CprE 288 – Introduction to Embedded Systems (Timers/Input Capture)

Instructors:
Dr. Phillip Jones

Announcements

- Exam 2: Week 12 (need to finalize if it will be on Tue or Thur)
  - i.e. Week of 11/5
- HW 5: Sunday 10/14
- **Project Teams:** to be announced.
- **<u>In class Project Activity:</u>** Tuesday 10/9. Directions to be given. Will be part of participation grade, and indirectly part of Project grade.
- Quiz 6: Thursday 10/11

Looking Forward

- There are generally three phases of the course:
  1. C Programming targeting low-level embedded concepts
  2. I/O Device Programming
  3. Architecture and Assembly programming

- The 2^{nd} and 3^{rd} phases are much more challenging than the 1^{st} phase

Textbook & Data Sheet: Read and ask questions

- Exam 2 will predominantly consist of questions of the form
  - **Program Configure Registers to meet these specs**
    - **UART, ADC, Input Capture, Output Compare, Timers, Interrupts**
    - **Each device has a section in the Datasheet and Textbook**
  - **Based on a given configuration, answer questions about how the program will behave**
    - **E.g. How long will something take to occur?**
    - **E.g. How many time a second with something occur?**
  - **Explain why a given configuration is incorrect for implementing a specified behavior**
  - **Assuming a given configuration, write a short program to implement a specific behavior**
  - **ADC calculation problem**

Announcements

- **<u>Quiz 6 (15 min</u>)**: Thursday 10/11, Textbook reading: Section 9.1, 9.2 (**your one-side of 1 page of notes will be collected for <u>Class Participation</u>**)
  - **Datasheet readings will be emailed to the class.**
- **Exam 2: Will come up fast**
- This week lab will use an Ultra sound
  - Textbook reading: Section 9.1, 9.2

Overview of Today's Lecture

- Input Capture Review
  - Textbook reading: Section 9.1, 9.2

INPUT CAPTURE

Input Capture

Capture the times of events

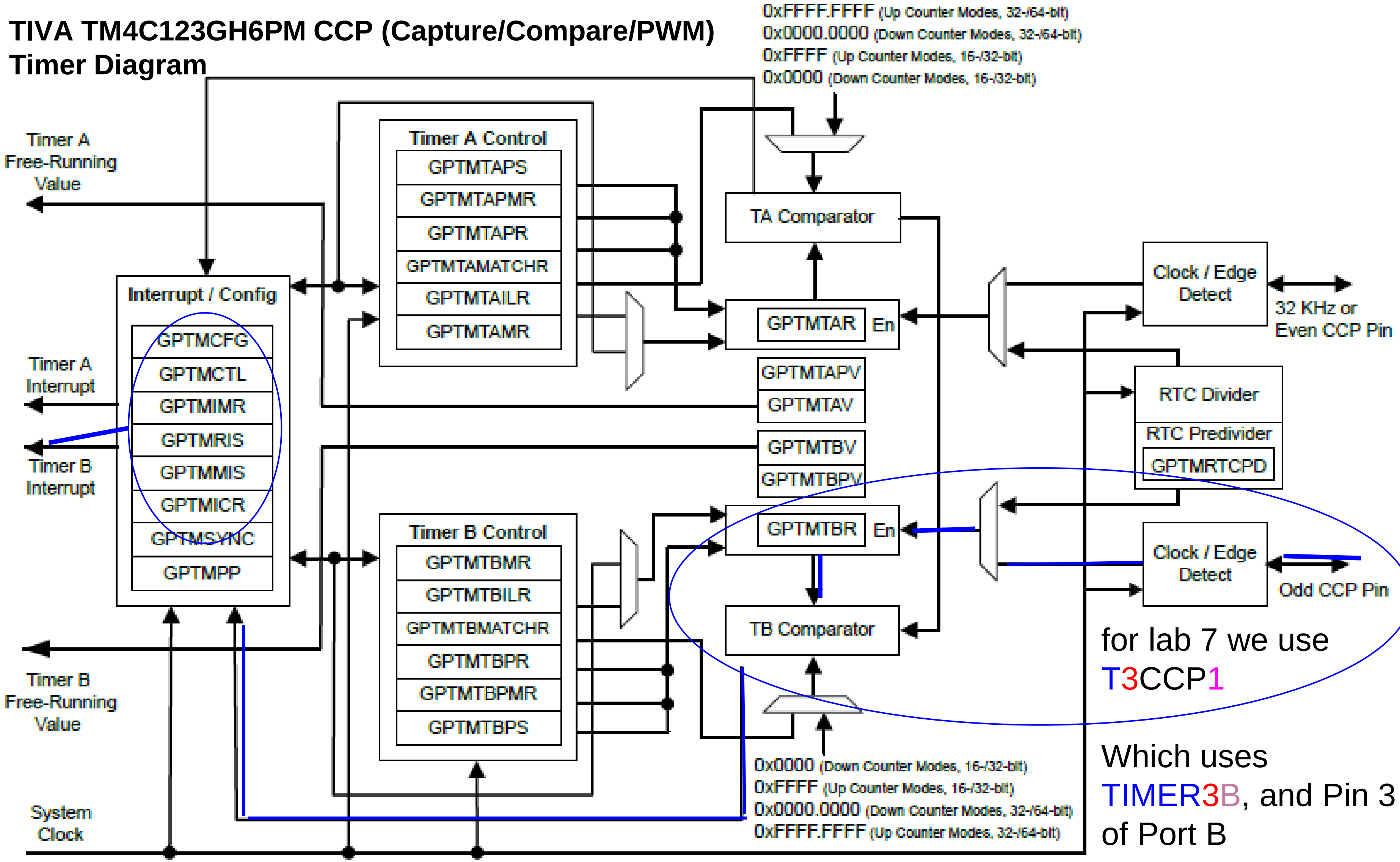
Many applications in microcontroller applications:

- Measure rotation rate
- Remote control
- Sonar devices
- Communications

Generally, any input that can be treated as a series of events, where the precise measure of event times is important

