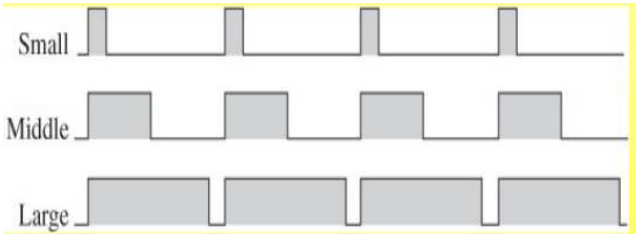
ECE/CS 5780/6780: Embedded System Design

Chris J. Myers

Lecture 13: Output Compare

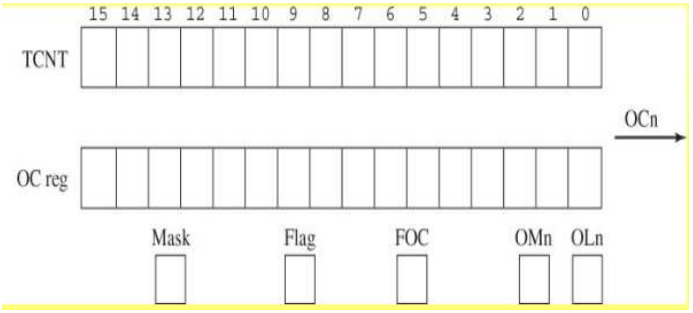
Variable Duty Cycle Square Wave



Basic Principles of Output Capture

- *Output compare* can create square waves, generate pulses, implement time delays, and execute periodic interrupts.
- Can also use with input capture to measure frequency.
- Each output capture module has:
  - An external output pin, OCn
  - A flag bit
  - A force control bit FOCn
  - Two control bits, OMn, OLn
  - An interrupt mask bit (arm)
  - A 16-bit output compare register

Basic Components of Output Compare



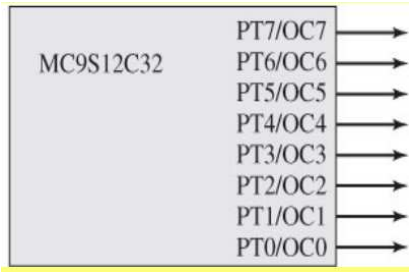
Basic Principles of Output Compare (cont)

- Output compare pin can control an external device.
- Output compare event occurs and sets flag when either:
  1. The 16-bit TCNT matches the 16-bit OC register
  2. The software writes a 1 to the FOC bit.
- OMn, OLn bits specify effect of event on the output pin.
- Two or three actions result from a compare event:
  1. The OCn output bit changes
  2. The output compare flag is set.
  3. An interrupt is requested if the mask is 1.

Applications of Output Compare

- Can create a `fixed` time delay.
  1. Read the current 16-bit TCNT
  2. Calculate TCNT+`fixed`
  3. Set 16-bit output compare register to TCNT+`fixed`
  4. Clear the output compare flag
  5. Wait for the output compare flag to be set
- Delay of steps 1 to 4 sets the minimum delay.
- Maximum delay is 65,536 cycles.

Output Compare Interface on 6812



Control Bits and Flags

- Output compares are on port T (i.e., **PTT**).
- Set pin to output compare mode by setting bit to 1 in **TIOS**.
- Output compare registers are **TC0**, . . . , **TC7**.
- Arm interrupts using **TIE**.
- Flags are found in **TFLG1**.
- Set effect of trigger using **TCTL1** and **TCTL2**.
- Can force an output compare by setting bit to 1 in **CFORC**.

OMn	OLn	Effect of when TOCn=TCNT
0	0	Does not affect OCn
0	1	Toggle OCn
1	0	Clear OCn=0
1	1	Set OCn=1

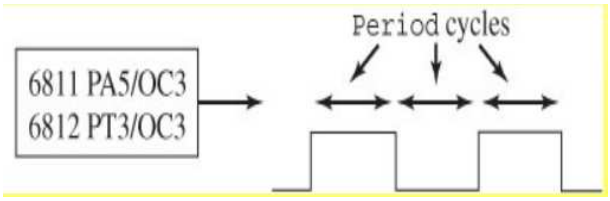
Output Compare 7

- When TC7=TCNT, can set or clear any output compare pins.
- OC7M register selects pins to be affected by OC7 event.
- OC7D register specifies value of pin after OC7 event.

