Timing of Events

Suppose that we want produce a pulse on a digital line that was exactly 500 ms in length?

- What would the code look like?

Timing of Events

```
// Assume it is pin 0 of port B

PORTB = PORTB | 1;
delay_ms(500);
PORTB = PORTB & ~1;
```

Timing of Events

```
// Assume it is pin 0 of port B

PORTB = PORTB | 1;
delay_ms(500);
PORTB = PORTB & ~1;
```

This will work, but why is it undesirable?

Timing of Events

This will work, but why is it undesirable?

`delay_ms()` is implemented by using a for() loop

- The microcontroller can't do anything else while it is looping
- Have to loop a precise number of times (not always easy to do)

Timing of Events: Another Example

Suppose we would want to measure the width of a pulse. How would we implement this?

Timing of Events: Another Example

How would we implement this?

```
// Wait for pin to go high
while(PINB & 0x1 == 0){};

// Now count until it goes low
for(counter = 0; PINB & 0x1; ++counter)
{
  delay_ms(1);
}
// Now: counter is the width of
//   of the pulse in ms
```

Timing of Events: Another Example

Again: the program cannot be doing anything else while it is waiting

Counter/Timers in the Mega8

The mega8 incorporates three counter/timer devices in hardware. The mega2560 has these + 3 more

These can:

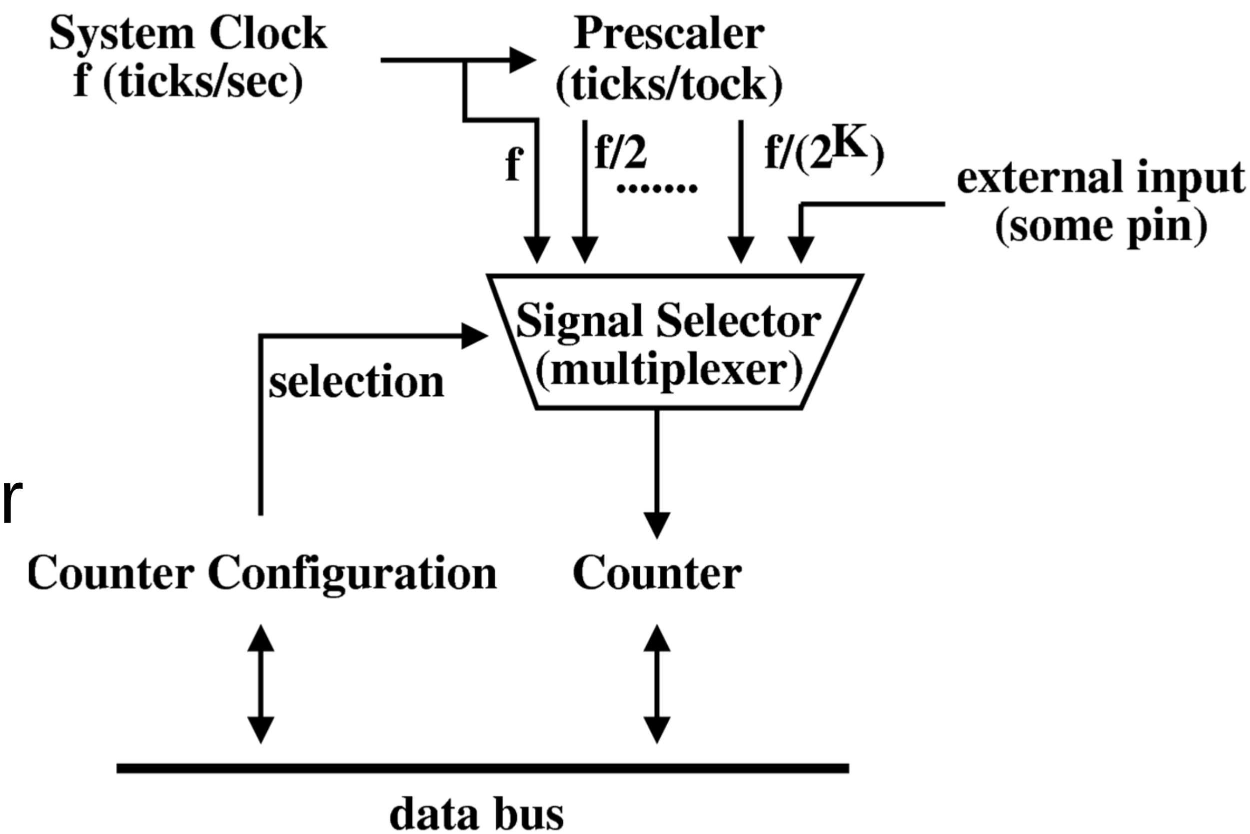
- Be used to count the number of events that have occurred (either external or internal)
- Act as a clock

