Embedded Programming AVR

C++ for Developers

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- Bit Manipulation
- Using Bit Manipulation
- Typical program
- ATMega328p Architecture
- Including AVR files

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Numerical Bases

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Numerical Bases (Radixes)

A base (or radix) is the number of unique digits (including zero) used to represent numbers in a positional numeral system.

Where each position represents a power of the base.

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Base 10 (decimal)

The “normal” base we use in everyday life. We have 10 different digits used to describe a number.

For example 9372 in a base 10 system would be:

(9 x 10 ^ 3) + (3 x 10 ^ 2) + (7 x 10 ^ 1) + (2 x 10 ^ 0) =

(9 x 1000) + (3 x 100) + (7 x 10) + (2 x 1) =

9000 + 300 + 70 + 2 = 9372

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Base 2 (Binary)

In lower levels we often use the binary system. It works the same but with base 2. To describe the same number 9732 it would like this: 00**1**0 0**1**00 **1**00**1** **11**00

(0x2^15) + (0x2^14) + **(1x2^13)** + (0x2^12) + (0x2^11) + **(1x2^10)** + (0x2^9) + (0x2^8) + **(1x2^7)** + (0x2^6) + (0x2^5) + **(1x2^4)** + **(1x2^3)** + **(1x2^2)** + (0x2^1) + (0x2^0) =

8192 + 1024 + 128 + 16 + 8 + 4 = 9732

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Bits - Binary Digits

Common technology is based on the binary system where it is:
1 or 0
High or low
On or off

One byte = eight bits.

So for example when we declare an **int** which holds 4 bytes - it hold 32 bits in memory where the largest number can be:
1111 1111 1111 1111 1111 1111 1111 1111 or in decimal 4 294 967 295

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Signed / unsigned

Remember when we talked about signed and unsigned variables? This refers to the most significant bit (MSB) deciding if the number is positive(0) or negative(1) - signing the number. That's why an integer can hold a number between:

0111 1111 1111 1111 1111 1111 1111 1111 (2 147 483 647)
1000 0000 0000 0000 0000 0000 0000 0000 (- 2 147 483 647)

The negative number is written in what is called **two's complement**

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Base 16 (hexadecimal)

Also often used when coding embedded. Adds the digits : A(10) , B(11), C(12), D(13), E(14) and F(15) to the base 10 system. 9372 would look like this:

249C =

(2 x 16 ^ 3) + (4 x 16 ^ 2) + (9 x 16 ^ 1) + (C(12) x 16 ^ 0) =
(2 x 4096) + (4 x 256) + (9 x 16) + (12 x 1) =
8192 + 1024 + 144 + 12 = 9382

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Embedded use

Both base 2 (binary) and base 16 (hexadecimal) are commonly used in low-level code.
Memory addresses and hardware registers are often written in hexadecimal, using the prefix 0x to indicate that the value is base 16. For example: 0x00 or 0xFF.

In embedded systems, functionality is often controlled through flags (or bits) that can be either HIGH (1) or LOW (0).
Binary literals can be written directly in C++ using the prefix 0b, for example: 0b00101000

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Bit Manipulation

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What is bit manipulation?

This is a way to manipulate and read bits in a logical way.

For example:

Instead of having a boolean we can bit 16 booleans into an integer by reading each bit as a true or false value.