Periodic Interrupt Using Output Capture

```
#define PERIOD  1000
unsigned short Time;
void OC6_Init(void){
  asm sei         // Make atomic
  TSCR1 = 0x80;
  TSCR2 = 0x02;  // 1 MHz TCNT
  TIOS |= 0x40;  // activate OC6
  TIE  |= 0x40;  // arm OC6
  TC6 = TCNT+50; // first in 50us
  Time = 0;      // Initialize
  asm cli }      // enable IRQ
void interrupt 14 OC6handler(void){
  TC6 = TC6+PERIOD; // next in 1 ms
  TFLG1 = 0x40;     // acknowledge C6F
  Time++; }
```


Square-Wave Generation



Square-Wave Generation

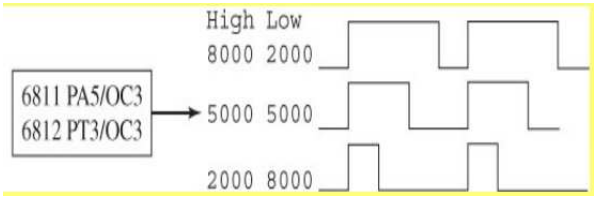
```
unsigned short Period; // in usec
void ritual(void) {
  asm sei              // make atomic
  TIOS |= 0x08;        // enable OC3
  DDRT |= 0x08;        // PT3 is output
  TSCR1 = 0x80;        // enable
  TSCR2 = 0x01;        // 500 ns clock
  TCTL2 = (TCTL2&0x3F)|0x40; // toggle
  TIE |= 0x08;         // Arm output compare 3
  TFLG1 = 0x08;        // Initially clear C3F
  TC3 = TCNT+50;       // First one in 25 us
  asm cli }
void interrupt 11 TC3handler(void){
  TFLG1 = 0x08;        // ack C3F
  TC3 = TC3+Period;}   // calculate Next
```

Square-Wave Generation Overhead

Component	6812
Process the interrupt (cycles,μs)	9=2.25μs
Execute the entire handler (cycles,μs)	20=5μs
Total time (μs)	7.25μs

Freq.	Period	Interrupt every (cycles)	Time to process (cycles)	Overhead (%)
10 Hz	100 ms	100,000	29	0.03
100 Hz	10 ms	10,000	29	0.3
1 kHz	1 ms	1000	29	3
5 kHz	200 μs	200	29	14.5
1/P	P (μs)	P	29	2900/P

Pulse-Width Modulation



Pulse-Width Modulated Square-Wave

```
unsigned short High; // Cycles High
unsigned short Low;  // Cycles Low
void Init(void){
  asm sei            // make atomic
  TIOS |= 0x08;      // enable OC3
  DDRT |= 0x08;      // PT3 is output
  TSCR1 = 0x80;      // enable
  TSCR2 = 0x01;      // 500 ns clock
  TIE |= 0x08;       // Arm output compare 3
  TFLG1 = 0x08;      // Initially clear C3F
  TCTL2 = (TCTL2&0x3F)|0x40; // toggle
  TC3 = TCNT+50;     // first right away
  asm cli
}
```

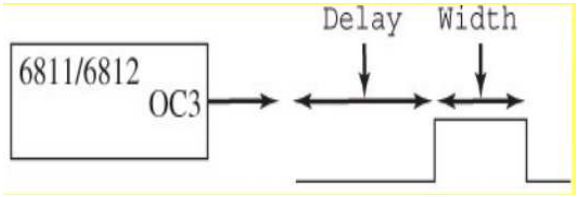

Pulse-Width Modulated Square-Wave (cont)

```
void interrupt 11 TC3handler (void){
  TFLG1 = 0x08;     // ack C3F
  if(PTT&0x08){     // PT3 is now high
    TC3 = TC3+High; // 1 for High cyc
  }
  else{             // PT3 is now low
    TC3 = TC3+Low;  // 0 for Low cycles
  }
}
void main(void){
     High=8000; Low=2000;
     ritual();
     while(1);
}
```


Pulse-Width Modulation Overhead

Component	6812
Process the interrupt (cycles)	9
Execute the handler (cycles)	27-28
Total time T (cycles)	36-37