Timer 0

- Possible input sources:
  - Pin T0 (PD4)
  - System clock
    - Potentially divided by a “prescaler”
- 8-bit counter
- When the counter turns over from 0xFF to 0x0, an interrupt (an event) can be generated (more on this next time)

Generic Timer Implementation

- Prescaler: divides clock frequency
- Multiplexer: selects one of the inputs to drive the counter
- Counter: increment on low-to-high transition of its input



Timer 0 (and Timer 1)

Possible prescalers:

- 8
- 64
- 256
- 1024

Timing Example

Suppose:

- f=16MHz clock
- Prescaler of 1024
- We wait for the timer to count from 0 to 156

How long does this take?

Timer 0 Example

$$delay = \frac{1024 * 156}{16{,}000{,}000} = 9948\ \mu s \approx 10\ ms$$

Timer 0 Code Example

```
timer0_config(TIMER0_PRE_1024);   // Init: Prescale by 1024

timer0_set(0);       // Set the counter to 0

<Do something else for a while>
while(timer0_read() < 156) {
   <Do something while waiting>
};

// Break out of while loop after ~10 ms
```

See Atmel HOWTO for example code (timer_demo2.c)

Timer 0 Example

Advantage over delay_ms():

- Can do other things while waiting
- Timing is much more precise
  – We no longer rely on a specific number of instructions to be executed

Timer 0 Example

One caution:

- “something else” cannot take very much time

(we have a solution for this – coming soon!)

Next Example

How do we time a delay of 100 usecs?

Next Example

How do we time a delay of 100 usecs?

$$counts * prescale = .0001 * clock\_freq$$
$$= .0001 * 16000000$$
$$= 1600$$

Next Example

How do we time a delay of 100 usecs?

$$counts * prescale = .0001 * clock\_freq$$
$$= .0001 * 16000000$$
$$= 1600$$
$$200 \quad * \quad 8 \quad = 1600$$
$$OR$$
$$25 \quad * \quad 64 \quad = 1600$$

Timer 0 Code Example

```
timer0_config(TIMER0_PRE_8);   // Init: Prescale by 1024

timer0_set(0);       // Set the timer to 0

<Do something else for a while>
while(timer0_read() < 200) {
   <Do something while waiting>
};

// Break out of while loop after ~100 us
```

Skip to interrupts…

Example 3: Timing the Width of a Pulse

- Input: port B, pin 1
- How long is the pin high?

Timing a Pulse Width: Our Original Implementation

```
// Wait for pin to go high
while(PINB & 0x1 == 0){};

// Now count until it goes low
for(counter = 0; PINB & 0x1; ++counter)
{
  delay_ms(1);
}
// Now: counter is the width of
//   of the pulse in ms
```

Example: Timing a Pulse Width

```
// Init: Prescale by 1024
timer0_config(TIMER0_PRE_1024);

// Wait for pin to go high
while(PINB & 0x2 == 0){
  <Do something while waiting>
};
timer0_set(0);       // Set the timer to 0

while((PINB & 0x2) != 0) {
  <Do something while waiting>
};
pulse_width = timer0_read();
```

Example: Timing a Pulse Width

What is the “resolution” of pulse_width?

Example: Timing a Pulse Width

What is the “resolution” of pulse_width?