Figure 11-1. GPTM Module Block Diagram

TIVA TM4C123GH6PM CCP (Capture/Compare/PWM) Timer Diagram



for lab 7 we use T3CCP1

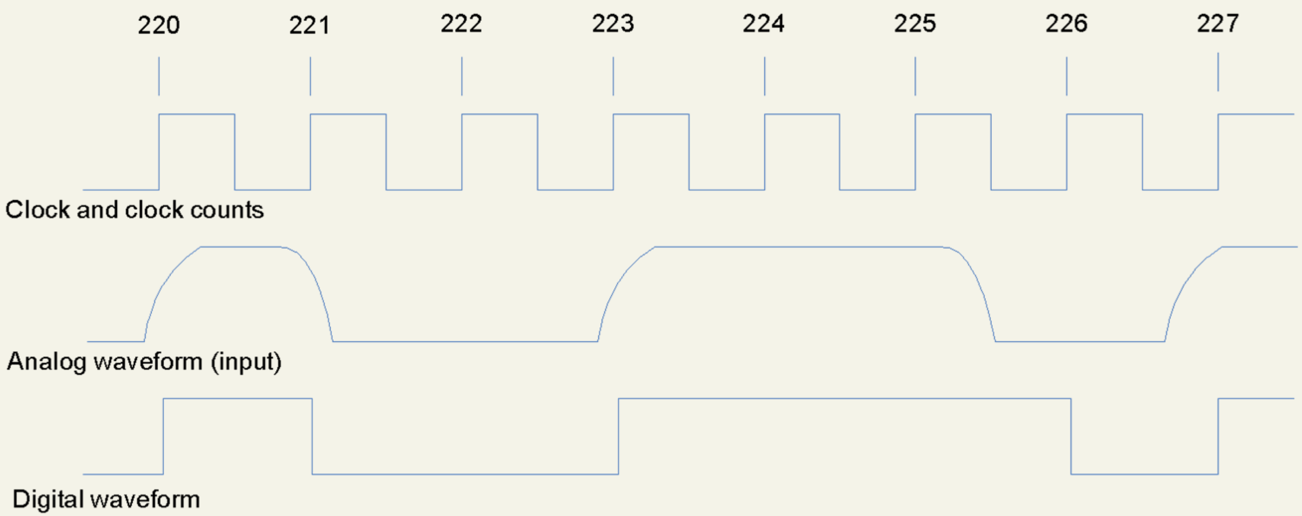
Which uses TIMER3B, and Pin 3 of Port B

(More on pages 704-707 of datasheet)

Input Capture

An event is a transition of binary signal

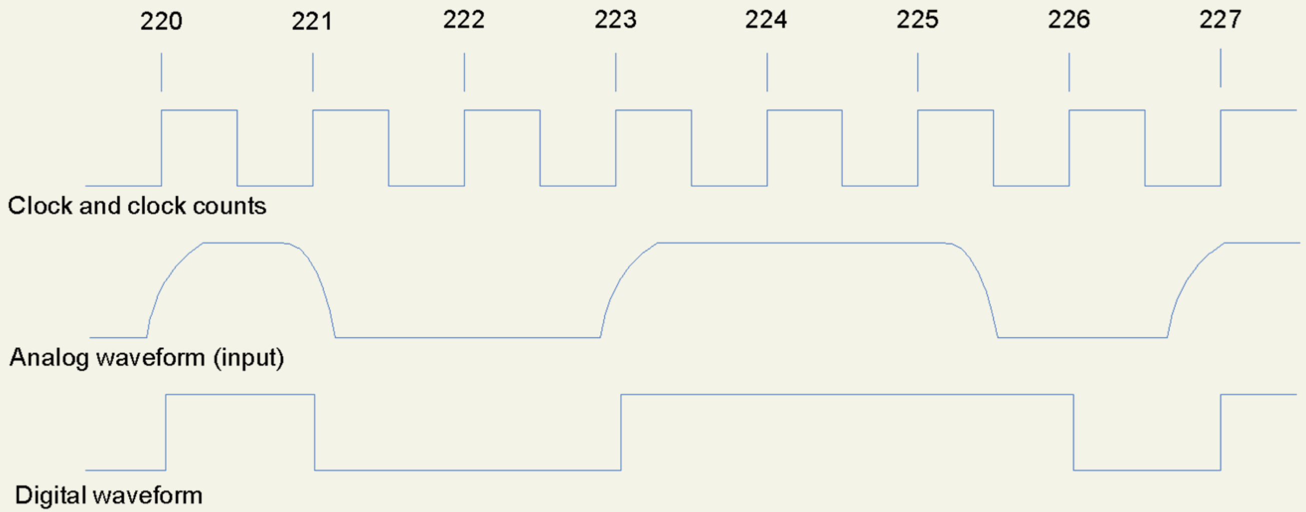
Example: How many events make up the following **waveform?**



Input Capture

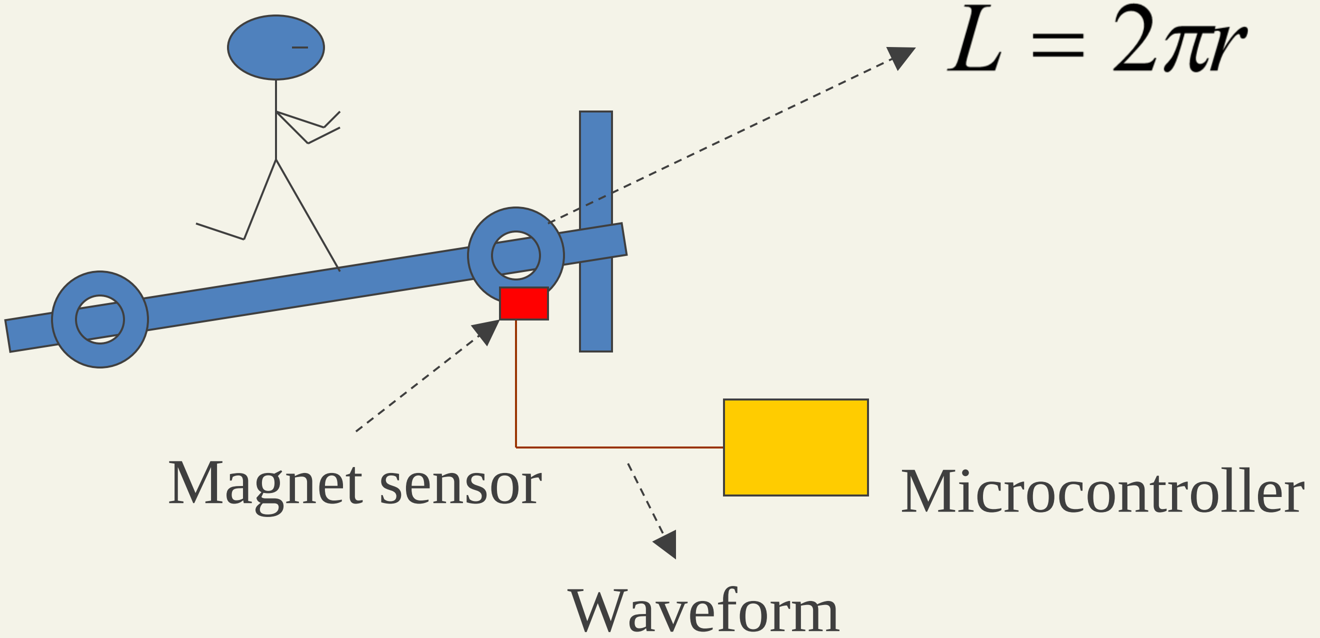
An input digitalized and then times captured

