

Part A

1. [Conceptual understanding; Easy; 4 marks]

- Memory-mapped I/O is where hardware registers used to control hardware peripherals are mapped into the address space of the system. [2 marks]
- Interacting with memory mapped I/O is typically achieved using pointers. [2 marks]

2. [Conceptual understanding; Easy; 2 marks]

- One mark for any of the following:
 - Can run concurrently to the rest of the system.
 - Reduced power consumption.
 - Lower latency
 - Predictable latency
 - Computation can be executed in parallel.

[2 marks]

3. [Conceptual understanding; Moderate; 2 marks]

- One mark for one of the following:
 - Memory latency.
 - Operating system task scheduling.
 - Unpredictable I/O Latency
 - Interrupts
- One mark for one of the following:
 - Embedded systems are often used in safety-critical applications where a task taking longer than expected can lead to missed deadlines with potentially fatal consequences.
 - For controlling systems it is typically essential to respond to events with predictable latency.

[1 mark]

4. [Conceptual understanding; Easy; 2 marks]

- One mark for any of the following:
 - Enter deep sleep states when the device is idle
 - Reduce the clock frequency of the device
 - Reduce sampling rate of ADC inputs
 - Disable unused modules
 - Use fixed-point arithmetic instead of floating-point
 - General code optimisations
 - Reduce the amount of DRAM

[2 marks]

Part B

5. [Coding; Moderate/Hard; 15 marks]

[15 marks]

- Example code:

```
void IRAM_ATTR crosswalk_button() {
    // ISR body
}

unsigned int * gpio_config = (unsigned int *) (0x30001000);
unsigned int * gpio_write = (unsigned int *) (0x30001000);
unsigned int * gpio_read = (unsigned int *) (0x30001000);

const int R_LED = 0;
const int Y_LED = 9;
const int G_LED = 10;
const int CWG_LED = 13;
const int CWR_LED = 14;

void setup() {
    // calls the ISR crosswalk_button when pin 5 goes high
    attachInterrupt(5, crosswalk_button, RISING);
    state = 0;

    // Set output GPIO pins
    *gpio_config = (1 << R_LED);
    *gpio_config = *gpio_config | (1 << Y_LED);
    *gpio_config = *gpio_config | (1 << G_LED);
    *gpio_config = *gpio_config | (1 << CWG_LED);
    *gpio_config = *gpio_config | (1 << CWR_LED);

    // alternatively
    // *gpio_config = 1 | (1 << 9) | (1 << 10) | (1 << 13) | (1 << 14);
}

unsigned int state = 0;

void loop() {

    if(state == 0) {

        *gpio_write = (1 << R_LED) | (1 << CWG_LED);

        delay(30000); // delay(N) delays execution by N milliseconds
        state = 1;
        return;
    }

    if(state == 1) {

        for(int i=0; i<4; i++) {
            *gpio_write = (1 << R_LED) | (1 << Y_LED) | (1 << CWG_LED);
            delay(250);
            *gpio_write = (1 << R_LED) | (1 << Y_LED);
            delay(250);
        }
    }
}
```

```

    }

    state = 2;
    return;
}

if(state == 2) {

    *gpio_write = (1 << G_LED) | (1 << CWR_LED);

    delay(30000);
    state = 3;
    return;
}

if(state == 3) {

    *gpio_write = (1 << Y_LED) | (1 << CWR_LED);

    delay(2000);
    state = 0;
    return;
}

// ERROR we are in an undefined state
// FLASH ALL THE LIGHTS
while(true) {
    *gpio_write = 0;
    delay(250);
    *gpio_write = (1 << R_LED) | (1 << Y_LED) |
                  (1 << G_LED) | (1 << CWG_LED) | (1 << CWR_LED);
    delay(250);
}
}

```

6. [Coding; Hard; 10 marks]

- Example code:

[10 marks]

```

unsigned int isr_fired = 0;

void IRAM_ATTR crosswalk_button() {
    // ISR body
    if( (state == 1) || (state == 2) ) {
        isr_fired = 1;
    }
}

unsigned int * gpio_config = (unsigned int *) (0x30001000);
unsigned int * gpio_write = (unsigned int *) (0x30001000);
unsigned int * gpio_read = (unsigned int *) (0x30001000);

const int R_LED = 0;
const int Y_LED = 9;