0010 0110 1100 0101

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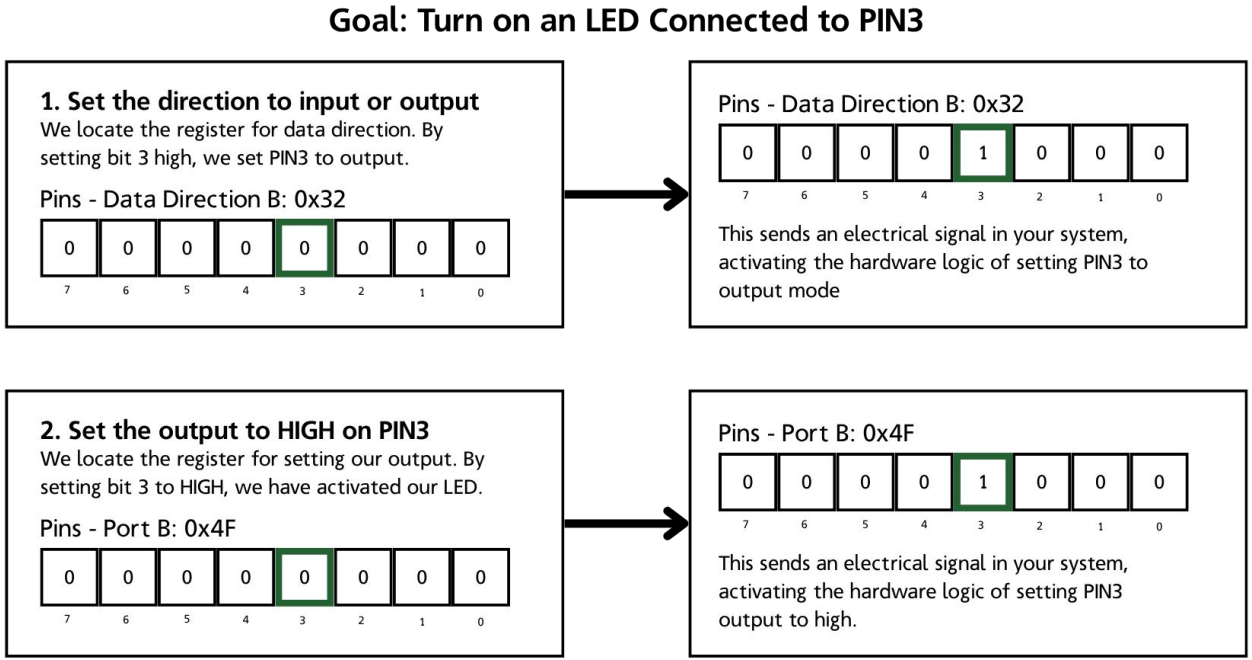
Example: Turning on a LED



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Registers

By using bit manipulation - we can set the registers in our MCU.

By setting bit number 3 to 1 - we have activated the functionality in our hardware.

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Shift operators

By using << or >> we “shift” the bits to the left (<<) or the right (>>).

0001 0110 << 2 = 0101 1000
0001 0110 << 3 = 1011 0000

If we take a look at the decimal values:
0010 0110 = 22
1001 1000 = 88 (22 * 2 ^ 2)
1011 0000 = 176 (22 * 2 ^ 3)

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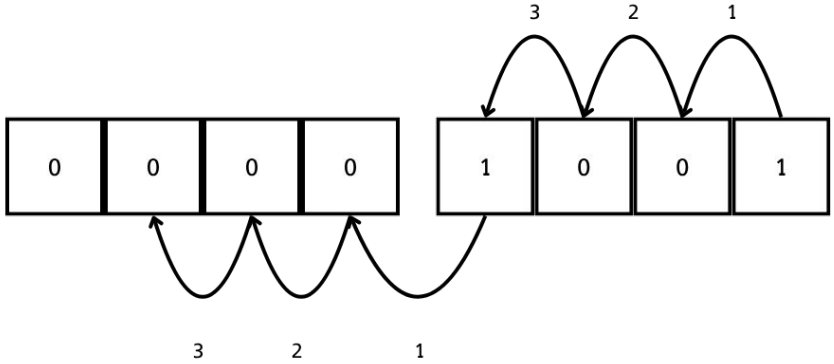
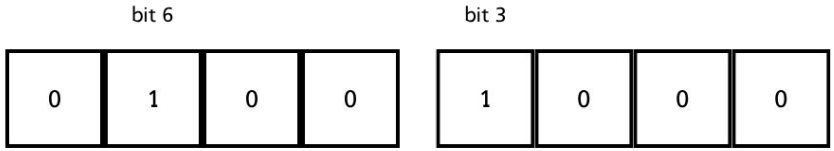
Statement: 9 << 3





Result: 72

Remembering the binary system:

1 * 2 ^ 6 + 1 * 2 ^ 3 =
64 + 8 =
72

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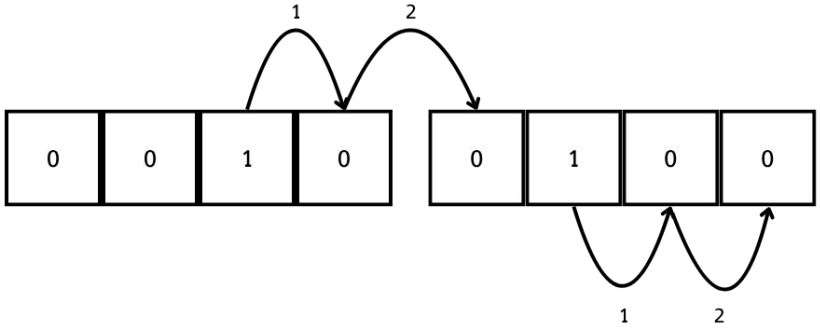
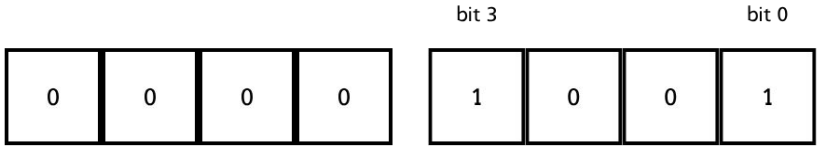
Statement: 36 >> 2





Result: 9

Remembering the binary system:

1 * 2 ^ 3 + 1 * 2 ^ 0 =
8 + 1 =
9

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Shift operators

We can now see that:

<< operator

- number * 2 ^ shift

>> operator

- number / 2 ^ shift

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Why are they used?

If we want to set bit five in a register, instead of writing:

- 32 (which in binary is 0x0010 0000, the third bit)
  How would we even do this dynamically?

We can instead target it by doing:

- 1 << 5 (which in binary also is 0x0010 0000)

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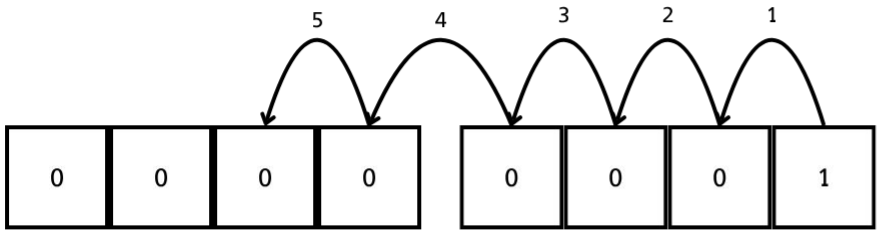
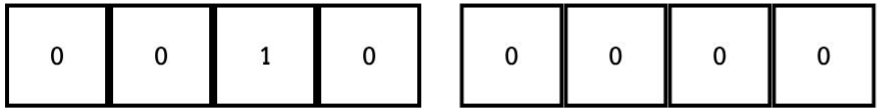
Setting a register would look like this

Statement: 1 << 5



Result: Bit 5 is now set!



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Boolean Operators

To further our bit manipulation, we make use of boolean operators.

- | *or*-operator. One need to be true
- & *and*-operator. Both need to be true
- ~ *not*-operator. Negate the statement
- ^ *xor*-operator. True if not equal

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| *or*-operator

Statement: 1010 | 0010

1	0	1	0	Number 1
0	0	1	0	Number 2
1 | 0	0 | 0	1 | 1	0 | 0	Comparison
1	0	1	0	Result

Returns 1 if any (or both) of the two comparing bits are 1. Otherwise 0.

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& *and*-operator

Statement: 1010 & 0010

1	0	1	0	Number 1
0	0	1	0	Number 2
1 & 0	0 & 0	1 & 1	0 & 0	Comparison
0	0	1	0	Result

Returns 1 if both of the two comparing bits are 1. Otherwise 0.

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~ *not*-operator

Statement: ~(1010 & 0010)

1	0	1	0	Number 1
0	0	1	0	Number 2
1 & 0	0 & 0	1 & 1	0 & 0	Comparison
0	0	1	0	Before negation
1	1	0	1	Result

Negates the the value.

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^ *xor*-operator

Statement: 1010 ^ 0010

1	0	1	0	Number 1
0	0	1	0	Number 2
1 ^ 0	0 ^ 0	1 ^ 1	0 ^ 0	Comparison
1	0	0	0	Result

Will return true if the comparing bits are different. False if they are equal.

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Implementation of bit manipulation

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Setting registers (or-operator)

```
// Set the data direction to output
DDRB |= (1 << LED_PIN);
```

DDRB is a register with 8 bits: 0000 0000
LED_PIN is PIN5 in this register.

To set it we:

- Bit shift: 0000 0001 << 5 = 0010 0000
- Use the or-operator: 0000 0000 | 0010 0000 = 0010 0000

Now we have set that bit in register!