Example: The input is understood as events occurring at the following times: 220, 221, 223, 226, and 227 with initial state as low



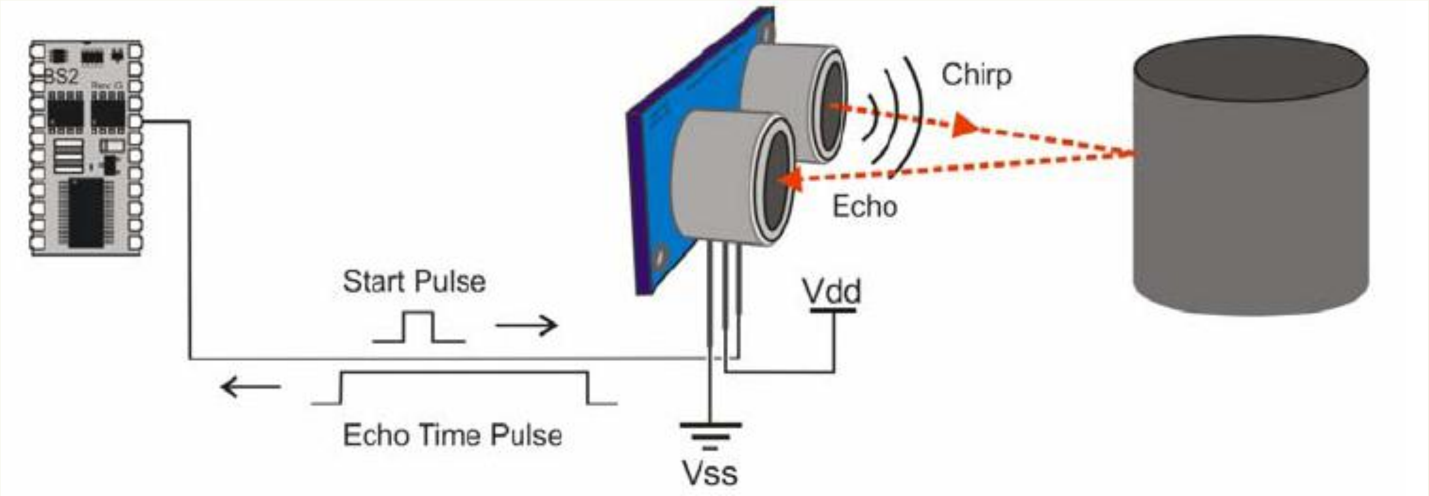
Application: Speedometer

How to detect the speed of a treadmill?

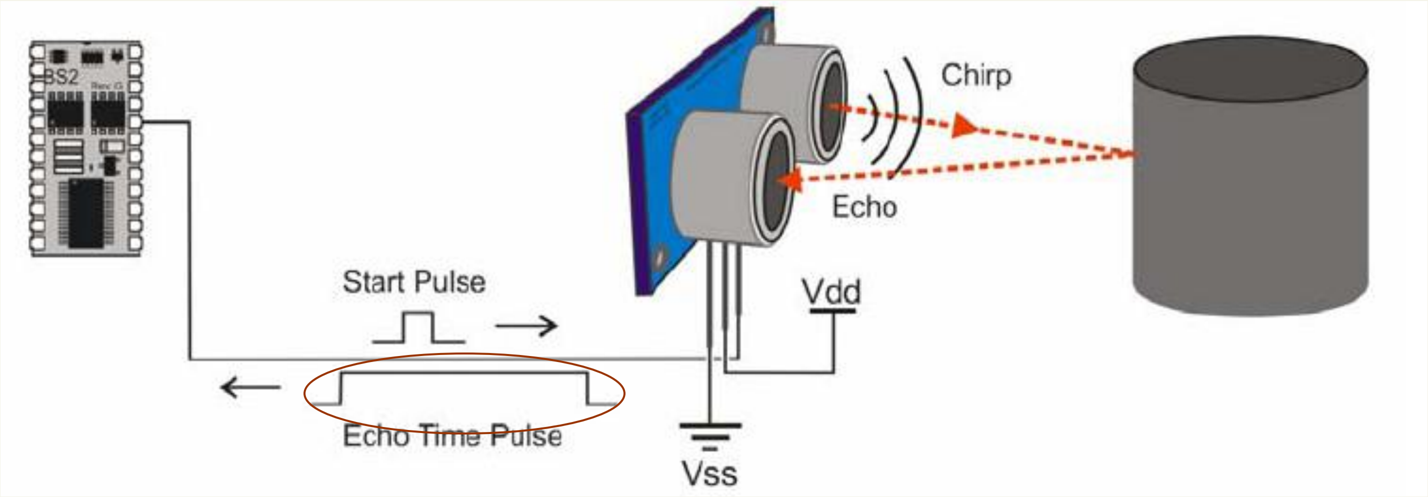


Application: Sonar Device

Ping))) sensor: ultrasound distance detection device



Sonar Principle



Sound Speed in Lab Temperature: About 340m/s
Pulse width proportional to round-trip distance

