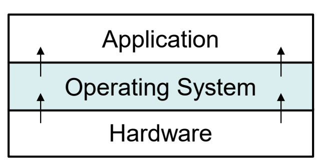
EE445M/ECE380L.12
Embedded and Real-Time Systems/ Real-Time Operating Systems

Lecture 1: Introduction, TM4C123 Microcontroller, ARM Cortex-M

Operating System

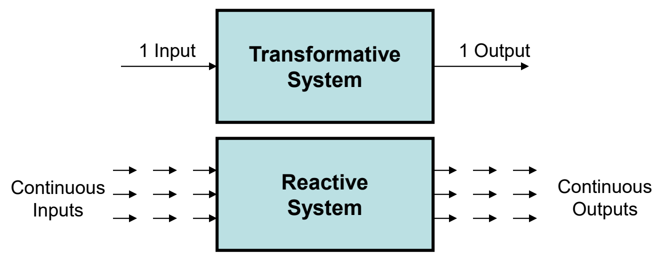
- Manage, provide abstractions for hardware



– CPU -> Parallel tasks, threads (Labs 2-3)
– Storage -> Files (Lab 4)
– Memory -> Heap, processes (Lab 5)
– I/O -> Hardware-specific (Lab 6)

Reactive Systems

- Interactive, event-driven
  - Parallel input/output events/streams
  - Some are real-time (limits on reaction time)



➢Embedded systems, GUIs

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Parallel Processing (1)

- Distributed systems
  - Multiple computers, separate memory, I/O or network link
    - Simultaneous execution of two or more software tasks
    - E.g. Lab 6 (CAN), Internet

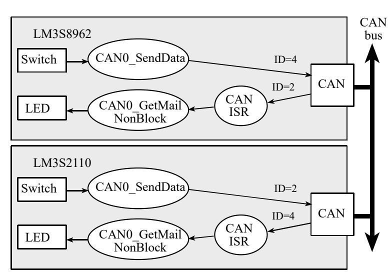

Figure 9.6. Simple CAN network.

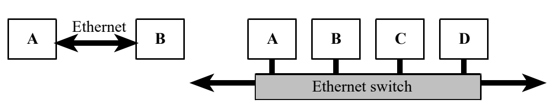

Figure 9.14. Ethernet has a bus-based topology.

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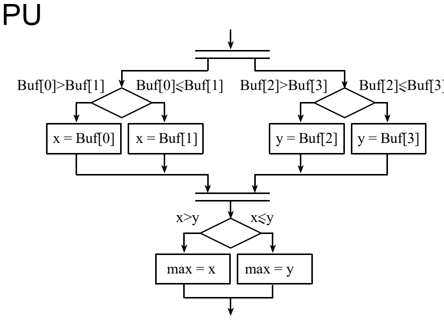
Parallel Processing (2)

- Multi-processing
  - Multiple processors, shared memory
    - Simultaneous execution of two or more software programs (tasks)
    - E.g. multicore CPU, GPU



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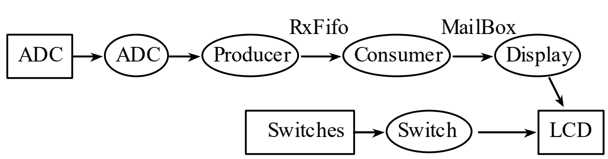
Parallel Processing (2)

- Multi-threading / Multi-tasking
  - Single processor/core (in a distributed and/or multi-processor system)
    - One foreground and multiple background threads (interrupt-driven)
    - Multiple foreground threads using a thread scheduler (*operating system, OS*)



    - Multiple independent programs (tasks)

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Class Setup

- Class web page
  - http://www.ece.utexas.edu/~gerstl/ee445m_s22/
- Canvas
  - Announcements, lab report upload, grades
- Communication
  - Piazza for general class discussion
  - Gradescope for exam grading and feedback
  - Mailing list: s22_ee445m@utlists.utexas.edu (all Professor & TAs)
- Office hours
  - Prof. (Zoom/EER 5.882), TAs (Zoom/lab): See online posted Weekly Schedule Prof.'s Zoom office hours scheduled via Canvas