Delayed Pulse Generation



Delayed Pulse Generation

```
void Pulse(unsigned short Delay,
     unsigned short Width){
  asm sei          // make atomic
  TIOS |= 0x08;    // enable OC3
  DDRT |= 0x08;    // PT3 is output
  TSCR1 = 0x80;    // enable
  TSCR2 = 0x01;    // 500 ns clock
  TC7 = TCNT+Delay;
  TC3 = TC7+Width;
  OC7M = 0x08;     // connect OC7 to PT3
  OC7D = 0x08;     // PT3=1 when TC7=TCNT
  TCTL2=(TCTL2&0x3F)|0x80; // PT3=0 when TC3=TCNT
  TFLG1 = 0x08;    // Clear C3F
  TIE |= 0x08;     // Arm C3F
  asm cli
}
```


Delayed Pulse Generation (cont)

```
void interrupt 11 TC3handler(void){
  OC7M = 0;       // disconnect OC7 from PT3
  OC7D = 0;
  TCTL2 &=~0xC0;  // disable OC3
  TIE &= ~0x08;   // disarm C3F
}
```


Frequency Measurement

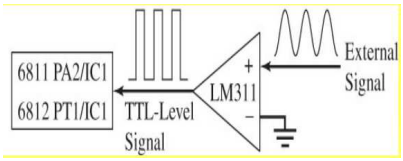
- Direct measurement of frequency involves counting input pulses for a fixed amount of time.
- Can use input capture to count pulses, and output capture to create a fixed time interval.
- Input Capture handler increments `Counter`.
- Output compare handler calculates frequency:

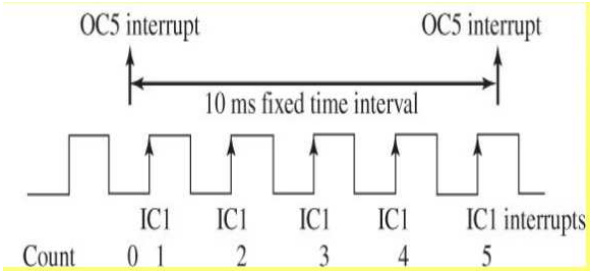
$$f = \frac{\texttt{Counter}}{\texttt{fixed time}}$$

- The frequency resolution is:

$$f = \frac{1}{\texttt{fixed time}}$$

Frequency Measurement





Frequency Measurement

```
#define Rate 20000  //  10 ms
void Init(void) {
  asm sei       // make atomic
  TIOS |= 0x20; // enable OC5
  TSCR1 = 0x80; // enable
  TSCR2 = 0x01; // 500 ns clock
  TIE |= 0x22;  // Arm OC5 and IC1
  TC5 = TCNT+Rate;   // First in 10 ms
  TCTL4 = (TCTL4&0xF3)|0x04; /* C1F set on rising edges */
  Count = 0;    // Set up for first
  Done = 0;     // Set on measurements
  TFLG1 = 0x22; // clear C5F, C1F
  asm cli
}
```


Frequency Measurement (cont)

```
void interrupt 9 TC1handler(void){
  Count++;      // number of rising edges
  TFLG1 = 0x02; // ack, clear C1F
}
void interrupt 13 TC5handler(void){
  TFLG1= 0x20;      // Acknowledge
  TC5 =  TC5+Rate;  // every 10 ms
  Freq = Count;     // 100 Hz units
  Done = 0xff;
  Count = 0;        // Setup for next
}
```

Conversion Between Frequency and Period

- Could measure frequency from period measurement:

$$f = \frac{1}{p}$$

- If range of period measurement is 36μs to 32ms with resolution of 500ns, frequency range is 31 to 27,778Hz.

$$f = \frac{1}{p} \cdot \frac{1}{500ns} = \frac{2000000}{p}$$

- Resolution relationship is not as obvious:

$$\Delta f = \frac{1}{(1/f) - \Delta p} - f = \frac{1}{(1/f) - 500ns} - f$$

Relationship Between Frequency and Period

Frequency (Hz)	Period (μs)	Δf (Hz)
31,250	32	500
20,000	50	200
10,000	100	50
5,000	200	13
2,000	500	2
1,000	1,000	0.5
500	2,000	0.13
200	5,000	0.02
100	10,000	0.005
50	20,000	0.001
31.25	32,000	0.0005

Period Measurement with $\Delta p = 1$ms

- Each rising edge generates input capture interrupt.
- Output compare used to increment a software counter, `Time`, every 1 ms.
- Period is number of 1-ms output compare interrupts between one rising edge to the next rising edge.
- Range is 0 to 65s determined by the 16-bit size of `Time`.