- Each “tock” is:

$$delay = \frac{1024}{16,000,000} = 64\ \mu s$$

Example: Timing a Pulse Width

So, with pulse_width tocks:

$$delay = \frac{1024 * pulse\_width}{16{,}000{,}000} = 64 * pulse\_width\ \mu s$$

Example: Timing a Pulse Width

```
// Init: Prescale by 1024
timer0_config(TIMER0_PRE_1024);

// Wait for pin to go high
while(PINB & 0x2 == 0){
  <Do something while waiting>
};
timer0_set(0);        // Set the timer to 0

while((PINB & 0x2) != 0) {
  <Do something while waiting>
};
pulse_width = read_timer0();
```

Note: the longer "something" takes, the larger the possible error in timing

Other Timers Besides Timer 0

Timers 1, 3, 4, 5:

- 16 bit counter
- Prescalers: 1, 8, 64, 256, 1024

Timer 2:

- 8 bit counter
- Prescalers: 1, 8, 32, 64, 128, 256, 1024

Note

See oulib documentation for the list of possible prescalers for the timers

Interrupts

- Hardware mechanism that allows some event to temporarily interrupt an ongoing task
- The processor then executes a small piece of code called: **interrupt handler** or **interrupt service routine** (ISR)
- Execution then continues with the original program

Some Sources of Interrupts (Mega8)

External:

- An input pin changes state
- The UART receives a byte on a serial input

Internal:

- A clock
- Processor reset
- The on-board analog-to-digital converter completes its conversion

Interrupt Example

Suppose we are executing code from your main program:

LDS R1 (A) ← **PC**

LDS R2 (B)

CP R2, R1

BRGE 3

LDS R3 (D)

ADD R3, R1

STS (D), R3

An Example

Suppose we are executing code from your main program:

```
LDS R1 (A)
LDS R2 (B)   ← PC
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3
```

An Example

Suppose we are executing code from your main program:

LDS R1 (A)

LDS R2 (B)

CP R2, R1 ← **PC**

BRGE 3

LDS R3 (D)

ADD R3, R1

STS (D), R3

An Example

An interrupt occurs (EXT_INT1):

LDS R1 (A)

LDS R2 (B)

CP R2, R1 ← **PC**

BRGE 3

LDS R3 (D)

ADD R3, R1

STS (D), R3

An Example

Execute the interrupt handler

LDS R1 (A)

LDS R2 (B)

CP R2, R1

▶ BRGE 3 ← remember this location

LDS R3 (D)

ADD R3, R1

STS (D), R3

An Example

Execute the interrupt handler

LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3

PC

EXT_INT1:

LDS R1 (G)
LDS R5 (L)
ADD R1, R2
:
RETI

An Example

Execute the interrupt handler

LDS R1 (A)

LDS R2 (B)

CP R2, R1

▶ BRGE 3

LDS R3 (D)

ADD R3, R1

STS (D), R3

EXT_INT1:

LDS R1 (G)

PC → LDS R5 (L)

ADD R1, R2

:

RETI

An Example

Execute the interrupt handler

LDS R1 (A)
LDS R2 (B)
CP R2, R1
▶ BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3

EXT_INT1:

LDS R1 (G)
LDS R5 (L)
PC → ADD R1, R2
:
RETI

An Example

Execute the interrupt handler

LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3

EXT_INT1:

LDS R1 (G)
LDS R5 (L)
ADD R1, R2
:
RETI

PC

An Example

Return from interrupt

LDS R1 (A)

LDS R2 (B)

CP R2, R1

▶ BRGE 3

LDS R3 (D)

ADD R3, R1

STS (D), R3

EXT_INT1:

LDS R1 (G)

LDS R5 (L)

ADD R1, R2

:

PC → RETI

An Example

Return from interrupt

LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3 ← **PC**
LDS R3 (D)
ADD R3, R1
STS (D), R3

EXT_INT1:

LDS R1 (G)
LDS R5 (L)
ADD R1, R2
:
RETI

An Example

Continue execution with original

LDS R1 (A)

