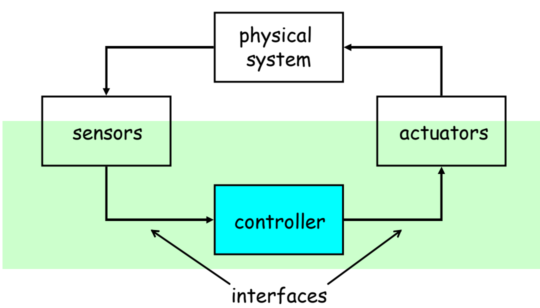
Interfacing

- Connecting the computation capabilities of a microcontroller to external signals
  - Transforming variable values into voltages and vice-versa
  - Digital and analog
- Issues
  - How many signals can be controlled?
  - How can digital and/or analog inputs be used to measure different physical phenomena?
  - How can digital and/or analog inputs be used to control different physical phenomena?

Controlling and reacting to the environment

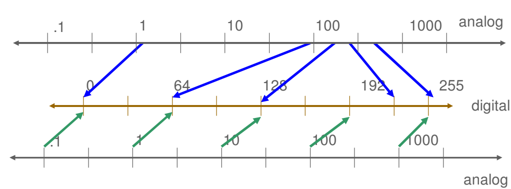
- To control or react to the environment we need to interface the microcontroller to peripheral devices
  - Microcontroller may contain specialized interfaces to sensors and actuators
- Things we want to measure or control
  - light, temperature, sound, pressure, velocity, position
- Sensors
  - e.g., switches, photoresistors, accelerometers, compass, sonar
- Actuators
  - e.g., motors, relays, LEDs, sonar, displays, buzzers

Typical control system



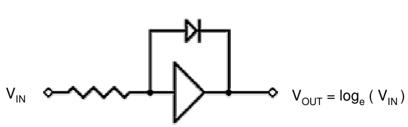
Analog to digital conversion

- Map analog inputs to a range of binary values
  - 8-bit A/D has outputs in range 0-255
- What if we need more information?
  - linear vs. logarithmic mappings
  - larger range of outputs (16-bit a/d)



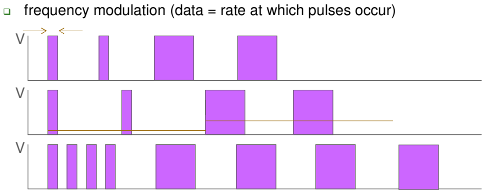
Logarithm of a signal

- Usually use an op-amp circuit
- Often found as a pre-amplifier to ADC circuitry
- Simple circuit to computer natural logarithm



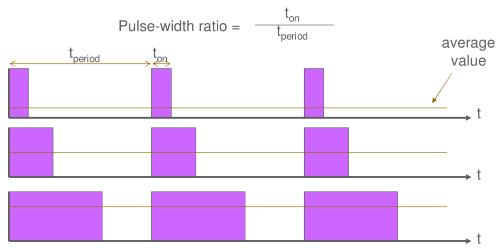
Digital to analog conversion

- Map binary values to analog outputs (voltages)
- Most devices have a digital interface – use time to encode value
- Time-varying digital signals – almost arbitrary resolution
  - pulse-code modulation (data = number or width of pulses)
  - pulse-width modulation (data = duty-cycle of pulses)
  - frequency modulation (data = rate at which pulses occur)



Pulse-width modulation

- Pulse a digital signal to get an average “analog” value
- The longer the pulse width, the higher the voltage



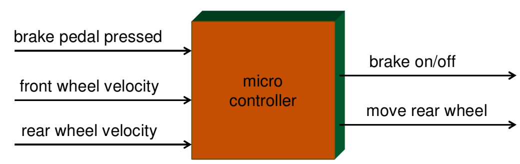
Why pulse-width modulation works

- Most mechanical systems are low-pass filters
  - Consider frequency components of pulse-width modulated signal
  - Low frequency components affect components
    - They pass through
  - High frequency components are too fast to fight inertia
    - They are “filtered out”
- Electrical RC-networks are low-pass filters
  - Time constant (τ = RC) sets “cutoff” frequency that separates low and high frequencies

