

05: PWM

Microcontrollers

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PWM

Modes of operation for timers

Timers can

- ▶ count upwards or downwards,
- ▶ fire IRQs on overflows or when certain values are matched,
- ▶ and manipulate pin levels on these events.

→ This gives rise to different modes of operation.

The three timers of the ATmega32 provide at least four modes:

- ▶ Normal mode
We used this mode in the example of the periodic timer interrupt every 1024 μ s.
- ▶ Clear Timer on Compare Match (CTC) mode
- ▶ Single slope PWM mode
- ▶ Phase correct PWM mode

Output compare

Do something when TCNT matches with the **Output Compare Register (OCR)**.

- ▶ Raise an interrupt
- ▶ Clear TCNT register
- ▶ Change the **output compare pin (OC)**, e.g., toggle pin to generate a square wave.¹

Can be used to generate a **pulse-width modulation (PWM)** signal.

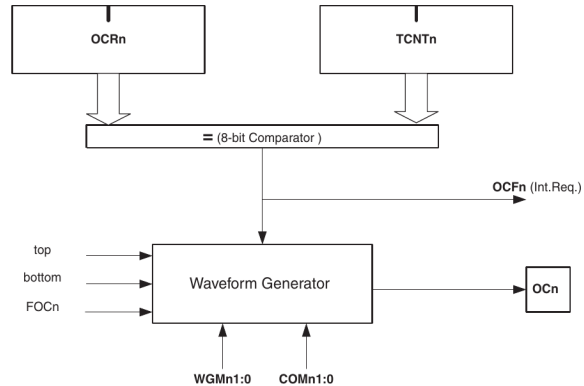


Figure: Output compare unit, [ATmega32, p. 71, fig. 29]

¹ This is set by the compare match output mode. See [ATmega32, p. 125] for timer 2.

Normal mode

The timer simply counts from BOTTOM to MAX, after which it restarts at BOTTOM.

- ▶ BOTTOM is zero. MAX is $2^n - 1$ for n -bit timers.
- ▶ A **timer overflow** flag TOV_n is set when the timer becomes zero again and an interrupt is raised.
- ▶ The counter value can be updated at any time.

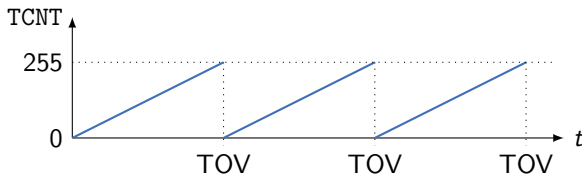


Figure: 8-bit timer example for normal mode. MAX is 255.

Example

```
1 #include <avr/interrupt.h>
2
3 ISR (TIMER0_OVF_vect) {
4     /* TCNT0 became zero and raised an overflow interrupt. */
5 }
6
7 void init() {
8     /* Timer/counter control register for timer/counter 0. (p80)
9      * Set (waveform generation) mode to 'normal'.
10     * Set compare match output mode to 'normal' (OCO pin disconnected).
11     * Set clock select to internal clock with prescaler 8. */
12    TCCR0 = (1 << CS01);
13    /* Set TOIE0 bit (timer overflow interrupt enable for timer/counter 0) */
14    TIMSK |= (1 << TOIE0);
15
16    /* Set global interrupt enable bit. */
17    sei();
18 }
```

See register description in [ATmega32, p. 80].

Custom periods

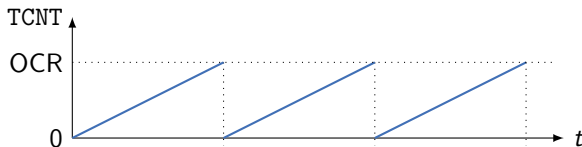
Assume we want *shorter, arbitrary timer periods* than the full period from 0 to $2^n - 1$.

- ▶ We could re-initialize the counter register to some value $b > 0$ in the overflow ISR.
- ▶ But if we do that in software then we have to take an vague interrupt latency into account.

Custom periods

Assume we want **shorter, arbitrary timer periods** than the full period from 0 to $2^n - 1$.

- ▶ We could re-initialize the counter register to some value $b > 0$ in the overflow ISR.
- ▶ But if we do that in software then we have to take an vague interrupt latency into account.
- ▶ The timer mode **Clear Timer on Compare Match Mode** (CTC) resets the timer when TCNT reaches TOP.
 - ▶ The TOP value is stored in the register OCR.
 - ▶ It holds that $0 \leq \text{TCNT} \leq \text{OCR}$.



Typically, OC pin is either disconnected or in toggle mode.