LDS R2 (B)

CP R2, R1

BRGE 3

LDS R3 (D) ← **PC**

ADD R3, R1

STS (D), R3

EXT_INT1:

LDS R1 (G)

LDS R5 (L)

ADD R1, R2

:

RETI

An Example

Continue execution with original

LDS R1 (A)

LDS R2 (B)

CP R2, R1

BRGE 3

LDS R3 (D)

ADD R3, R1 ← **PC**

STS (D), R3

EXT_INT1:

LDS R1 (G)

LDS R5 (L)

ADD R1, R2

:

RETI

Interrupt Routines

Generally a very small number of instructions

- We want a quick response so the processor can return to what it was originally doing
- No delays, waits, or floating point operations in the ISR…

Timer 0 Interrupt

We can configure the timer to generate an interrupt every time that the timer's counter "rolls over" from 0xFF to 0x00

Timer 0 Interrupt Example

Suppose:

- 16MHz clock
- Prescaler of 1024

How often is the interrupt generated?

Timer 0 Example

$$interval = \frac{1024 * 256}{16{,}000{,}000} = 16.384\ ms$$

Timer 0
Interrupt Service Routine (ISR)

An ISR is a type of function that is called when the interrupt is generated

```
ISR(TIMER0_OVF_vect) {
    // Toggle the LED attached to bit 0 of port B
    PORTB ^= 1;
};
```

What is the flash frequency?

Timer 0
Interrupt Service Routine (ISR)

```
ISR(TIMER0_OVF_vect) {
    // Toggle the LED attached to bit 0 of port B
    PORTB ^= 1;
};
```

What is the flash frequency?

$$frequency = \frac{16{,}000{,}000}{1024 * 256 * 2} = 30.5176\ Hz$$

Example I:
ISR Initialization in Main Program

```
// Interrupt occurs every (1024*256)/16000000 = .016384 seconds
timer0_config(TIMER0_PRE_1024);

// Enable the timer interrupt
timer0_enable();

// Enable global interrupts
sei();

 while(1) {
   // Do something else
 };
```

Timer 0 with Interrupts

This solution is particularly nice:

- “something else” does not have to worry about timing at all
- PB0 state is altered **asynchronously** from what is happening in the main program

Next Example: Timer 0 Example II

$$interval = \frac{1024 * 256}{16{,}000{,}000} = 16.384\ ms$$

How many interrupts do we need so that we toggle the state of PB0 every second?

Timer 0 Example II

How many interrupts do we need so that we toggle the state of PB0 every second?

$$counts = \frac{1000\ ms}{16.384\ ms} = 61.0352$$

We will assume 61 is close enough.

Example II: Interrupt Service Routine (ISR)

```
ISR(TIMER0_OVF_vect) {
    static uint8_t counter = 0;
    ++counter;
    if(counter == 61) {
        // Toggle output state every 61st interrupt:
        //  This means: on for ~1 second and then off for ~1 sec
        PORTB ^= 1;
        counter = 0;
    };
};
```

See Atmel HOWTO for example code (timer_demo.c)

Example II: Interrupt Service Routine (ISR)

```
uint8_t counter = 0;

ISR(TIMER0_OVF_vect) {
    ++counter;
    if(counter == 61) {
        // Toggle output state every 61st interrupt:
        //  This means: on for ~1 second and then off for ~1 sec
        PORTB ^= 1;
        counter = 0;
    };
};
```

See Atmel HOWTO for example code (timer_demo.c)

Example II: Initialization (same as before)

```
// Initialize counter
counter = 0;

// Interrupt occurs every (1024*256)/16000000 = .016384 seconds
timer0_config(TIMER0_PRE_1024);

// Enable the timer interrupt
timer0_enable();

// Enable global interrupts
sei();

 while(1) {
   // Do something else
 };
```

Timer 0 Example II

What is the flash frequency?