Anti-lock brake system

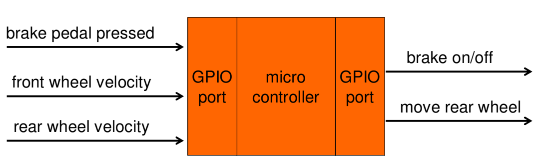
- Rear wheel controller/anti-lock brake system
  - Normal operation
    - Regulate velocity of rear wheel
  - Brake pressed
    - Gradually increase amount of breaking
    - If skidding (front wheel is moving much faster than rear wheel) then temporarily reduce amount of breaking
- Inputs
  - Brake pedal
  - Front wheel speed
  - Rear wheel speed
- Outputs
  - Pulse-width modulation rear wheel velocity
  - Pulse-width modulation brake on/off

Rear wheel controller/anti-lock brake system



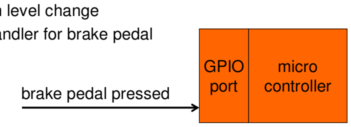
Basic I/O ports (brakes)

- Check if brake pedal pressed – or interrupt
  - brakePressed = read (brakePedalPort)
- Turn brake on/off
  - write (brakePort, onOff)
- Move rear wheel
  - write (rearWheel, onOff)



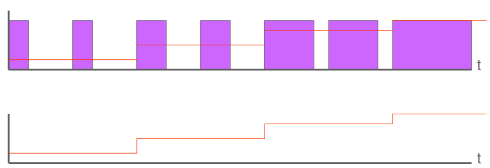
Polling vs. interrupts

- Software must repeatedly check
  - Brake pedal port
  - How often?
  - Need to make sure not to forget to do so (use timer)
- Use automatic detection capability of processor
  - Connect brake pedal to input capture or external interrupt pin
  - Interrupt on level change
  - Interrupt handler for brake pedal



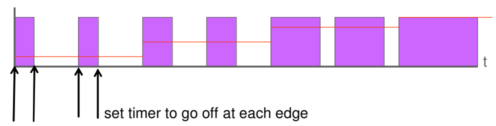
Pulse-width modulation for brakes

- To pump the brakes gradually increase the duty-cycle (t_{on}) until car stops



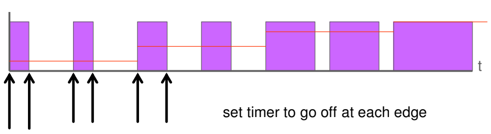
Brake pump setup

- Use timer to turn brake on and off
  - Apply brake
  - Set timer to interrupt after "on" time
  - Disengage brake
  - Set time to interrupt after "off" time
  - Repeat
- How do we tell which interrupt is which?



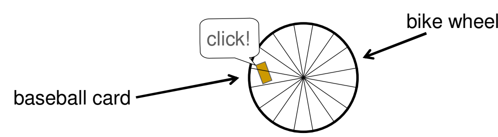
Brake pump setup (cont'd)

- Change value of "on" time to change analog average
  - average output = (on + off) / (period)
- How do we decide on the period of the pulses?
- Using two timers
  - One to set period (auto-reload)
  - One to turn it off at the right duty cycle



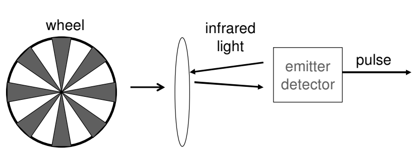
Shaft encoders

- Need to determine the rear wheel velocity
  - Use sensor to detect wheel moving
- Determine speed of a bicycle
  - Attach baseball card so it pokes through spokes
  - Number of spokes is known
  - Count clicks per unit time to get velocity
- Baseball card sensor is a shaft encoder



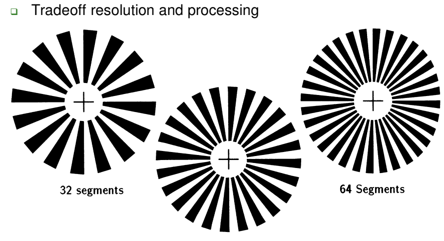
Shaft encoders

- Instead of spokes we'll use black and white segments
- Black segments absorb infrared light, white reflects
- Count pulses instead of clicks



IR reflective patterns

- How many segments should be used?
  - More segments give finer resolution
  - Fewer segments require less processing
  - Tradeoff resolution and processing