Clear Timer on Compare Match mode

Example applications:

- ▶ Generate a **square wave signal** at the OC pin with a period of $2 \cdot (1 + OCR)$ timer ticks.²
- ▶ Count external events and raise an interrupt after k events. (Pulse accumulator mode.)

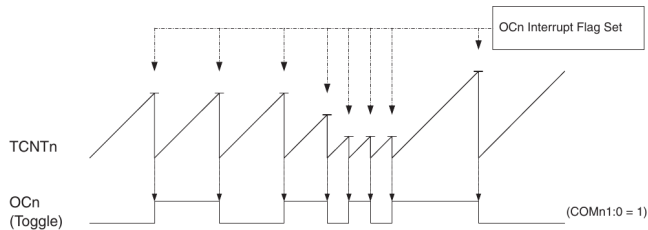


Figure: [ATmega32, p. 74]

Changing OCR is done in the ISR of the compare match.

- ▶ Otherwise, TCNT may have overtaken OCR, never match, and overflow after hitting MAX.

² See [ATmega32, p. 74].

Example: Toggle a pin every 43 ticks

In this example we would like to toggle the pin OC0 precisely every 43 CPU cycles.

- ▶ We use CTC mode to have the timer being cleared upon compare match.
- ▶ We set the output mode to toggle the OC0 pin.
- ▶ We set compare match register to 42.

```
1 void init() {  
2     /* Toggle pin OC0 after 43 cycles. TCNT0 cycles in [0, 42]. */  
3     OCR0 = 42;  
4  
5     /* Timer/counter control register for timer/counter 0. (p80)  
6     * Set (waveform generation) mode to 'CTC'.  
7     * Set compare match output mode of OC0 to 'toggle'.  
8     * Set clock select to internal clock without prescaler. */  
9     TCCR0 = (1 << WGM01) | (1 << COM00) | (1 << CS00);  
10 }
```

- ▶ There is no need for an ISR.

The pulse-width modulation (PWM) is a digital modulation:

- ▶ It allows to encode a value $d \in [0, 1]$ using a digital signal $x(t)$ in a time period p .
- ▶ Simply set x high for a d -th fraction of the time. The value d is called the **duty cycle**³.
- ▶ To sum up, a PWM signal is a function $[0, 1] \rightarrow \{0, 1\}$ to encode a value $[0, 1]$ as its mean.
- ▶ Of course, microcontrollers generate *time-discrete* PWM signals.

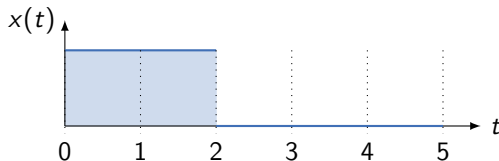
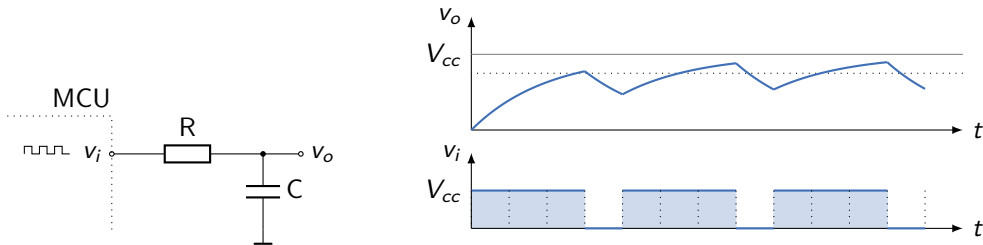


Figure: A single period of a (time-discrete) PWM signal with a duty cycle of 0.4 or 40 %.

³ Dt. Tastverhältnis

Demodulation of a PWM

We demodulate a PWM by a low pass to get the steady component. This gives **analog output**.



With duty cycle $d \in [0, 1]$, we have $d \cdot V_{cc}$ as steady component.

- ▶ Low-pass cut-off frequency is $f_c = \frac{1}{2\pi RC}$.
- ▶ Increasing time constant $\tau = RC$ is costly (larger components) and causes longer response times.
- ▶ To reduce oscillation of v_o we therefore strive for a **higher PWM frequency**.

PWM applications for microcontrollers

- ▶ digital-analog conversion
- ▶ dimming LEDs or displays
- ▶ fan control
- ▶ frequency converter for motor control

In many applications the load has a low-pass characteristic:

- ▶ receiving electrical system
- ▶ inertial of a motor or mechanical system
- ▶ human visual perception of light

If the PWM **frequency is sufficiently high** then need no explicit filters.

- ▶ Otherwise, we need external capacitors and/or inductors to filter the PWM signal.