Period Measurement with $\Delta p = 1$ms

```
#define RESOLUTION 2000
void Ritual(void){
  asm sei        // make atomic
  TIOS |= 0x08;  // enable OC3
  TSCR1  = 0x80; // enable
  TSCR2 = 0x01;  // 500 ns clock
  TFLG1 = 0x0A;  // Clear C3F,C1F
  TIE = 0x0A;    // Arm OC3 and IC1
  TCTL4 = (TCTL4&0xF3)|0x04; /* C1F set on rising edges */
  while((TFLG1&0x02)==0); // wait rising
  TFLG1 = 0x02;    // Clear C1F
  TC3 = TCNT+RESOLUTION;
  Cnt=0; OverFlow=0; Done=0;
  asm cli
}
```

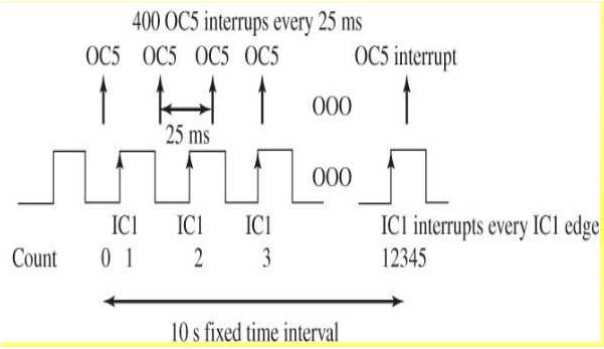

Period Measurement with $\Delta p = 1$ms (cont)

```
void interrupt 11 TC3handler(void){
  TFLG1 = 0x08;         // Acknowledge
  TC3 = TC3+RESOLUTION; // every 1 ms
  Cnt++;
  if(Cnt==0) OverFlow=0xFF; }
void interrupt 9 TC1handler(void){
  TFLG1 = 0x02;         // ack, clear C1F
  if(OverFlow){
    Period = 65535;     // greater than 65535
    OverFlow = 0;
  } else
    Period = Cnt;
  Cnt = 0;              // start next measurement
  Done = 0xFF; }
```


Frequency Measurement with $\Delta f = 0.1$Hz

- If count pulses in 10-s time interval, then number of pulses is frequency with units of 1/10s or 0.1 Hz.
- Setting output compare to interrupt every 25 ms, means that 400 interrupts creates a 10-s time delay.
- Number of input capture interrupts during this interval is the input frequency in units of 0.1 Hz.

Basic Timing Involved in Frequency Measurement



Frequency Measurement with $\Delta f = 0.1$Hz

```
#define PERIOD 50000  //  25 ms
void Init(void) {
asm sei          // make atomic
  TIOS| = 0x20;  // enable OC5
  TSCR1  = 0x80; // enable
  TSCR2 = 0x02;  // 500 ns clock
  TIE = 0x22;    // Arm OC5 and IC1
  TCTL4 = (TCTL4&0xF3)|0x04; // rising
  Count = 0;     // Set up for first
  Done = 0;      // Set on measurement
  FourHundred = 0;
  TC5 = TCNT+PERIOD; // First in 25 ms
  TFLG1 = 0x22;      // Clear C5F,C1F
asm cli
}
```


Frequency Measurement with $\Delta f = 0.1$Hz (cont)

```
void interrupt 9 TC1handler(void){
  Count++;       // number of rising edges
  TFLG1 = 0x02;  // ack, clear C1F
}
void interrupt 13 TC5handler(void){
  TFLG1 = 0x20;      // Acknowledge
  TC5 = TC5+PERIOD;  // every 25 ms
  if (++FourHundred==400){
    Freq = Count;    //  0.1 Hz units
    FourHundred = 0;
    Done = 0xff;
    Count = 0;     // Setup for next
  }
}
```


Pulse Accumulator

- Pulse accumulator is enabled when **PAEN** is 1.
- 16-bit event counter (**PACNT**).