* Temperature affects sound speed

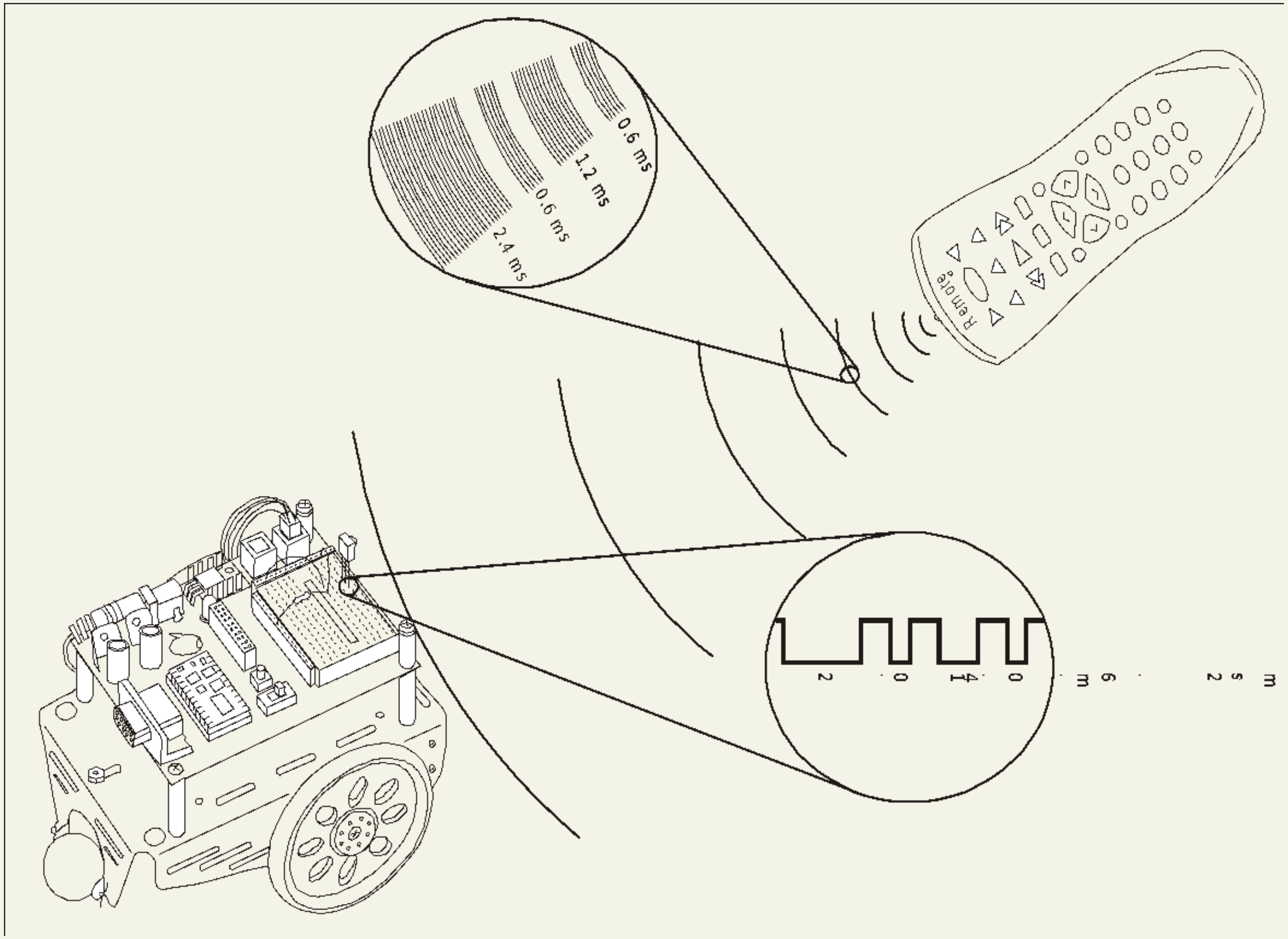
Sonar Principle

Assume 62.5KHz Input Capture clock
1ms <=> 62.5 clocks <=> 34cm

Time Diff.	Clock Count	One-way Distance
2ms	125	0.34m
4ms	250	0.68m

How to capture the times of rising edge and falling edge?

Application: Remote Control (Decoding)



Input Capture: Design Principle

Time is important!

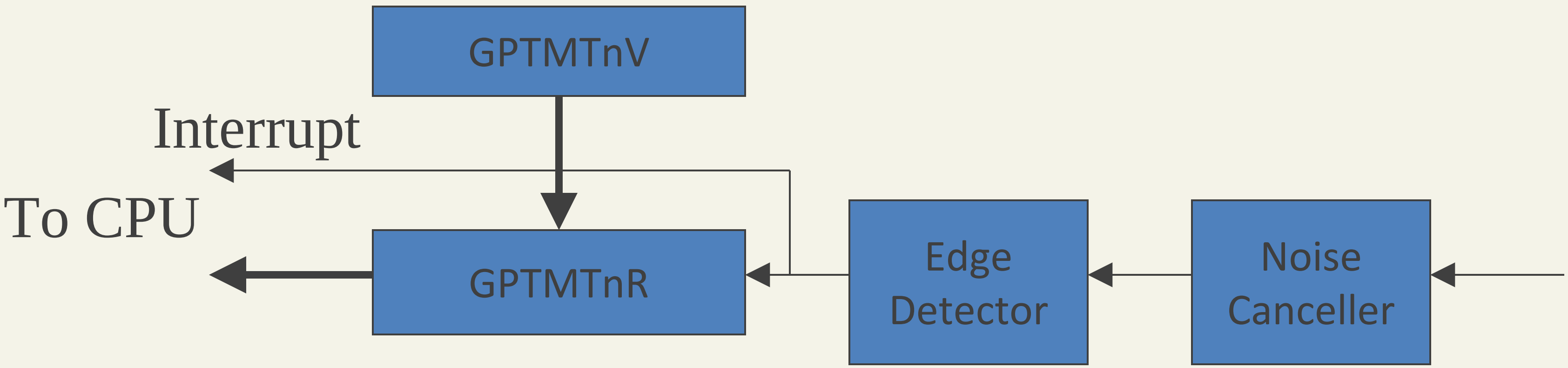
How could a microcontroller capture the time of an event, assuming a clock count can be read?

- Keep polling the input pin?
- Use an interrupt?
- ???

Precise timing is needed!

Input Capture: Design Principle

Time value (clock count) is captured first then read by the CPU



GPTMTnV: Timer n Value Register (n is A or B)
GPTMTnR: Timer Register (in Edge-Time mode, this register is loaded with the value in GPTMTnV at the last input edge event)

Input Capture: Design Principle

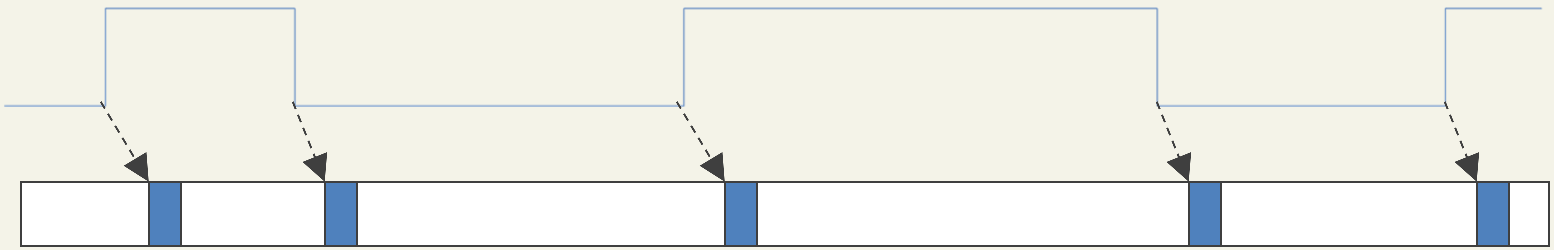
What happens in hardware and software when and after an event occurs

- The event's time is *captured* in the GPTMTnR (timer register)
- An interrupt is raised to the CPU
- CPU executes the input capture ISR, which reads the timer register and completes the related processing

The captured time is *precise* because it's captured immediately when the event occurs

The ISR should read the timer register and complete its processing fast enough to avoid loss of events