Timer 0 Example II

What is the flash frequency?

$$frequency = \frac{16{,}000{,}000}{1024 * 256 * 61 * 2} \approx 0.5\ Hz$$

- Skip to PWM

Interrupts and Timers

Timing can often involve a cascade of multiple counters:

- prescaler (1 … 1024)
- Timer0 (256)
- Counter within an interrupt routine (any)

Each counter implements a frequency division

Information Encoding

Many different options for encoding information for transmission to/from other devices:

- Parallel digital
- Serial digital (Project 2)
- Analog: use voltage to encode a value

Information Encoding

An alternative: pulse-width modulation (PWM)

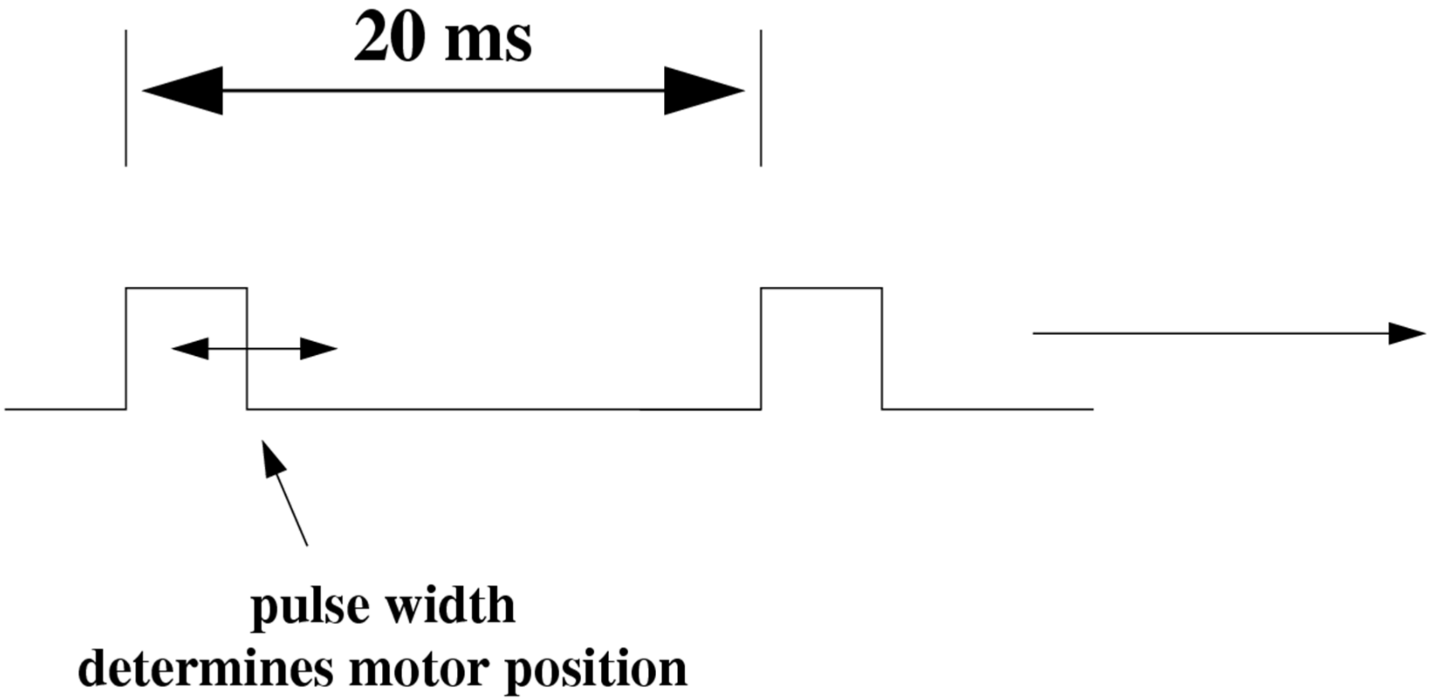
- Information is encoded in the time between the rising and falling edge of a pulse

PWM Example:

RC Servo Motors

- 3 pins: power (red), ground (black), and command signal (white)
- Signal pin expects a PWM signal

PWM Example



Internal circuit translates pulse width into a goal position:

- 0.5 ms: 0 degrees
- 1.5 ms: 180 degrees

RC Servo Motors

- Internal potentiometer measures the current orientation of the shaft
- Uses a **Position Servo Controller**: the difference between current and commanded shaft position determines shaft velocity.
- Mechanical stops limit the range of motion
  - These stops can be removed for unlimited rotation

PWM Example II: Controlling LED Brightness

What is the relationship of current flow through an LED and the rate of photon emission?