PAMOD	**PEDGE**	Mode	Counts when	Sets **PAIF**
0	0	Event counting	PT7 falls	PT7 falls
0	1	Event counting	PT7 rises	PT7 rises
1	0	Gated time	PT7=1	PT7 falls
1	1	Gated time	PT7=0	PT7 rises

- In *gated time accumulation* mode, counter incremented by a free-running clock (E clock divided by 64).
- Interrupt occurs when **PAIF** is set if **PAII** is set.
- **PAOVF** bit is set when **PACNT** overflows.
- If **PAOVI** is set, interrupt occurs on overflow.

Frequency Measurement Using Pulse Accumulator

```
;returns Reg D = freq in Hz
Freq  bclr DDRT,#$80  ;PT7 is input
      movb #$40,PACTL ;count falling
      movw #0,PACNT
      movb #$02,PAFLG ;clear PAOVF
      ldy #100
      bsr Timer_Wait10ms  ;Program 2.6
      brclr PAFLG,#$02,ok ;check PAOVF
bad   ldd #65535 ;too big
      bra out
ok    ldd PACNT ;units in Hz
out   rts
```


Pulse-Width Measurement Using Pulse Accumulator

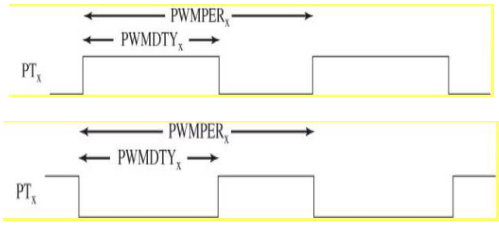
```
;returns Reg D = pulse width in 16us
Puls  bclr DDRT,#$80      ;PT7 is input
      movb #$60,PACTL     ;measure high
      movw #0,PACNT
      movb #$02,PAFLG     ;clear PAOVF
loop  brclr PAFLG,#$01,loop
      brclr PAFLG,#$02,ok ;check PAOVF
bad   ldd #65535          ;too big
      bra out
ok    ldd PACNT ;units in 16us
out   rts
```

Pulse-Width Modulation on the MC9S12C32

- Dedicated hardware can create PWM signals on port P with no overhead.
- **MODRR** register can connect PWM system to port T pins.
- **PWME** register used to enable PWM channels.
- Either three 16-bit channels or up to six 8-bit channels.
- **CON01** bit connects two 8-bit channels to form one 16-bit channel (similarly for **CON23** and **CON45**).

Pulse-Width Modulation on the MC9S12C32 (cont)

- Output is high number of counts in corresponding **PWMDTY** register, and total counts in a cycle in the corresponding **PWMPER** register.



Clock Choice

- Many possible choices for the clock.
- A and B clocks configurd by the **PWMPRCLK** register as a divided down version of the E clock between E and E/128.
- SA clock is the A clock divided by two times value in **PWMSCLA** register.
- SB clock is the B clock divided by two times value in **PWMSCLB** register.
- Channels 0, 1, 4, and 5 can use either A or SA clock while channels 2 and 3 use either the B or SB clock.

8-bit Pulse-Width Modulated Output (10ms Period)

```
void PWM_Init(void){
  MODRR |= 0x01;   // PT0 with PWM
  PWME |= 0x01;    // enable channel 0
  PWMPOL |= 0x01;  // PT0 high then low
  PWMCLK |= 0x01;  // Clock SA
  PWMPRCLK = (PWMPRCLK&0xF8)|0x04; // A=E/16
  PWMSCLA = 5;     // SA=A/10, 0.25*160=40us
  PWMPER0 = 250;   // 10ms period
  PWMDTY0 = 0;     // initially off
}
void PWM_Duty0(unsigned char duty){
  PWMDTY0 = duty; // 0 to 250
}
```


8-bit Pulse-Width Modulated Output (1s Period)

```
void PWM_Init(void){
  MODRR |= 0x08;  // PT3 with PWM
  PWME |= 0x08;   // enable channel 3
  PWMPOL |= 0x08; // PT3 high then low
  PWMCLK &=~0x08; // Clock B
  PWMCTL |= 0x20; // Concatenate 2+3
  PWMPRCLK = (PWMPRCLK&0x8F)|0x60; // B=E/64
  PWMPER23 = 62500; // 1s period
  PWMDTY23 = 0;     // initially off
}
// Set the duty cycle on PT3 output
void PWM_Duty(unsigned short duty){
  PWMDTY23 = duty; // 0 to 62500
}
```