Interfacing shaft encoders

- Use interrupt on GPIO pin
  - Every interrupt, increment counter
- Use timer to set period for counting
  - When timer interrupts, read GPIO pin counter
  - velocity = counter * “known distance per click” / “judiciously chosen period”
  - Reset counter
- Pulse accumulator function
  - Common function
  - Some microcontrollers have this in a single peripheral device
  - Basically a counter controlled by an outside signal
    - Signal might enable counter to count at rate of internal clock – to measure time
    - Signal might be the counter’s clock – to measure pulses
  - ATmega16 has external clock source for timer/counter

General interfaces to microcontrollers

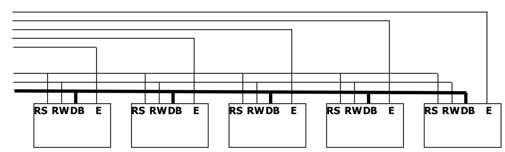
- Microcontrollers come with built-in I/O devices
  - Timers/counters
  - GPIO
  - ADC
  - Etc.
- Sometimes we need more . . .
- Options
  - Get a microcontroller with a different mix of I/O
  - Get a microcontroller with expansion capability
    - Parallel memory bus (address and data) exposed to the outside world
    - Serial communication to the outside world

I/O ports

- The are never enough I/O ports
- Techniques for creating more ports
  - port sharing with simple glue logic
  - decoders/multiplexors
  - memory-mapped I/O
  - port expansion units
- Direction of ports is important
  - single direction port easier to implement
  - timing important for bidirectional ports

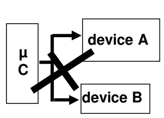
Port sharing

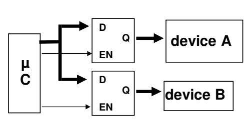
- If signals all in same direction and have a separate guard signal, then able to share without glue logic
- Example: connect 5 LCD displays to microcontroller
  - can share connections to RS, RW, and DB but not E
  - changes on E affect display – must guarantee only one is active



Forced sharing

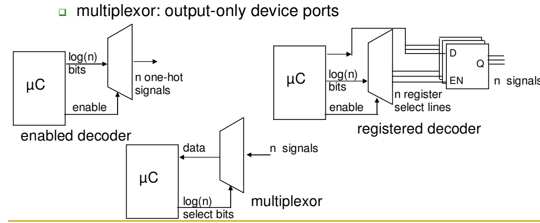
- Conflict on device signals (e.g., one signal affects both)
  - solution is to insert intervening registers that keep signals stable
  - registers require enable signals which now need ports as well





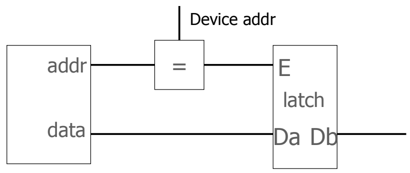
Decoders and multiplexors

- Encode n single-bit device ports using log n bits of a controller port
  - enabled decoder: one-hot, input-only device ports
  - registered decoder: input-only (but not one-hot) device ports
  - multiplexor: output-only device ports



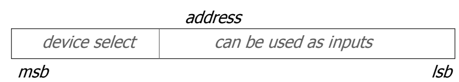
Memory-mapped I/O

- Address bus selects device
- Data bus contains data



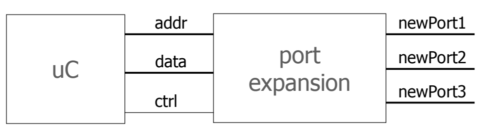
Memory-mapped I/O

- Partition the address space
- Assign memory-mapped locations
- Software
  - loads read from the device
  - stores write to the device
- Can exploit unused bits for device input-only ports



Port expansion units

- Problem of port shortage so common port expansion chips exist
- Easily connect to the microprocessor
- Timing on ports may be slightly different
- May not support interrupts

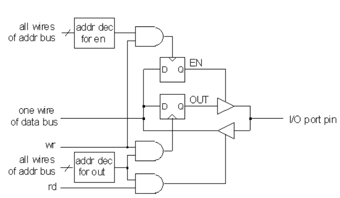


Connecting to the outside world

- Exploit specialized functions (e.g., UART, timers)
- Attempt to connect directly to a device port without adding interface hardware (e.g., registers), try to share registers if possible but beware of unwanted interactions if a signal goes to more than one device
- If out of ports, must force sharing by adding hardware to make a dedicated port sharable (e.g., adding registers and enable signals for the registers)
- If still run out of ports, then most encode signals to increase bandwidth (e.g., use decoders)
- If all else fails, then backup position is memory-mapped I/O, i.e., what we would have done if we had a bare microprocessor

