on the TM4C123 LaunchPad

4.2.2 Tasks

4.2.2.1 Task 1 — Adjust the Blink Rate

Modify the delay routine in **Example 1** to change the blinking speed of the Red LED. Experiment with different delay values until the LED blinks at approximately **1 Hz** (about one second ON and one second OFF).

4.2.2.2 Task 2 — Cycle Through Multiple Colors

Expand **Example 2** to include additional colors by combining the Red, Green, and Blue LEDs. Create a program that automatically cycles through all color combinations listed in Table 4.5.

Hint: Use a loop to step through the color sequence repeatedly instead of writing separate code for each color.