Course Overview

- Labs (50%)
  - Lab 1: UART, display, ADC (EE445L review)
  - Lab 2: RTOS kernel
  - Lab 3: Scheduling
  - Lab 4: File & disk I/O
  - Lab 5: Memory, process loader
  - Lab 6: Networking, robot interfaces
  - Lab 7: Robot racing (last week of classes)

  (Labs 1–5: Teams of 2; Labs 6–7: Teams of 3-5)
- Exams (50%)
  - Midterm: Thu, 3/24, in class (tentative)
  - Final: Sat, 5/14, 9am-noon (regularly scheduled)
- Graduate project (20%)
  - Independent RTOS project (proposal by end of February)

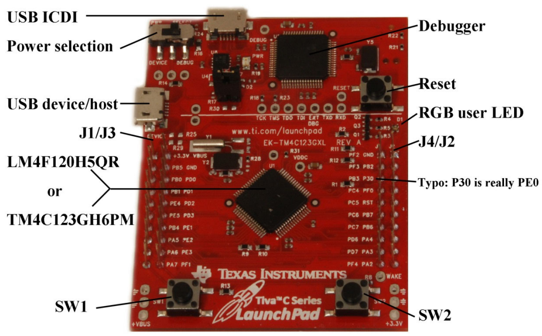
Announcements

- Labs
  - *No activities this week*
  - TA demos & partner selection next week
  - Lab 1 starts in week 3
- Equipment to get (recommended: each student)
  - TM4C123 LaunchPad board (Lab 1)
  - ST7735 LCD display (Lab 1) – requires soldering
  - Optional: USB logic analyzer (Lab 2), multimeter (Lab 6/7)
- We will provide (on loan, return at end of class)
  - Sensor & motor board, robot parts (optionally: display/Wifi)
- Setup laptop to be able to work independently
  - ARM environment: Keil µVision 5.x (not 4.7x!) or gcc
  - Starter and driver code: ValvanoWareTM4C123v5
  - Putty or HyperTerminal (serial terminal)

Lab Access
(When We Return to Campus)

- Lab space: EER 1.806 (Embedded Systems Lab)
  - Used for checkouts/demos, TA office hours
  - PCs, soldering stations, scopes, logic analyzers, …
  - Shared with EE445L & Senior Design
- MakerSpace
  - Free for any student
  - Laser cutters, PCB mill, 3D printers, …

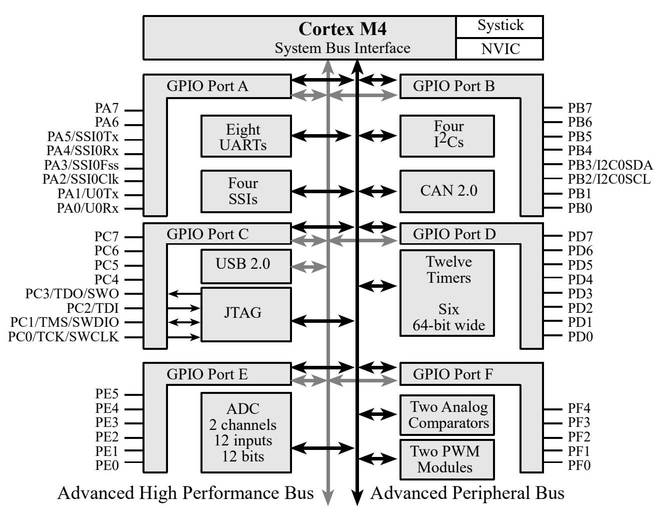
Texas Instruments LaunchPad



Debug connections:
- Female-male connectors (attach to top)
  - https://www.adafruit.com/products/826
  - DigiKey H1505-ND (Hirose DF11-2428SCA)