64-bit General-purpose I/O port

- Suppose we wanted a 64-bit I/O port
- If EN is true, then we have an output pin
- If EN is false, then we have an input pin

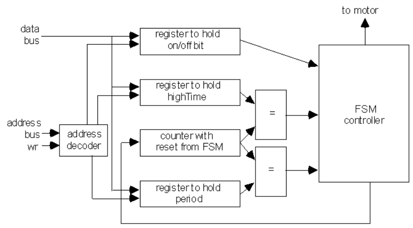


64-bit I/O port software

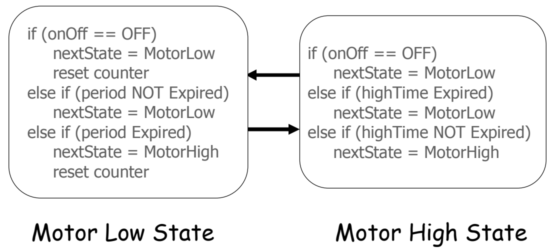
- We need 8 8-bit registers to store/write the 64 bits
  - Select the EN addresses to be $...000 to $...007
  - Select OUT addresses to be $...010 to $...017
- Read 15th bit
  - load value at address $...011 (2nd set of OUT regs)
  - logical AND with 0x80
  - bit position 7 of result is 15th bit
- Write the 47th bit
  - read OUT register at $...015
  - set bit position 7 to desired value (or with 0x80)
  - store in $...015
  - load EN register at $...005
  - set bit to output
  - store value back to $...005

External PWM Unit

- Design a system to control a digital
- Solution: design a PWM unit



External PWM FSM Controller



External PWM software

```
// in initialization code
Write off to onOff register

// do some stuff

// set up PWM
Repeat for each motor
   Write highTime and period registers

// turn motors on
Repeat for each motor
   Write on to the onOFF register

// more stuff
```


Some example I/O devices

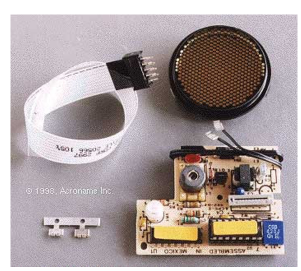
- Sonar range finder
- Compass
- IR proximity detector
- Accelerometer
- Bright LED

Sonar range finder

- Uses ultra-sound (not audible) to measure distance
- Time echo return
- Sound travels at approximately 343m/sec
  - need at least a 34.3kHz timer for cm resolution
- One simple echo not enough
  - many possible reflections
  - want to take multiple readings for high accuracy

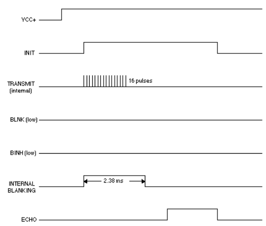
Polaroid 6500 sonar range finder

- Commonly found on old Polaroid cameras, now a frequently used part in mobile robots
- Transducer (gold disc)
  - charged up to high voltage and “snapped”
  - disc stays sentisized so it can detect echo (acts as microphone)
- Controller board
  - high-voltage circuitry to prepare disc for transmitting and then receiving



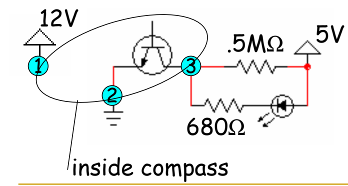
Polaroid 6500 sonar range finder (cont'd)

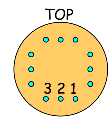
- Only need to connect two pins to microcontroller
  - INIT - start transmitting
  - ECHO - return signal
- Some important information from data sheet
  - INIT requires large current (greater than microcontroller can provide – add external buffer/amplifier)
  - ECHO requires a pull-up resistor (determine current that needs to flow into microcontroller pin - size resistor so proper voltage is on pin



Compass

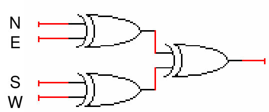
- Four compass directions (each has three pins)
- One-hot/two-hot encoding
  - one-hot for N, E, S, W
  - two-hot for NE, SE, SW, NW





Compass (cont'd)