Single slope PWM generation

- ▶ The PWM is output at the output compare pin.
- ▶ Let a timer TCNT repeatedly count from a value BOTTOM to a value MAX.
 - ▶ Set the PWM output high on timer overflow.
 - ▶ Set the PWM output low on ORC match.

- ▶ The PWM period is 2^n timer clock ticks for an n -bit timer.
- ▶ The duty cycle is $OCR / 2^n$, if output is not inverted.
- ▶ There is also an inverted mode.

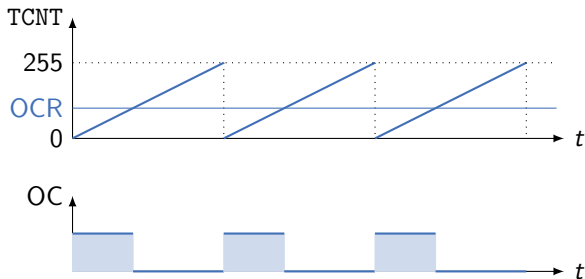


Figure: 8-bit timer single-slope example.

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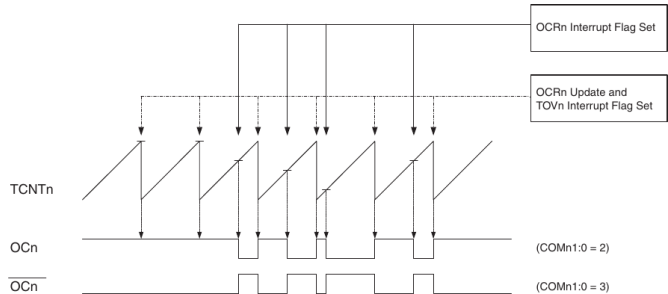


Figure: See [ATmega32, p. 75, fig. 32]

Single slope PWM generation

```
1 #include <avr/io.h>
2
3 void init() {
4     /* Set PB3 (OC0 pin) to output */
5     DDRB |= (1 << PB3);
6     /* Duty cycle of 192/256 = 75% */
7     OCR0 = 192;
8
9     /* Timer/counter control register for timer/counter 0. (p80)
10     *
11     * Set (waveform generation) mode to 'Fast PWM'.
12     * Set compare match output mode of OC0 to 'non-inverted PWM'.
13     * Set clock select to internal clock without prescaler. */
14     TCCR0 = (1 << WGM01) | (1 << WGM00) | (1 << COM01) | (1 << CS00);
15 }
```


Dual slope PWM generation

The timer register TCNT runs from BOTTOM to MAX and back again.

- ▶ On OCR match while upcounting, OC is cleared.
- ▶ On OCR match while downcounting, OC is set.

- ▶ The PWM period is 2^{n+1} timer clock ticks for an n -bit timer.
- ▶ The duty cycle is again $OCR / 2^n$ for non-inverted mode.
- ▶ There is also an inverted mode.

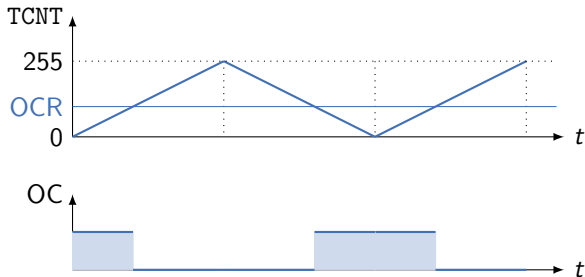


Figure: 8-bit timer dual-slope example.

Dual slope PWM generation

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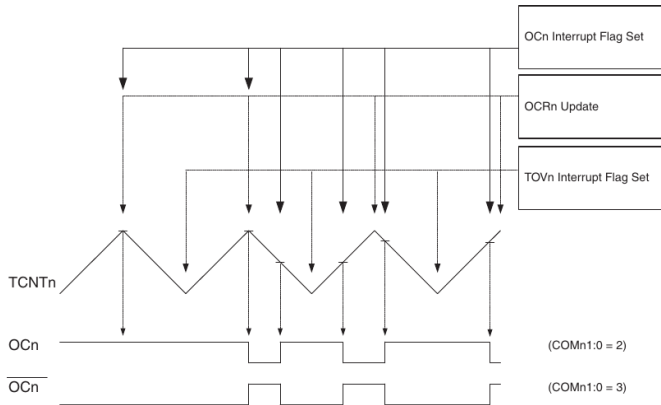
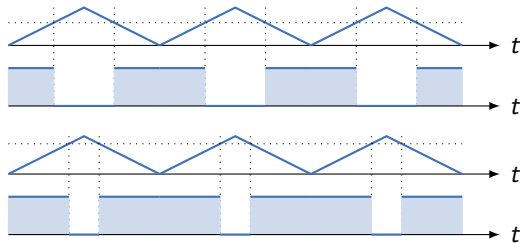
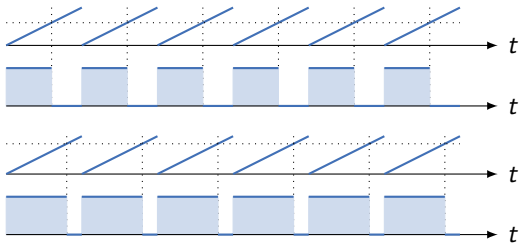