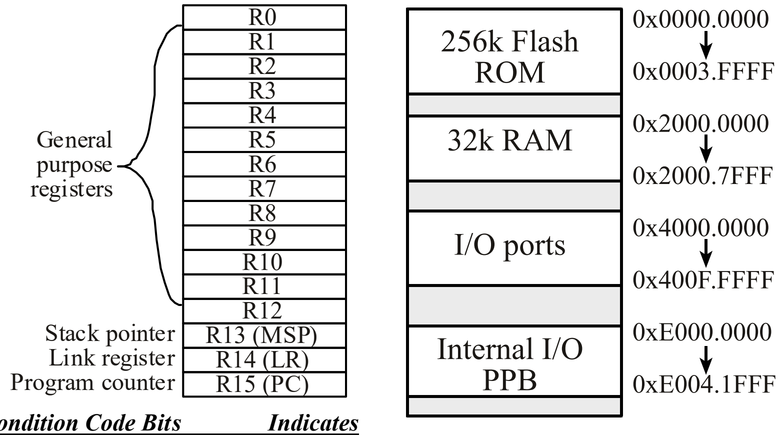
- **Reference material**
  - http://www.ece.utexas.edu/~gerstl/ee445m_s22/resources.html
  - http://www.ece.utexas.edu/~valvano/arm/ (starter files, example projects)
- **TI manuals**
  - http://www.ti.com/lit/ug/spmu296/spmu296.pdf (LaunchPad User's Guide)
  - http://www.ti.com/lit/ds/symlink/tm4c123gh6pm.pdf (TM4C123 data sheet)
  - http://www.ti.com.cn/cn/lit/ug/spmu159a/spmu159a.pdf (Cortex-M4 instruction set)
- **ARM manuals**
  - https://static.docs.arm.com/ddi0439/b/DDI0439B_cortex_m4_r0p0_trm.pdf (Cortex-M4 technical reference)

Texas Instruments TM4C123



ARM Cortex-M4
+ 256K EEPROM
+ 32K RAM
+ JTAG
+ SysTick
+ ADC
+ UART
+ General-Purpose I/O
- 4x 8-bit (A, B, C, D)
- 1x 6-bit (E)
- 1x 5-bit (F)

Registers, Memory-map



Condition Code Bits		***Indicates***
N	negative	Result is negative
Z	zero	Result is zero
V	overflow	Signed overflow
C	carry	Unsigned overflow

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ARM Thumb Instruction Set

- Arithmetic/Logic

```
AND R1, R2, R3                ; register
EOR/ORR R1,R2,#-1             ; immediate, 12-bit
LSR R1,R1,#4                  ; logic shift
ADD{S} R1,R2,R3, LSL #2       ; R1=R2+R3*4  {set condition codes}
SUB{S} R1,R3, ASR #2          ; R1=R1+R3/4  {set condition codes}
CMP R2,R3                     ; compare
```

- Data movement

```
MOV R0,#100                   ; immediate
ADR R0,Label                  ; load address
LDR R0,=Label                 ; uses PC-relative
STR{H} R1,[R0]                ; indexed  {16-bit halfword}
LDR{{S}H} R1,[R0,#n]          ; offset indexed  {{signed} halfword}
```

- Control

```
B Target                      ; unconditional
BEQ/BNE Target                ; (in)quality
BLO/BLS/BHI/BHS Target        ; unsigned <,<=,>,>=
BLT/BLE/BGT/BGE Target        ; signed <,<=,>,>=
```

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Function calls

```
void delay (int cnt){
  while (cnt--);
}

void main(void) {
 delay(10);
}
```

```
delay
      SUB     R0,R0,#0x01
      BNE     delay
      BX      LR

main
     MOV     R0,#0x0A
     BL      delay
```

AAPCS: Parameters in **R0-R3**, return in **R0**

Follow the link register LR

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Stack

```
void function1 (void)
{
  output(0x01);
}

int main (void) {
  …
  function1();
  …
}
```

```
function1
        PUSH   {R4-R6,LR}
        MOV    R0,#0x01
        MOV    R4,#12
        BL     output
        POP    {R4-R6,PC}

main
...
        BL     function1
...
```

R4-R11 must be saved

Draw a stack picture

The accesses happen in order of decreasing (push)/increasing (pop) register numbers, with the lowest numbered register using the lowest memory address (top of stack) and the highest number register using the highest memory address