Input Capture: Design Principle



Interrupt

CPU Interrupt processing

CPU Foreground computation

Input Capture: Design Principle

How to program the interrupt handler to

- Count the number of pulses
- Calculate pulse width
- Decode IR signals
- And do many other functions …

```
IntRegister(INT_TIMER3B, TIMER3B_Handler); //in main

void TIMER3B_Handler(void)
{
    // YOUR PROCESSING
}
```

Tiva TM4C123GH6PM 16/32-bit Timer as Input Capture Unit

Tiva TM4C123GH6PM has 6, multi-purpose 16/32-bit timer units with

- Input capture units (IC)
- Output compare units (OC)
- Pulse width modulation output (PWM)
- And other features

Figure 11-1. GPTM Module Block Diagram

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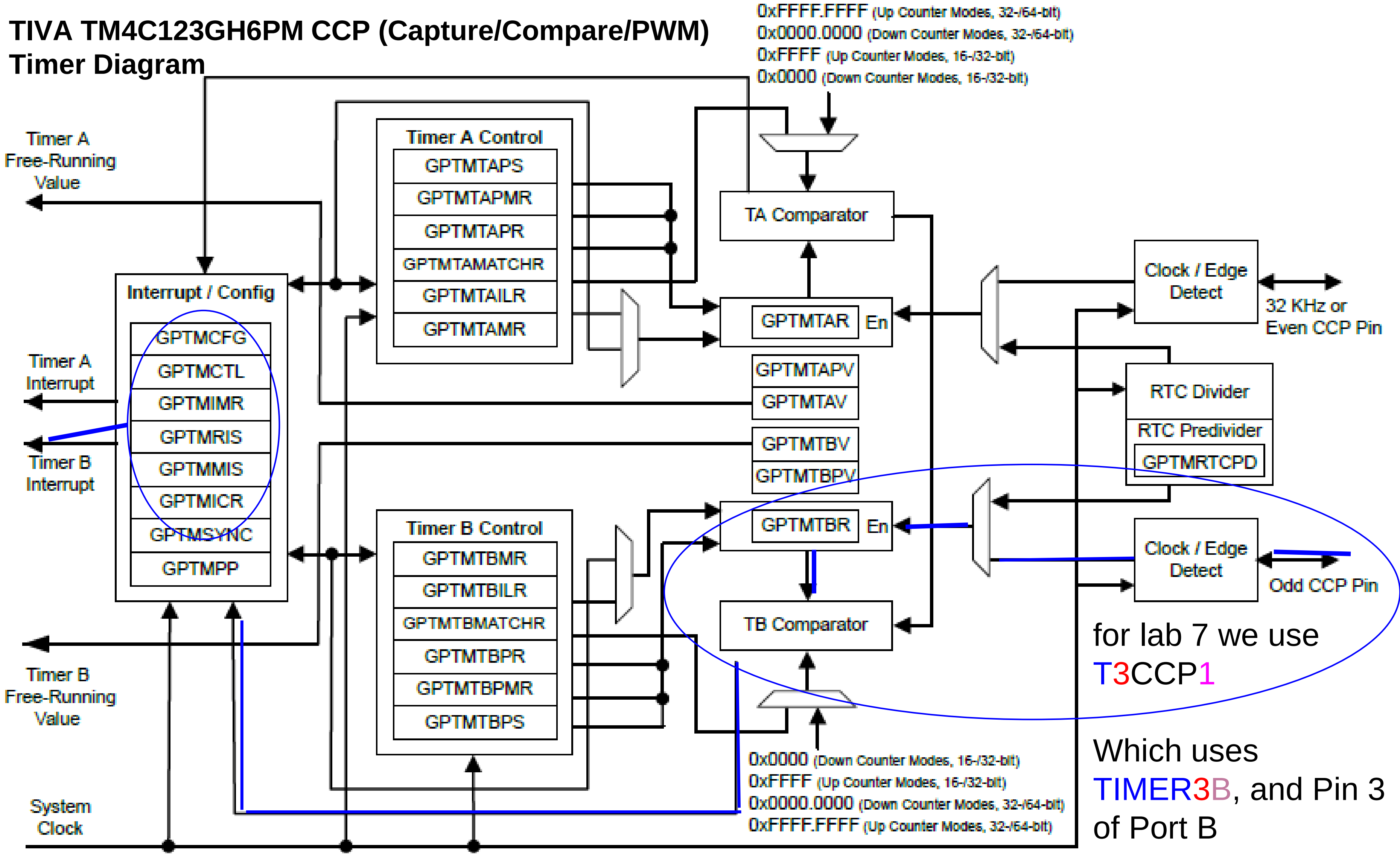


for lab 7 we use T3CCP1

Which uses TIMER3B, and Pin 3 of Port B

(More on pages 704-707 of datasheet)

Tiva TM4C123GH6PM 16/32-bit Timer as Input Capture Unit

When an edge is detected at input capture pin, current TIMERx_TnV_R (GPTMTnV) value is captured (saved) into TIMERx_TnR_R (GPTMTnR)

Time is captured **immediately** (when an event happens) and read by the CPU later

Use Input Capture: Example

```
int last_event_time;

int main(void){
    //configurations and inits
    IntRegister(INT_TIMER3B, TIMER3B_Handler);
}
void TIMER3B_Handler(void)
{
   int event_time = TIMER3_TBR_R;
    // read current event time
   // YOUR PROCESSING CODE
}
```

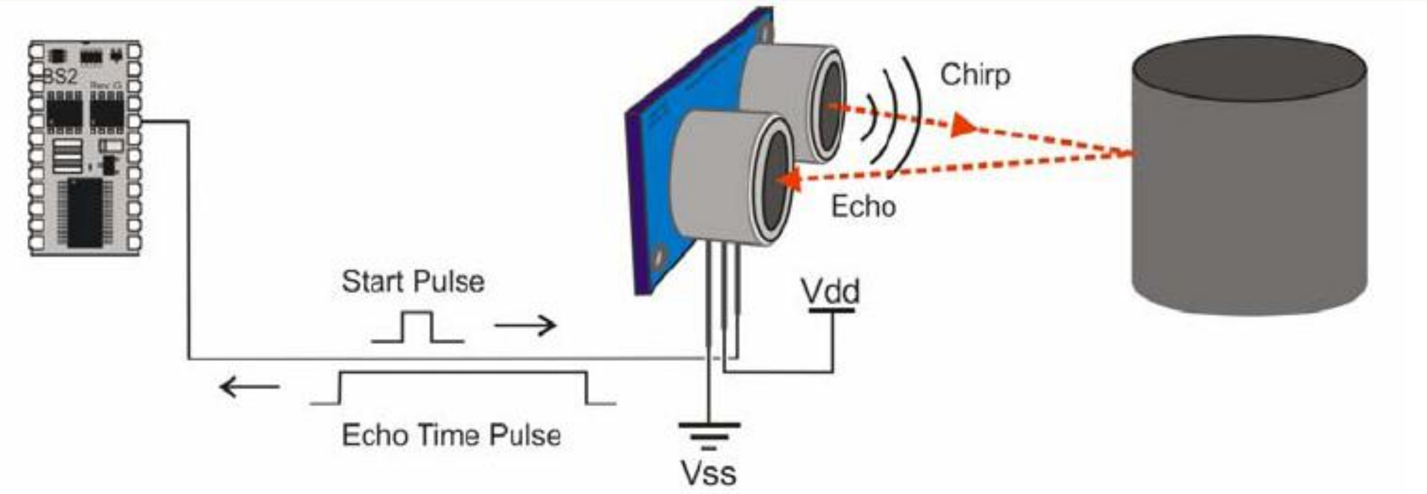
Notes:

- Use Interrupt to process input capture events
- Read captured time from TIMER3_TBR_R

Lab 7 General Idea of Programming

General idea:

- Configure Timer3B for input capture
- Generate a pulse to activate the PING))) sensor
- Capture the time of rising edge event
- Capture the time of falling edge event
- Calculate time difference and then distance to any object

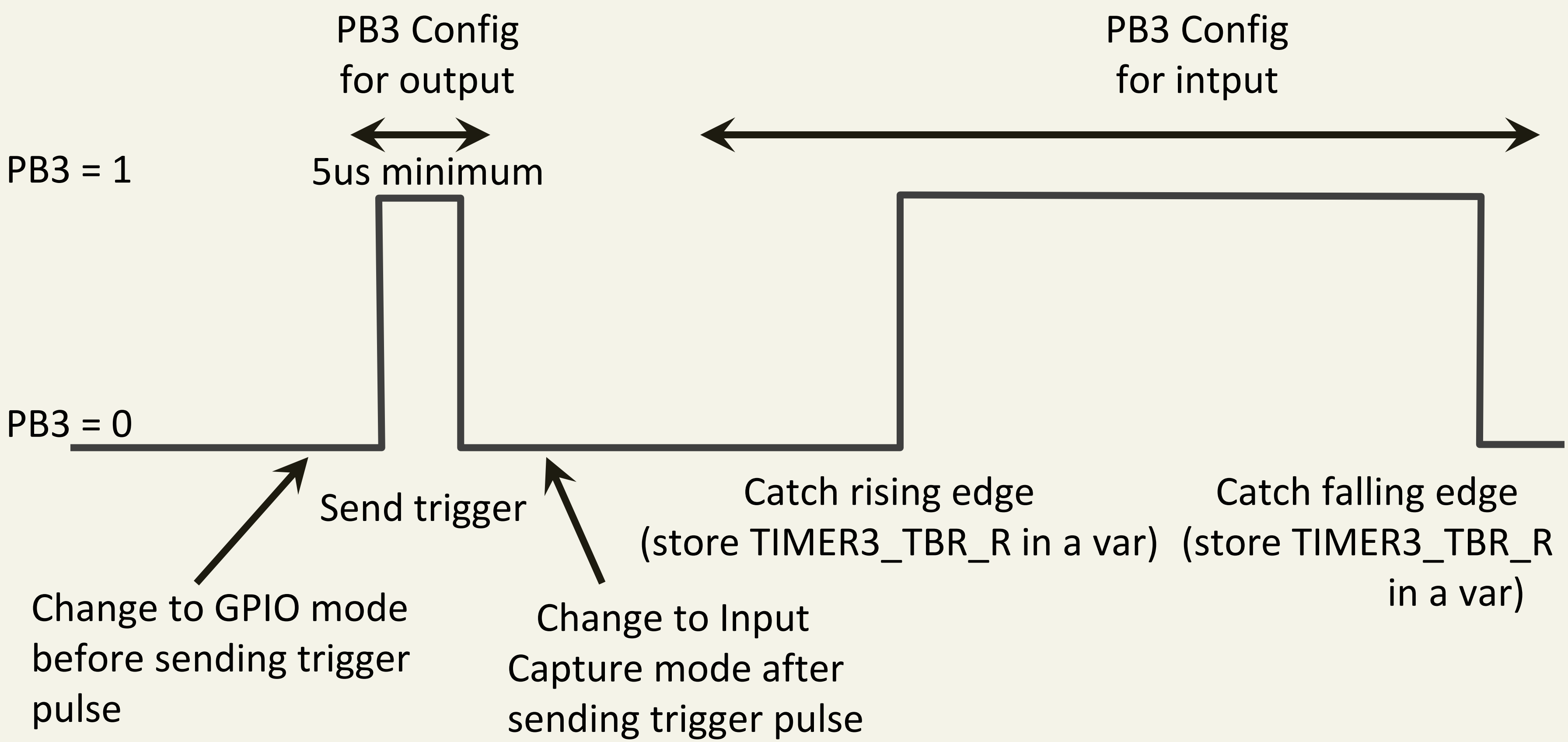


Application: Sonar Device

PING Sensor Datasheet:

- http://class.ece.iastate.edu/cpre288/resources/docs/28015-PING-v1.3.pdf

Lab 7 General Idea of Programming



Remember only one pin (i.e PB3) used to communicate with the PING))) sensor

Timer Programming Interface

GPTMCTL: GPTM (General Purpose Timer) Control

GPTMCFG: GPTM Configuration

GPTMTnMR: GPTM Timer n Mode (n is A or B)

GPTMTnILR: GPTM Timer n Interval Load

GPTMIMR: GPTM Interrupt Mask Register

GPTMMIS: GPTM Masked Interrupt Status

GPTMICR: GPTM Interrupt Clear Register

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16-bit Timer Programming Interface

Inside GPTMCTL:

- **TnPWML 6, 14** (A, B): PWM Output Level
- **TnOTE 5, 13** (A, B): Output trigger enable
- **TnEVENT 3:2, 11:10** (A, B): Event Mode (Edge Select)
- **TnSTALL 1, 9** (A, B): Timer n Stall Enable
- **TnEN 0, 8** (A, B): Timer n Enable
- **RTCEN 4** : RTC Stall Enable

GPTMCTL (TIMERx_CTL_R)

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
	reserved															
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	reserved	TBPWML	TBOTE	reserved	TBEVENT		TBSTALL	TBEN	reserved	TAPWML	TAOTE	RTCEN	TAEVENT		TASTALL	TAEN
Type	RO	RW	RW	RO	RW	RW	RW	RW	RO	RW	RW	RW	RW	RW	RW	RW
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

TnEVENT: GPTM **Timer n Event Mode** – Which edge will trigger an interrupt?

00: Positive (rising) edge

01: Negative (falling) edge

10: Reserved

11: Both

TnEN: GPTM **Timer n Enable Bit** – Set this bit to enable Timer n.