Figure: See [ATmega32, p. 76, fig. 33]

Dual slope PWM generation

```
1 #include <avr/io.h>
2
3 void init() {
4     /* Set PB3 (OC0 pin) to output */
5     DDRB |= (1 << PB3);
6     /* Duty cycle of 192/256 = 75% */
7     OCR0 = 192;
8
9     /* Timer/counter control register for timer/counter 0. (p80)
10      *
11      * Set (waveform generation) mode to 'Phase correct PWM'.
12      * Set compare match output mode of OC0 to 'clear on compare match when
13      * up-counting'.
14      * Set clock select to internal clock without prescaler. */
15     TCCR0 = (1 << WGM00) | (1 << COM01) | (1 << CS00);
16 }
```

Single slope versus dual slope



ATmega32 calls single slope mode the *fast PWM mode*:

- ▶ It has double the frequency (half the period) of the dual slope mode.⁴
- ▶ Higher frequency allows for smaller external components, e.g., capacitors for DAC applications.

ATmega32 calls dual slope mode the *phase correct PWM mode*:

- ▶ Increasing the duty cycle in the single slope mode makes a phase shift to the right.
- ▶ In the dual slope mode the pulse width changes *in phase* with the timer period.

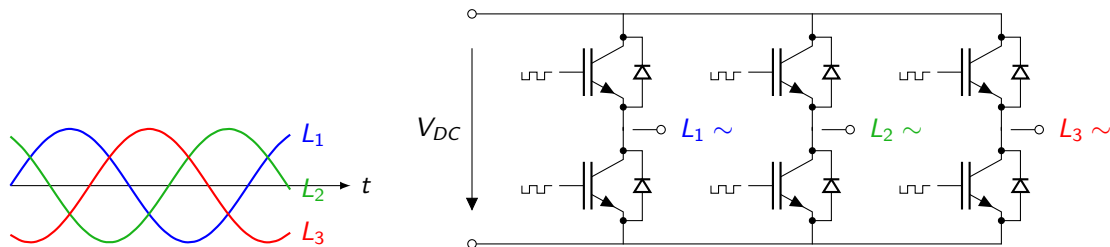
⁴

The period in dual slope mode is not exactly doubled, but it is $2(2^n - 1)$ timer ticks for an n -bit timer, as the timer values BOTTOM and TOP are not repeated.

The issue with phase shifts

Example: Three-phase inverter for motion control.

- ▶ Phases are 120° -shifted sinus signals and generated by PWM signals. The current signal value corresponds to the duty cycle of a PWM signal.



- ▶ In single slope mode, the change of the duty cycle introduces changes in the phase shift in the PWM signal. Hence, the sinus signals are shifted – depending on the signal value!

Conclusion: Phase shifts of PWM signals can be pathological when we have multiple PWM signals that are related to each other.

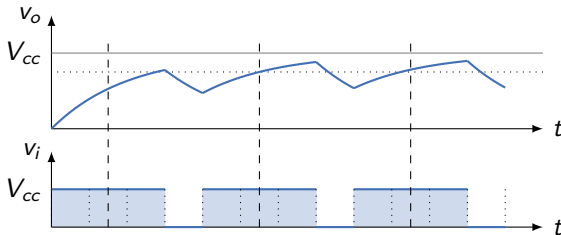
Dual slope PWM and measuring analog input

For closed-loop control, like motor control, we need to measure feedback signals.

- ▶ Thought experiment: Read back analog output v_o generated by a low-pass filtered PWM v_i .

Let's read back in the timer overflow ISR:

- ▶ Single slope PWM: Here v_o is at a local minimum, which is bad.
- ▶ Dual slope PWM: Timer overflow is in the middle of a high phase. Here v_o is closer to its steady component, so error is lower.