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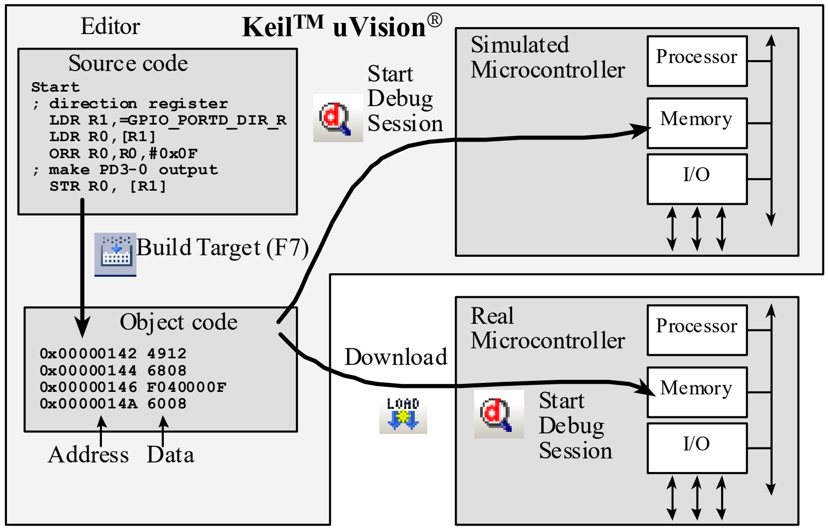
SW Development Environment



General-Purpose I/O (GPIO)

Address	7	6	5	4	3	2	1	0	Name
400F.E608	-	-	GPIOF	GPIOE	GPIOD	GPIOC	GPIOB	GPIOA	SYSCTL_RCGCGPIO_R
xxxx.x3FC	DATA	DATA	DATA	DATA	DATA	DATA	DATA	DATA	GPIO_PORTx_DATA_R
xxxx.x400	DIR	DIR	DIR	DIR	DIR	DIR	DIR	DIR	GPIO_PORTx_DIR_R
xxxx.x420	SEL	SEL	SEL	SEL	SEL	SEL	SEL	SEL	GPIO_PORTx_AFSEL_R
xxxx.x510	PUE	PUE	PUE	PUE	PUE	PUE	PUE	PUE	GPIO_PORTx_PUR_R
xxxx.x51C	DEN	DEN	DEN	DEN	DEN	DEN	DEN	DEN	GPIO_PORTx_DEN_R

- **Initialization**
  1. Turn on clock in **`SYSCTL_RCGCGPIO_R`**
  2. Wait two bus cycles (two NOP instructions)
  3. Set *DIR* to 1 for output or 0 for input
  4. Clear *AFSEL* & *AMSEL* bits to 0 to select regular I/O
  5. Set *DEN* bits to 1 to enable data pins
- **Input/output from pin**
  6. Read/write **`GPIO_PORTx_DATA_R`**

Bit-Specific Port I/O

- Bit-specific addressing is used to access port data register
  - Define address offset as $4*2^b$, where b is the selected bit position
  - 256 possible bit combinations (0-8)
  - Add offsets for each bit selected to base address for the port
  - Other bits masked during access
  - **`DATA_R`** @ *base*+$3FC equals all bits

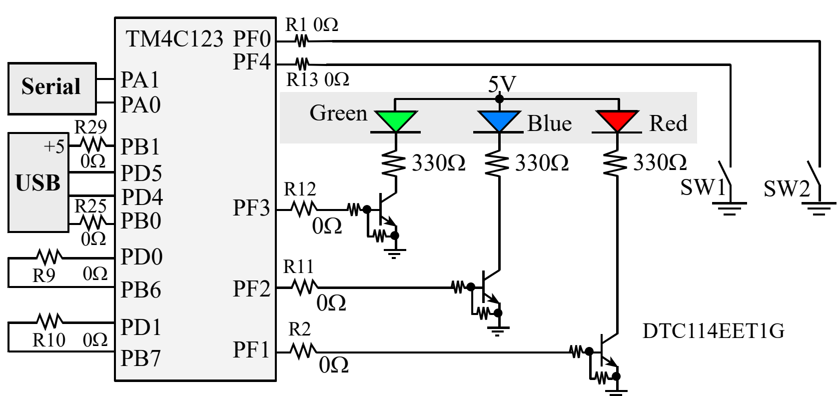
If we wish to access bit	*Constant*
7	0x0200
6	0x0100
5	0x0080
4	0x0040
3	0x0020
2	0x0010
1	0x0008
0	0x0004