Make sure a timer is *disabled* before trying to change its settings.

(from p. 737 of datasheet)

GPTMCFG (TIMERx_CFG_R)

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
	reserved															
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	reserved													GPTMCFG		
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RW	RW	RW
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

GPTMCFG: GPTM Configuration

0x0: “Concatenated” mode. (16/32 bit timers use 32 bits, 32/64 bit timers use 64 bits.)

0x1: Concatenated mode, and timers are set to RTC (real-time clock) counter configuration.

0x4: 16/32 bit timers are spilt into two 16-bit timers, timer A and timer B. 32/64 bit timers are split into two 32-bit timers.

Other values for GPTMCFG: are reserved.

(p. 727 of datasheet)

GPTMTnMR (TIMERx_TnMR_R)

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
	reserved															
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	reserved				TAPLO	TAMRSU	TAPWMIE	TAILD	TASNAPS	TAWOT	TAMIE	TACDIR	TAAMS	TACMR	TAMR	
Type	RO	RO	RO	RO	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

GPTMTnMR: GPTM Timer n Mode – Controls Timer mode.

When in concatenated mode, GPTMTAMR controls the concatenated timer and GPTMTBMR is ignored.

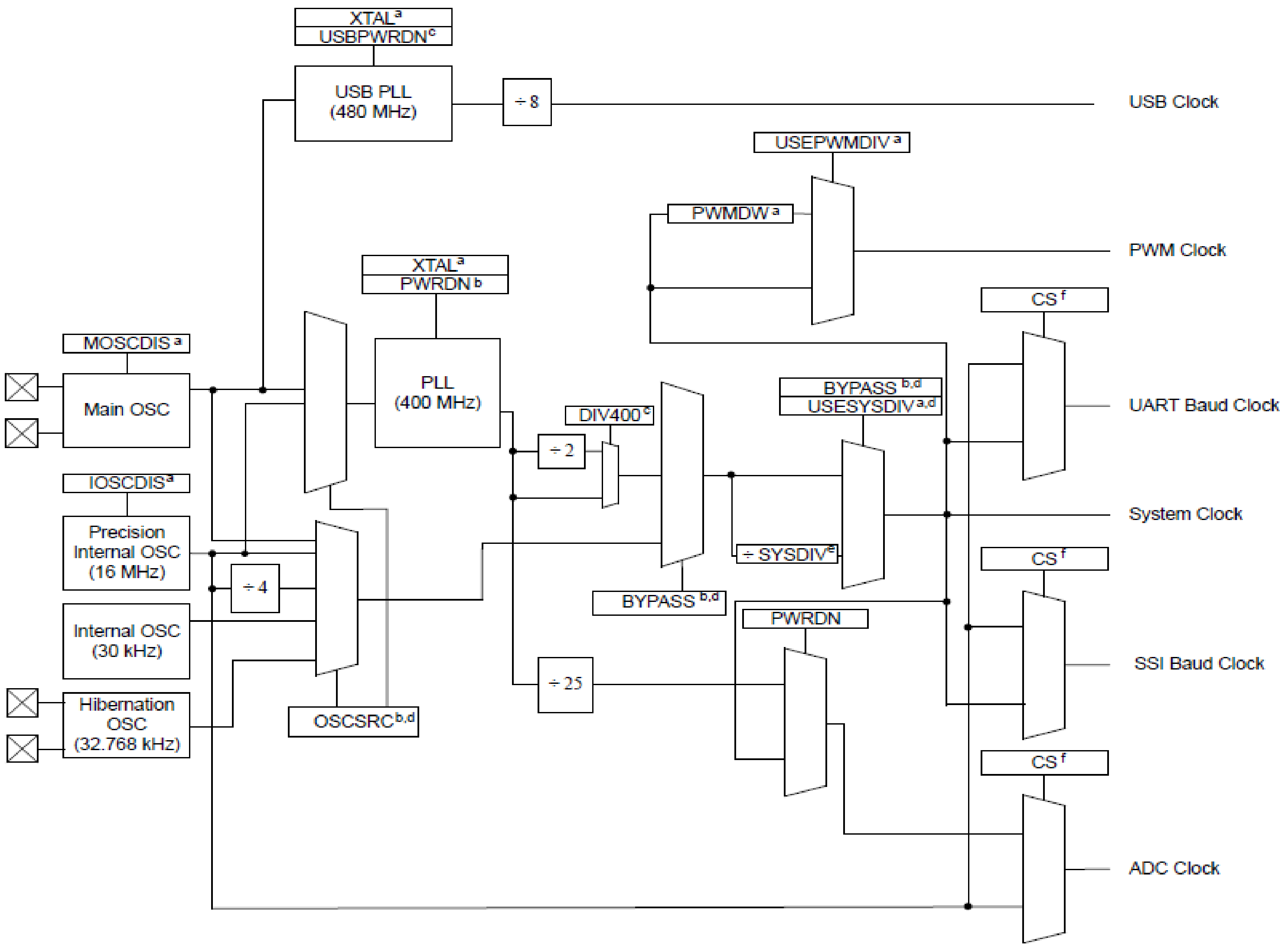
TnMR: Timer n Mode

- **0x0**: Reserved
- **0x1**: One-Shot Timer Mode
- **0x2**: Periodic Timer Mode
- **0x3**: Capture Mode

(p. 729 (Timer A) & 733 (Timer B) of datasheet)

TM4C123 Clock Sources

Figure 5-5. Main Clock Tree



GPTMTnILR (TIMERx_TnILR_R)

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
	TBILR															
Type	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW
Reset	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	TBILR															
Type	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW	RW
Reset	0	0	1	0	0	1	1	0	0	1	0	0	1	0	1	1

When timer n is counting up GPTMTnILR contains the upper bound. When counting down GPTMTnILR contains the initial value for timer n.

Important Note: In lab 7, if **TIMER3_TBILR_R** is set to the max 0xFFFF (default), then the prescalar register (**TIMER3_TBPS_R**) will concatenate with the timer value register to make a **24-bit** register. To get the correct values you must read from **both** **TIMER3_TBPS_R** & **TIMER3_TBR_R** and shift accordingly. **TIMER3_TBPS_R** is the **most significant 8 bits** in the 24 bit register.

(p. 757, 761, 770)

GPTMIMR (TIMERx_IMR_R)

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
	reserved															WUEIM
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RW
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	reserved				TBMIM	CBEIM	CBMIM	TBTOIM	reserved			TAMIM	RTCIM	CAEIM	CAMIM	TATOIM
Type	RO	RO	RO	RO	RW	RW	RW	RW	RO	RO	RO	RW	RW	RW	RW	RW
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

For any interrupt in GPTMIMR write to the corresponding bit:

- 0 to disable the interrupt
- 1 to enable the interrupt

CnEIM: Timer n Capture Mode Event Interrupt Mask

(p. 745 of datasheet)

GPTMMIS (TIMERx_MIS_R)

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
	reserved															WUEMIS
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	reserved				TBMMIS	CBEMIS	CBMMIS	TBTOMIS	reserved			TAMMIS	RTCMIS	CAEMIS	CAMMIS	TATOMIS
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

The **GPTMMIS** register shows the status of *unmasked* interrupts. Each timer n has 1 ISR vector which all of its interrupts trigger, so it is necessary to check the GPTMMIS register to see which specific interrupts were set.