```

```

const int G_LED = 10;
const int CWG_LED = 13;
const int CWR_LED = 14;

void setup() {
    // calls the ISR crosswalk_button when pin 5 goes high
    attachInterrupt(5, crosswalk_button, RISING);
    state = 0;

    // Set output GPIO pins
    *gpio_config = (1 << R_LED);
    *gpio_config = *gpio_config | (1 << Y_LED);
    *gpio_config = *gpio_config | (1 << G_LED);
    *gpio_config = *gpio_config | (1 << CWG_LED);
    *gpio_config = *gpio_config | (1 << CWR_LED);

    // alternatively
    // *gpio_config = 1 | (1 << 9) | (1 << 10) | (1 << 13) | (1 << 14);
}

unsigned int state = 0;

void mod_delay(unsigned int in) {
    unsigned int start = millis();
    while( ~isr_fired || (start + in) > millis() ) { }
}

void loop() {

    if(state == 0) {

        *gpio_write = (1 << R_LED) | (1 << CWG_LED);

        delay(30000); // delay(N) delays execution by N milliseconds
        state = 1;
        return;
    }

    if(state == 1) {

        for(int i=0; i<4; i++) {
            *gpio_write = (1 << R_LED) | (1 << Y_LED) | (1 << CWG_LED);
            mod_delay(250);
            *gpio_write = (1 << R_LED) | (1 << Y_LED);
            mod_delay(250);
        }

        if(isr_fired) {
            state = 4;
            isr_fired = 0;
        } else {
            state = 2;
        }
    }
}

```

```

        return;
    }

    if(state == 2) {

        *gpio_write = (1 << G_LED) | (1 << CWR_LED);

        mod_delay(30000);

        if(isr_fired) {
            state = 4;
            isr_fired = 0;
        } else {
            state = 3;
        }
        return;
    }

    if(state == 3) {

        *gpio_write = (1 << Y_LED) | (1 << CWR_LED);

        delay(2000);
        state = 0;
        return;
    }

    if(state == 4) {
        // do stuff
        return;
    }

    // ERROR we are in an undefined state
    // FLASH ALL THE LIGHTS
    while(true) {
        *gpio_write = 0;
        delay(250);
        *gpio_write = (1 << R_LED) | (1 << Y_LED) |
                      (1 << G_LED) | (1 << CWG_LED) | (1 << CWR_LED);
        delay(250);
    }
}

```

Part C

7. [Conceptual understanding; Moderate; 3 marks]

- The highest resolution the timer can have is when the clock is running at it's fastest rate, $40MHz$. In this case the counter will increment every clock period $\frac{1}{40 \times 10^6} = 2.5 \times 10^{-8}s = 25ns$. **[3 marks]**

8. [Conceptual understanding; Moderate; 3 marks]

- To get the maximum period of time that this timer can measure we need to divide the clock by the highest amount that we can.

In this case **dival** is an 8-bit number meaning the maximum value we can divide the clock by is $2^8 - 1 = 255$.

Setting this divider value gives us a $divclk$ of $\frac{40MHz}{255} = 156862.75Hz$.

The counter is a 16-bit counter meaning that it can count to a maximum of $2^{16} - 1 = 65535$ cycles. Since our $divclk$ has a period of $1/156862.75 = 6.374\mu s$ the maximum value that this timer can count to is $(6.374 * 10^{-6}) * 65535 = 0.42seconds$. [3 marks]

9. [Coding; Hard; 10 marks]

- Example code:

[10 marks]

```
unsigned int* div_setup = (unsigned int*)(0xFFFF1000);
unsigned int* counter_setup = (unsigned int*)(0xFFFF1004);

void setup() {
    // counter increments every 2uS
    *counter_setup = 10000; // Set the maximum count to 10000

    // Set the alarm to be at the maximum counter value
    *counter_setup = *counter_setup | (10000 << 16);

    // Setup the clock divider and enable
    *div_setup = (1 << 31); // enables the timer
    *div_setup = *div_setup | (1 << 30); // enables the interrupt
    *div_setup = *div_setup | 80; // Divides the clock by 80
}
```

Solutions