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Unsetting registers (and- and not-operator)

```
// Set the output to low
PORTB &= ~(1 << LED_PIN);
```

PORTB is a register with 8 bits where bit number 5 is 1: 0010 0000

To unset it we:

- Bit shift: 0000 0001 << 5 = 0010 0000
- Use not-operator: ~(0010 0000) = 1101 1111
- Use and-operator: 0010 0000 & 1101 1111 = 0000 0000

If other bits where set in the register, they will not be changed!

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Toggling using the xor-operator

```
while(1) {
    PORTB ^= (1 << LED_PIN);
    _delay_ms(500);
}
```

While the loop runs we want to toggle the 5th bit in register PORTB.

If bit is set: 0010 0000

- shift operation result: 0010 0000
- xor-operation: 0010 0000 ^ 0010 0000 = 0000 0000.

Bit is now unset. This operation does not affect other bits in the register.

If bit is not set: 0000 0000

- shift operation result: 0010 0000
- xor-operation: 0000 0000 ^ 0010 0000 = 0010 0000.

Bit is now set.

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Reading input of a pin

```c
// GLOBALS
#define LED_PIN     PB5
#define BUTTON_PIN    PB4

int main(void) {

    // SETUP
    DDRB |= (1 << LED_PIN);
    PORTB &= ~(1 << LED_PIN);

    DDRB &= ~(1 << BUTTON_PIN);
    PORTB &= ~(1 << BUTTON_PIN);

    // SUPER LOOP
    while(1) {

        if (PINB & (1 << BUTTON_PIN)) {
            PORTB |= (1 << LED_PIN);
        } else {
            PORTB &= ~(1 << LED_PIN);
        }

        _delay_ms(5);
    }

    return 0;
}
```

```c
if (!(PINB & (1 << BUTTON_PIN))) {
    PORTB |= (1 << LED_PIN);
} else {
    PORTB &= ~(1 << LED_PIN);
}
```

Checking if pin5 is high, then button is pressed.

While not pressed:
PINB = 0000 0000
BTN = 0010 0000
PINB & BTN = false

While pressed:
PINB = 0010 0000
BTN = 0010 0000
PINB & BTN = true

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Embedded Bare Metal Structure

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File structure

- Global variables
- Setup
- Super-loop

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File structure

Global Variables

Declare variables used in the global scope

Setup

Initialize the components used in our program

Super-loop

The repeated task(s) performed by our MCU

```
#include <avr/io.h>
#include <avr/pgmspace.h>
#include <util/delay.h>

/*
GLOBAL VARIABLES
Declare and assign global variables.
*/

int main (void) {
    /*
    SETUP
    Initialize your drivers. This can include
    setting registers, setting a base state in
    other files and so on.
    */

    while(true) {
        /*
        SUPER-LOOP
        This is where the program runs until the MCU
        is turned off.
        */
    }

    // This point should never be reached
    return 0;
}
```

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Example LED program

- Defining my LED_PIN in global scope
- Setting up data direction and level
- Toggle the pin high and low

```c
#include <avr/io.h>
#include <avr/pgmspace.h>
#include <util/delay.h>

// GLOBALS
#define LED_PIN PB5

int main(void) {

    // SETUP
    DDRB |= (1 << LED_PIN);
    PORTB &= ~(1 << LED_PIN);

    // SUPER LOOP
    while(1) {
        PORTB ^= (1 << LED_PIN);
        _delay_ms(500);
    }

    return 0;
}
```

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ATMega328p Architecture

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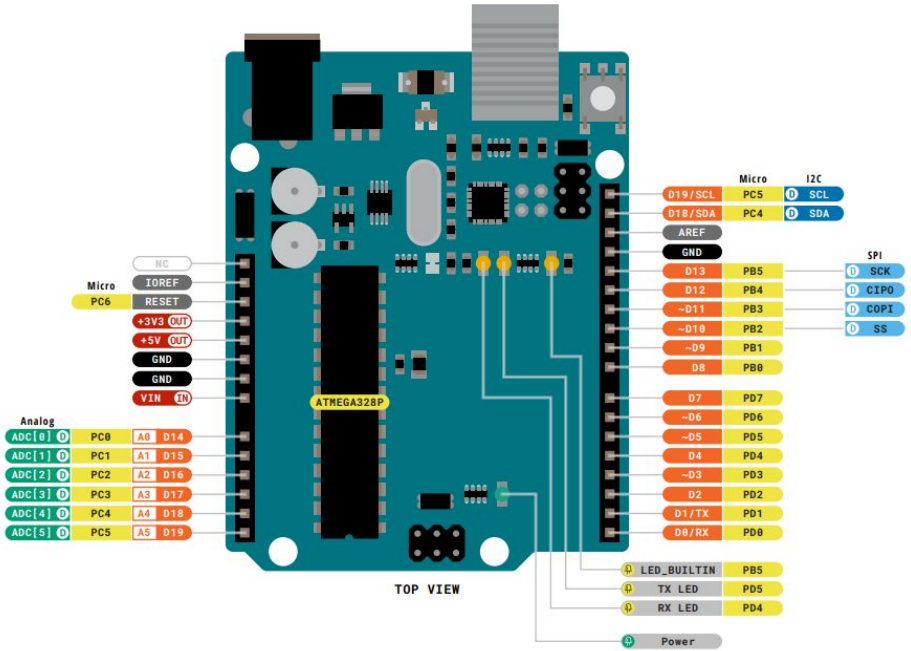
Pin out