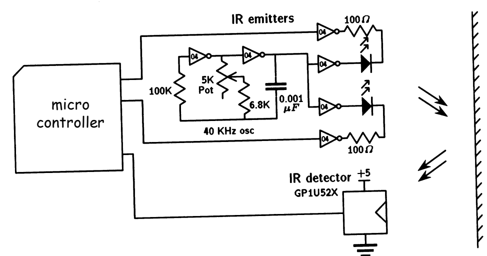
- Detecting a change in compass direction
  - 4 bits change from 0001 to 0011 to 0010 to 0110 to 0100 …
  - Always alternating between one bit on and two bits on
- Parity tree can detect difference between one and two bits being asserted
  - XOR tree of four bits (one TTL SSI package)
  - Output must change at least once for every change in orientation
  - Use interrupts to detect changes



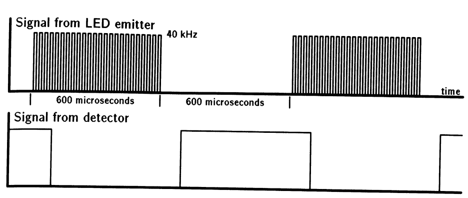
e.g.,
NE → E → SE
1100 → 0100 → 0110
0 → 1 → 0

IR proximity detector

- Oscillator must be set to match detector



IR frequency modulation



Proximity code

```
turn on emitter
sleep for 600us                  timer goes off
val_on = read detector           wake
turn off emitter
sleep for 600us                  timer goes off
val_off = read detector          wake
return ( val_on & ~val_off )
```

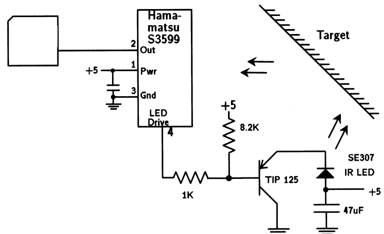
Mostly in main

Using interrupt handlers

```
turn on emitter
set timer
sleep              timer goes off
                   val_on = read detector
                   turn off emitter
                   reset timer
                   sleep              timer goes off (again)
                                      val_off = read detector
return ( val_on & ~val_off )          wake
```

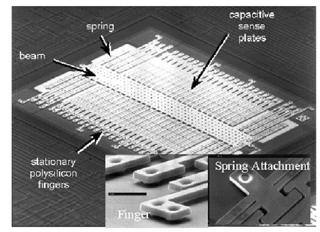
More integrated proximity detector

- Always sending out IR
- Detector drives LED (guaranteed to match frequency)



Accelerometer

- Micro-electro-mechanical system that measures force
  - F = ma (I. Newton)
  - Measured as change in capacitance between moving plates
  - Designed for a maximum g-force (e.g., 2-10g)
  - 2-axis and 3-axis versions
  - Used in airbags, laptop disk drives, etc.

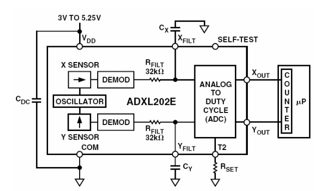


Accelerometer output

- Analog output too susceptible to noise
- Digital output requires many pins for precision
- Use pulse-width modulation
- What about gravity?

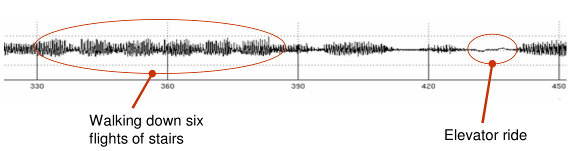
Analog Devices ADXL202

- 2-axis accelerometer
  - Set 0g at 50% duty-cycle
  - Positive acceleration increases duty cycle
  - Negative acceleration decreases duty cycle
  - 12.5% per g in either direction



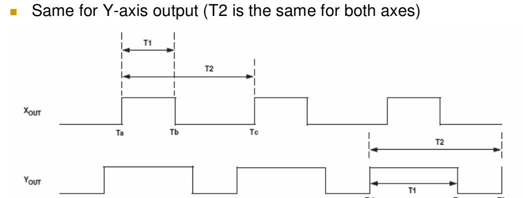
Typical measurement for ADXL202

- Noisy data – all forces are aggregated by accelerometer
- Sample trace at 250Hz



Typical signal from ADXL202

- Cause interrupts at Ta, Tb, and Tc from X-axis output
- 1. Look for rising edge, reset counter: Ta = 0
- 2. Look for falling edge, record timer: Tb = positive duty cycle
- 3. Look for rising edge, record timer, reset counter: Tc = period
- Repeat from 2
- Same for Y-axis output (T2 is the same for both axes)

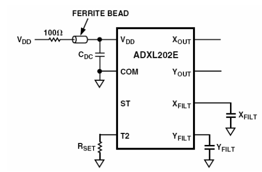


What to do about noise/jitter?