CnEMIS: Timer n, Capture Mode Event Flag

(p. 751 of datasheet)

GPTMICR (TIMERx_ICR_R)

	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
	reserved															WUECINT
Type	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RO	RW
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
	reserved				TBMCINT	CBECINT	CBMCINT	TBTOCINT	reserved			TAMCINT	RTCCINT	CAECINT	CAMCINT	TATOCINT
Type	RO	RO	RO	RO	W1C	W1C	W1C	W1C	RO	RO	RO	W1C	W1C	W1C	W1C	W1C
Reset	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

To clear an interrupt flag write a 1 to the corresponding bit in GPTMICR.

CnECINT: Clears the Timer n Capture Mode Event Flag

(p. 754 of datasheet)

Configure Timer3B for Lab 7

TIMER3_CTL_R: Enable, Edge Select.
TIMER3_CFG_R: 16-bit mode.
TIMER3_TBMR_R: Capture Mode, Edge-Time Mode, Count up.
TIMER3_TBILR_R: Set upper bound.
TIMER3_IMR_R: Enable capture interrupt.

Port B pin 3 (PB3) – It is Timer3B's Capture/Compare/PWMv (CCP) pin, and connects to the input/output pin of the PING sensor

IC Programming Example

```
volatile enum {LOW, HIGH, DONE} state;
volatile unsigned rising_time;        // start time of the return pulse
volatile unsigned falling_time;       // end time of the return pulse

/* start and read the ping sensor once, return distance in mm */
unsigned ping_read()
{
    …
}

/* ping sensor related to ISR */
void TIMER3B_Handler(void)
{
    …
}
```

Note 1: This code does not work for Lab 7 as it is.

Note 2: Does <u>not</u> follow timing example of slide 28.

```
/* send out a pulse on PB3 */
void send_pulse()
{
  GPIO_PORTB_DIR_R |= 0x08;              // set PB3 as output
  GPIO_PORTB_DATA_R |= 0x08;    // set PB3 to high
  // wait at least 5 microseconds based on data sheet
  GPIO_PORTB_DATA_R &= 0xF7;    // set PB3 to low
  GPIO_PORTB_DIR_R &= 0xF7;     // set PB3 as input
}

/* convert time in clock counts to single-trip distance in mm */
unsigned time2dist(unsigned time)
{
  …
}
```

Note 1: This code does not work for Lab 7 as it is.

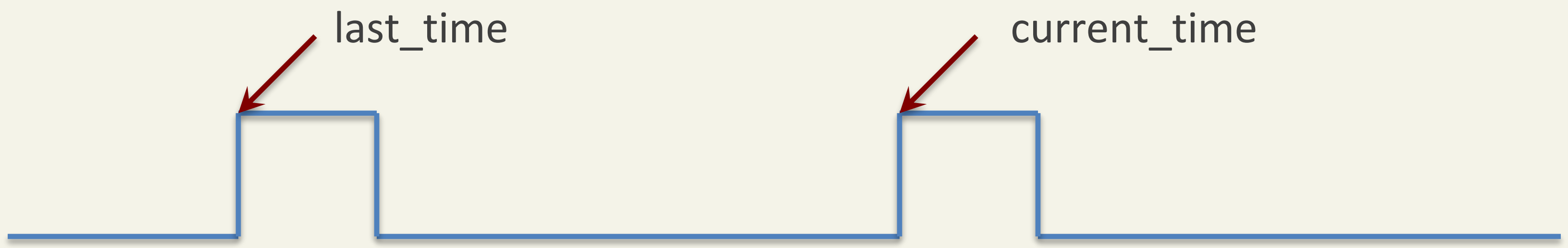
Note 2: Does not follow timing example of slide 28.

```
unsigned ping_read()
{
  send_pulse();                    // send the starting pulse to PING

  // TODO get time of the rising edge of the pulse

  // TODO get time of the falling edge of the pulse

  // Calculate the width of the pulse; convert to centimeters

}
```

ADD-ON SLIDES

CCP Programming Example

- Treadmill



Assume

- The sensor input is connected to Timer 1A Capture Compare PWM Pin (T1CCP0)
- L is the circumference (length of circle) of the wheel

CCP Programming Example

```c
volatile unsigned last_time = 0;
volatile unsigned current_time = 0;
volatile int update_flag = 0;

// ISR: Record the current event time
void TIMER1A_Handler(void)
{
   last_time = current_time;
   current_time = TIMER1_TAR_R;
   update_flag = 1;
}
```

Recall: We have to declare "volatile" for global variables changed by ISRs, otherwise a normal function may not see the changes

Polling- vs. Interrupt-Based Programming

Polling: Your code keeps checking I/O events

For Input Capture, your code may check CAE flag

```
while ((TIMER1_MIS_R & TIMER_MIS_CAEMIS) == 0)
    {}
print_speed();
TIMER1_ICR_R |= TIMER_ICR_CAECINT;
// clear ICF1
```

Note: CAEMIS is cleared by writing 1 to CAECINT. (**Always check the datasheet for such details.**)

Polling- vs. Interrupt-Based Programming

Why polling?

- Program control flow looks simple
- Interrupts have overheads added to the processing delay
- Not every programmer likes writing ISRs

Why NOT polling?

- The CPU cannot do anything else
- The CPU cannot sleep to save power
- Using ISRs can simplify the control structure of the main program

Overflow

Are we concerned with overflow in the calculation?

```
time_diff = current_time - last_time;
```

What happens if `current_time` is ***less*** than `last_time`?

If we use the prescalar register to concatenate with the 16-bit register to make a 24-bit register:

Overflow: Change from 0xFFFFFF to 0x000000

0xFFFFFF is 16777216 in decimal, it takes over 1 second for our 16MHz clock to overflow the timer. Considering the time scale of our PING))) sensor readings, we would never have more than 1 overflow at a time. One overflow can be accounted for easily.

Overflow

```
unsigned long time_diff;

overflow += (current_time < last_time);
time_diff = ((unsigned long)overflow<<24)
          + current_time - last_time;
update_flag = 0;
```

- Overflow occurred if current_time < last_time
- For each overflow, increase time_diff by 16,777,216 (2^{24})
- You have to use long integer which is 32-bit (0 to 2^{32}-1)