Controlling LED Brightness

What is the relationship of current flow through an LED and the rate of photon emission?

- They are linearly related (essentially)

Controlling LED Brightness

Suppose we pulse an LED for a given period of time with a digital signal: what is the relationship between pulse width and number of photons emitted?

Controlling LED Brightness

Suppose we pulse an LED for a given period of time with a digital signal: what is the relationship between pulse width and number of photons emitted?

- Again: they are linearly related (essentially)

- If the period is short enough, then the human eye will not be able to detect the flashes

Controlling LED Brightness

We need:

- To produce a periodic behavior, and
- A way to specify the pulse width (or the duty cycle)

How do we implement this in code?

Controlling LED Brightness

How do we implement this in code?

One way:

- Interrupt routine increments an 8-bit counter
- When the counter is 0, turn the LED on
- When the counter reaches some "duration", turn the LED off

Our Implementation I

```
volatile uint8_t duty = 0;

ISR(TIMER0_OVF_vect)
{
  static uint8_t counter = 255;

  ++ counter;
  if(counter == 0) PORTC |= 4;  // bit 2 high
  if(counter >= duty) PORTC &= ~4;  // b2 low

};
```

Our Implementation II

Another Implementation I

```
volatile uint8_t duration = 0;

ISR(TIMER0_OVF_vect)
{
  static uint8_t counter = 0;

  ++counter;
  if(counter >= duration)
      PORTB &= ~1;
  else if(counter == 0)
      PORTB |= 1;

}
```

Initialization Details

- Set up timer
- Enable interrupts
- Set duration in some way
  - In this case, we will slowly increase it

What does this implementation look like?

Initialization

```
int main(void) {
    DDRC = 0x04;
    PORTC = 0;

    duration = 0;

    // Interrupt configuration
    timer0_config(TIMER0_PRE8);  // Prescaler = 8

    // Enable the timer interrupt
    timer0_enable();

    // Enable global interrupts
    sei();
                :
```

PWM Implementation

What is the resolution (how long is one increment of “duration”)?

PWM Implementation

What is the resolution (how long is one increment of "duration")?

- The timer0 counter (8 bits) expires every 256 clock cycles

$$t = \frac{256}{16000000} = 16\ \mu s$$

(assuming a 16MHz clock)

PWM Implementation

What is the period of the pulse?

PWM Implementation

What is the period of the pulse?

- The 8-bit software counter expires every 256 interrupts

$$t = \frac{256 * 256}{16000000} = 4.096\ ms$$

Doing "Something Else"

```
        :
  unsigned int i;
  while(1) {
    for(i = 0; i < 256; ++i)
        duration = i;
        delay_ms(50);
    };
  };
}
```

ISR Example III

```
ISR(TIMER0_OVF_vect) {
    // Toggle the LED attached to bit 0 of port B
     PORTB ^= 1;
};

int main(void){
     timer0_config(TIMER0_PRE_8);
     timer0_enable();
     sei();

  while(1) {
    // Do something else
  };
```

What is the flash frequency?

Timer 0 Example III

What is the flash frequency?

$$frequency = \frac{16{,}000{,}000}{8 * 256 * 2} \approx 3.9\ KHz$$

ISR Example III:
How about this case?

```
ISR(TIMER0_OVF_vect) {
    // Toggle the LED attached to bit 0 of port B
    PORTB ^= 1;
    timer0_set(128);
};

int main(void){
    timer0_config(TIMER0_PRE_8);
    timer0_enable();
    sei();

  while(1) {
   // Do something else
  };
```

What is the flash frequency?