- Average over time – smoothing
  - Software filter – like switch debouncing
- Take several readings
  - use average for Tb and Tc or their ratio
- Running average so that a reading is available at all times
  - e.g., update running average of 4 readings
    current average = ¾ * current average + ¼ * new reading
- Take readings of both Tb and Tc to be extra careful
  - Tc changes with temperature
  - Usually can do Tc just once

Built-in filter

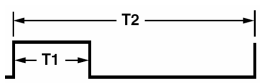
- Filter capacitors limited noise frequency
  - bandwidth limiting



Bandwidth	Capacitor Value
10 Hz	0.47 µF
50 Hz	0.10 µF
100 Hz	0.05 µF
200 Hz	0.027 µF
500 Hz	0.01 µF
5 kHz	0.001 µF

ADXL202 Output

- Accelerometer duty cycle varies with force
- 12.5% for each g
- R_{SET} determines duration of period
- At 1g duty-cycle will be 62.5% (37.5%)

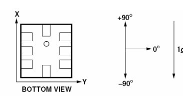


A(*g*) = (T1/T2 – 0.5)/12.5%
0*g* = 50% DUTY CYCLE
T2(s) = R_{SET}(Ω)/125MΩ

T2	R_{SET}
1 ms	125 kΩ
2 ms	250 kΩ
5 ms	625 kΩ
10 ms	1.25 MΩ

ADXL202 Orientation

- Sensitivity (maximum duty cycle change per degree) is highest when accelerometer is perpendicular to gravity



X Axis Orientation to Horizon (°)	X Output: X Output (g)	X Output: Δ per Degree of Tilt (mg)	Y Output (g): Y Output (g)	Y Output (g): Δ per Degree of Tilt (mg)
–90	–1.000	–0.2	0.000	17.5
–75	–0.966	4.4	0.259	16.9
–60	–0.866	8.6	0.500	15.2
–45	–0.707	12.2	0.707	12.4
–30	–0.500	15.0	0.866	8.9
–15	–0.259	16.8	0.966	4.7
0	0.000	17.5	1.000	0.2
15	0.259	16.9	0.966	–4.4
30	0.500	15.2	0.866	–8.6
45	0.707	12.4	0.707	–12.2
60	0.866	8.9	0.500	–15.0
75	0.966	4.7	0.259	–16.8
90	1.000	0.2	0.000	–17.5

PWM Calculations

- How big a counter do you need?
- Assume 7.37MHz clock
- 1ms period yields a count of 7370
  - This fits in a 16-bit timer/counter
- Should you use a prescaler for the counter?
- Bit precision issues

```
unsigned int positive;
unsigned int period;
unsigned int pos_duty_cycle;

BAD:
   pos_duty_cycle = positive/period;
BAD:
   pos_duty_cycle = ( positive * 1000 ) / period;
OKAY:
   pos_duty_cycle = ( (long) positive * 1000 ) / period;
```


Bright LED

- Easy to control intensity of light through pulse-width modulation
- Duty-cycle is averaged by human eye
  - Light is really turning on and off each period
  - Too quickly for human retina (or most video cameras)
  - Period must be short enough (< 1ms is a sure bet)
- LED output is low to turn on light, high to turn it off
  - Active low output

Sample code for LED

- Varying PWM output

```
volatile uint8_t width; /* positive pusle width */
volatile uint8_t delay; /* used to slow the pulse width changing */

SIGNAL (SIG_OVERFLOW2)
{
    if(delay++ == 20) { OCR2 = width++; delay = 0; }
}

int main (void)
{
    /* must make OC2 pin an output for the PWM to visible */
    DDRD = _BV(DDD7);
    /* use Timer 2 FastPWM and the overflow interrupt to update duty-cycle */
    TCCR2 = _BV (WGM21) | _BV (WGM20) | _BV (COM21) | _BV(COM20) | _BV(CS21) | _BV(CS20);
    TIMSK = _BV (TOIE2);
    /* setup initial conditions */
    delay = 0;
    /* enable interrupts */
    sei ();
    for (;;)
    { ; /* LOOP FOREVER as the interrupt will make necessary adjustment */ }
    return (0);
}
```


Fast PWM