Digital I/O

Can output or read HIGH/LOW

Analog Input

Can read voltage between 0 and 5V using ADC.

PWM

Can pulse at a set frequency, simulating different voltage outputs

Serial Communication

Specific pins connected to the peripherals used for different communication protocols.

Power Pins

5V, 3.3V and GND

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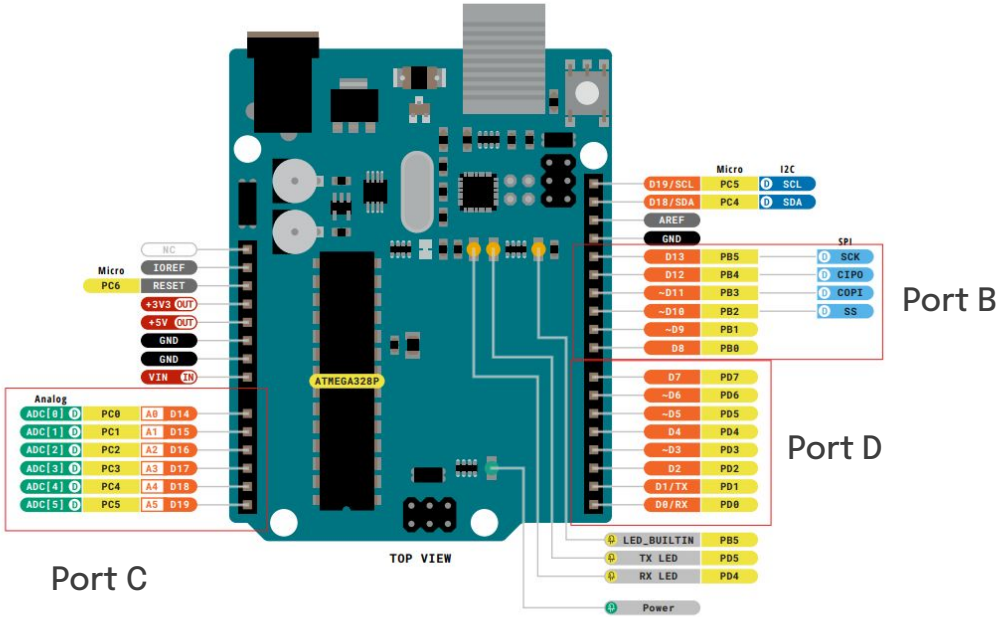
Pin out



Ports

Instead of controlling each pin separately through different registers - AVR designers grouped 8 pins together in blocks called **Ports**

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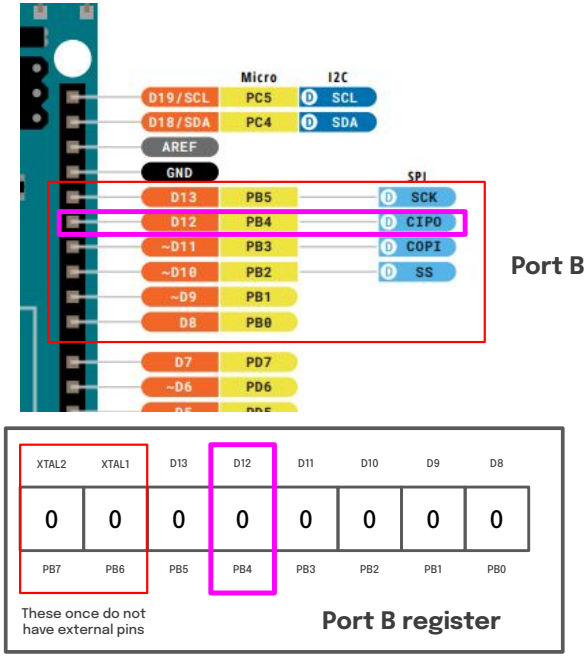
Pin out



Pin mapping

While the pins official name might be DIGITAL12 or GPIO12 - it is represented differently internally.