PWM on the Raspberry Pi

Any digital signal x with period p and mean value d , i.e., with the property $d = \frac{1}{p} \int_0^p x(t) dt$ is called a PWM signal with duty cycle d . What are good candidates?⁵

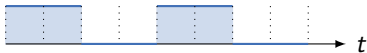
Assume we would like to have a duty cycle of 50% and a period of 8 cycles. Examples are:



(a) ATmega32, non-inverted mode



(b) ATmega32, inverted mode



(c) Doubling the frequency



(d) Maximum frequency

The BCM2835 SoC on the Raspberry Pi generates the last: it gives the **highest frequency**.

⁵ And how many candidates do exist?

- [ATmega32] *ATmega32: 8-bit AVR Microcontroller with 32KBytes In-System Programmable Flash.* Atmel Corporation. Feb. 2011.
- [BCM2835] *BCM2835 ARM Peripherals.* Broadcom Corporation. 2012. URL: <https://www.raspberrypi.org/app/uploads/2012/02/BCM2835-ARM-Peripherals.pdf>.

The PWM generation algorithm of the BCM2835

Assume we would like to generate a PWM signal with duty cycle $\frac{3}{7}$ and a period of 7. How do we achieve a good (high) resulting frequency?

6

Strictly speaking, the algorithm listing in [BCM2835] is incomplete due to broken typesetting. This is a translation into Python. The function `pwm()` is a so-called *generator* function that works like an iterator. Each time it is called the *yield* instruction returns the next PWM signal value.

The PWM generation algorithm of the BCM2835

Assume we would like to generate a PWM signal with duty cycle $\frac{3}{7}$ and a period of 7. How do we achieve a good (high) resulting frequency?

According to [BCM2835, p. 139], the algorithm to generate n high cycles out of m cycles, is as follows:⁶

```
1 def pwm(n, m):
2     k = 0
3     while True:
4         k += n
5         if k >= m:
6             k = k % m
7             yield 1      # Output a high
8         else:
9             yield 0      # Output a low
```

Two questions:

- ▶ Correctness: Why is this giving a duty cycle of n/m ?
- ▶ Quality: Why is this giving a good PWM signal frequency?

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Algorithm analysis: correctness

Lemma

Given that $n \leq m$ then after m invocations of $\text{pwm}(n, m)$ exactly n highs are output. Furthermore, the output is periodic with period m .

Proof. Let us rephrase the algorithm:

```
1 def pwm(n, m):  
2     k = 0  
3     while True:  
4         k += n  
5         if k >= m:  
6             k = k % m  
7             yield 1  
8     # Output a high  
9     else:  
10        yield 0        # Output a low
```

```
1 def pwm2(n, m):  
2     k = 0  
3     while True:  
4         k += n  
5         if k passes an m-multiple:  
6             # (k-n, k] contains                # a multiple of m  
7             yield 1        # Output a high  
8         else:  
9             yield 0        # Output a low
```

After m invocations of $\text{pwm2}(n, m)$:

- ▶ k is equal to $n \cdot m$. Hence, k passed an m -multiple exactly n times.
- ▶ Also, in $\text{pwm}(n, m)$ the variable k is zero again, so the output repeats after m cycles. □

Algorithm analysis: quality

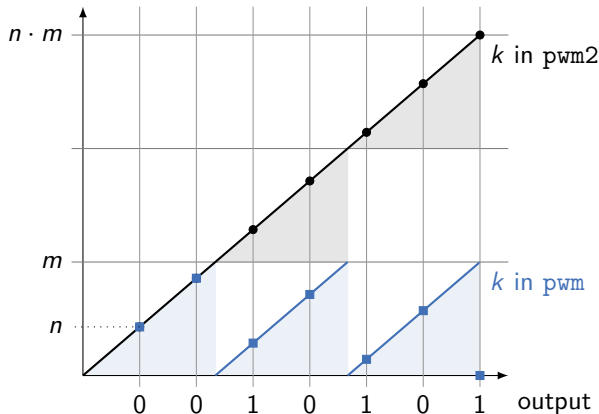


Figure: The variables k in the two algorithms for $m = 7$ and $n = 3$. They output a 1 when the black line crosses a horizontal line resp. when the blue line starts at zero again. The horizontal lines are equally spaced, hence the 1's in the output are more or less equally spaced: the PWM frequency is good.

Additional capabilities of ATmega32 timers

Some features are only provided by some timers:

	TCNT0	TCNT1	TCNT2
Input capture unit		•	
Phase and frequency correct mode		•	
Two output compare match pins		•	
Asynchronous mode with ext. crystal			•

Many details have been skipped:

- ▶ Different timer resolution modes
- ▶ Custom PWM periods
- ▶ Details on the double buffering of certain registers.

The TCNT1 alone provides 15 different modes in total.⁷

⁷ See [ATmega32, p. 109].