Timer 0 Example III

What is the flash frequency?

$$frequency = \frac{16{,}000{,}000}{8 * 128 * 2} \approx 7.8\ KHz$$

Hint: key trick for project 3

3 Different Timers

- Timer 0
- Timer 1
- Timer 2

Interrupt Service Routines

- Should be **very** short
  - No “delays”
  - No busy waiting
  - Function calls from the ISR should be short also
  - Minimize looping
  - No “printf()”
- Communication with the main program using global variables

Interrupts, Shared Data and Compiler Optimizations

- Compilers (including ours) will often optimize code in order to minimize execution time
- These optimizations often pose no problems, but can be problematic in the face of interrupts and shared data

Shared Data and Compiler Optimizations

For example:

```
A = A + 1;
C = B * A
```

Will result in ‘A’ being fetched from memory once (into a general-purpose register) – even though ‘A’ is used twice

Shared Data and Compiler Optimizations

Now consider:

```
while(1) {
    PORTB = A;
}
```

What does the compiler do with this?

Shared Data and Compiler Optimizations

The compiler will assume that ‘A’ never changes.

This will result in code that looks something like this:

```
R1 = A;  // Fetch value of A into register 1
while(1) {
   PORTB = R1;
}
```

The compiler only fetches A from memory once!

Shared Data and Compiler Optimizations

This optimization is generally fine – but consider the following interrupt routine:

```
ISR(TIMER0_OVF_vect){
  A = PIND;
}
```

Shared Data and Compiler Optimizations

This optimization is generally fine – but consider the following interrupt routine:

```
ISR(TIMER0_OVF_vect){
  A = PIND;
}
```

- The global variable ‘A’ is being changed!
- The compiler has no way to anticipate this

Shared Data and Compiler Optimizations

The fix: the programmer must tell the compiler that it is not allowed to assume that a memory location is not changing

- This is accomplished when we declare the global variable:

```
volatile uint8_t A;
```

Pulse-Width Modulation in Hardware

- The Atmel Mega processors will perform a wide-range of timing functions in hardware
- This includes the generation of pulse-width modulated signals
- Once configured, your main program need only to set the duty cycle of the PWM signal

Pulse-Width Modulation in Hardware

- Configuration includes:
  - Signal frequency (through the prescalers)
  - Signal polarity (high then low or vice-versa)
  - Resolution for specifying the duty cycle
- Use:
  - You need only specify changes to the duty cycle

PWM on the Atmel Mega2560s

Timers 1, 3, 4, 5: each have 3 PWM output channels associated with them (known as A, B, and C)

For our example here:

- Use 10 bits of the 16 available with the counter
- Counter counts from 0 to 1023, and then back to 0
- Output goes high at 0
- Output goes low at specified count
  - Specified by the “output compare” register

Initialization Example (Timer 4)

```
int main(void){
   // The timer 4 channel A pin is labeled “OC4A” on the Arduino
   //   circuit diagram
   DDRH = 0x8;

   // tocks/sec = 2,000,000/sec (with a 16,000,000 ticks/sec clock)
   timer4_config(TIMER4_PRE_8);

   // Configure for 10-bit PWM
   timer4_output_compare_config(TIMER4_OUTPUT_COMPARE_CONFIG_PWM_F_10);

   // Configure timer 4, channel A for PWM: high then low
   timer4_compare_output_A_mode_set(TIMER16B_COMPARE_OUTPUT_MODE_CLEAR);
   :
   :
```

Use Example

```
:
:
int16_t i;

 // Loop forever
while(1) {

     // Slowly increase the duty cycle on channel A
     for(i=0; i < 1024; ++i) {
             timer4_output_compare_A_set(i);
             delay_ms(1);
     };

     // Slowly bring the duty cycle back to zero
     for(i=1023; i > 0; --i) {
             timer4_output_compare_A_set(i);
             delay_ms(1);
     };
};
```

See examples_2560/pwm for more details