← In the example we can see that D8→D13 is mapped to PB(Port B) PB0→PB5.

This means that internally, D12 is actually represented as bit 4 in Port B.

The pin mapped names are actually included in the AVR library avr/io.h, so you can use PB4 in your program.

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Important registers for each PORT

You have the following registers which are good to keep track of. This example will use Port **B**.

- DDR**B** - Data Direction Register B
- PORT**B** - Depending on the Data Direction of the pin:
  - Enables/Disables internal pull-up resistor (handle floating values)
  - Sets pin HIGH/LOW
- PIN**B** - Check the current logical level of a physical pin

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Create an LED project

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Project: Light an LED while button is pressed

LED

- Set direction to output
- Set initializing output to 0

Button

- Set direction to input
- Disable internal pull-up resistor (we will have an external)
- Check if button is pushed

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1. Include the correct headers

Make sure to include the correct headers. For accessing the GPIOs on the ATmega328p and a blocking delay include:

```
#include <avr/io.h>
#include <avr/delay.h>
```

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2. Use defines to make the program more readable

After your includes, use defines to make your code more readable:

```
#include <avr/io.h>
#include <avr/pgmspace.h>
#include <util/delay.h>

// GLOBALS
#define LED_PIN     PB5
#define BUTTON_PIN    PB4

int main(void) {
```

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3. Initialize the LED

We set bit 5 in data direction register B to 1. Enabling output on GPIO13.

We then set bit 5 in the port register B to 0. Setting the output to low on GPIO13.

```
DDRB |= (1 << LED_PIN);
PORTB &= ~(1 << LED_PIN);
```

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4. Initialize the Button

We set bit 4 in data direction register B to 0. Setting GPIO12 to input mode.

We then set bit 4 in port register B to 0. Disabling the internal pull-up resistor for GPIO12.

```
DDRB &= ~(1 << BUTTON_PIN);
PORTB &= ~(1 << BUTTON_PIN);
```

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5. Logic in the super-loop

While(the mcu is powered on)

1. Check if the logical input on GPIO12 is high (bit 4 in the pin level register on port B).
   a. *If the logical input on GPIO12 is high*
      i. Set bit 5 in port register B to 1 - setting the output for GPIO13 to high.
   b. *Else*
      i. Unset bit 5 in port register B to 0 - setting the output for GPIO13 to low.
2. Wait 5 milliseconds

```
// SUPER LOOP
while(1) {

    if (PINB & (1 << BUTTON_PIN)) {
        PORTB |= (1 << LED_PIN);
    } else {
        PORTB &= ~(1 << LED_PIN);
    }

    _delay_ms(5);
}
```

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```c
#include <avr/io.h>
#include <avr/pgmspace.h>
#include <util/delay.h>

// GLOBALS
#define LED_PIN     PB5
#define BUTTON_PIN    PB4

int main(void) {

    // SETUP

    DDRB |= (1 << LED_PIN);
    PORTB &= ~(1 << LED_PIN);

    DDRB &= ~(1 << BUTTON_PIN);
    PORTB &= ~(1 << BUTTON_PIN);

    // SUPER LOOP
    while(1) {

        if (PINB & (1 << BUTTON_PIN)) {
            PORTB |= (1 << LED_PIN);
        } else {
            PORTB &= ~(1 << LED_PIN);
        }

        _delay_ms(5);
    }

    return 0;
}
```

Link to wokwi project:
https://wokwi.com/projects/445516715245466625

Link to GitHub project:
https://github.com/lafftale1999/cpp_for_developers/tree/main/week_5/3_use_cases_bit_manipulation/simple_led_project

Link to runnable .hex file:
https://drive.google.com/file/d/1J55hJkRvq13mgTq0UG6hni31FN5hQ3LG/view?usp=drive_link

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Try running the project

1. Download the .hex file
2. Open the wokwi project
3. Open the command palette:
    a. Right click in the code segment - press command palette
    b. Left click in the code segment and press F1
4. Click on "Upload Firmware and Start Simulation..."
5. Upload the .hex file you downloaded

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