Example: PF4 and PF0

```
Port F = 0x4005.D000
0x4005.D000+0x0004+0x0040
= 0x4005.D044
```

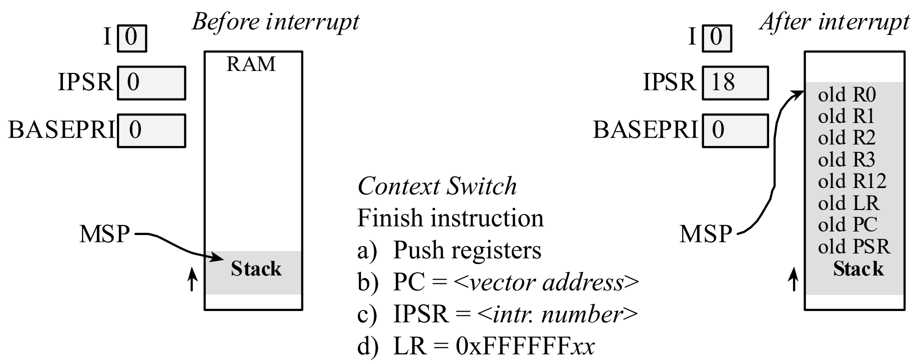
Provides friendly and atomic access to port pins

LaunchPad Switches and LEDs



- The switches on the LaunchPad
  - Negative logic, require internal pull-up (set bits in PUR)
- The PF3-1 LEDs are positive logic

Interrupts **



** More details in Lecture 3

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Interrupt Vectors

Startup.s

Vector address	Number	IRQ	ISR name in Startup.s	NVIC	Priority bits
0x00000038	14	-2	PendSV_Handler	NVIC_SYS_PRI3_R	23 – 21
0x0000003C	15	-1	SysTick_Handler	NVIC_SYS_PRI3_R	31 – 29
0x00000040	16	0	GPIOPortA_Handler	NVIC_PRI0_R	7 – 5
0x00000044	17	1	GPIOPortB_Handler	NVIC_PRI0_R	15 – 13
0x00000048	18	2	GPIOPortC_Handler	NVIC_PRI0_R	23 – 21
0x0000004C	19	3	GPIOPortD_Handler	NVIC_PRI0_R	31 – 29
0x00000050	20	4	GPIOPortE_Handler	NVIC_PRI1_R	7 – 5
0x00000054	21	5	UART0_Handler	NVIC_PRI1_R	15 – 13
0x00000058	22	6	UART1_Handler	NVIC_PRI1_R	23 – 21
0x0000005C	23	7	SSI0_Handler	NVIC_PRI1_R	31 – 29
0x00000060	24	8	I2C0_Handler	NVIC_PRI2_R	7 – 5
0x00000064	25	9	PWMFault_Handler	NVIC_PRI2_R	15 – 13
0x00000068	26	10	PWM0_Handler	NVIC_PRI2_R	23 – 21
0x0000006C	27	11	PWM1_Handler	NVIC_PRI2_R	31 – 29
0x00000070	28	12	PWM2_Handler	NVIC_PRI3_R	7 – 5
0x00000074	29	13	Quadrature0_Handler	NVIC_PRI3_R	15 – 13
0x00000078	30	14	ADC0_Handler	NVIC_PRI3_R	23 – 21
0x0000007C	31	15	ADC1_Handler	NVIC_PRI3_R	31 – 29
0x00000080	32	16	ADC2_Handler	NVIC_PRI4_R	7 – 5
0x00000084	33	17	ADC3_Handler	NVIC_PRI4_R	15 – 13
0x00000088	34	18	WDT_Handler	NVIC_PRI4_R	23 – 21
0x0000008C	35	19	Timer0A_Handler	NVIC_PRI4_R	31 – 29
0x00000090	36	20	Timer0B_Handler	NVIC_PRI5_R	7 – 5
0x00000094	37	21	Timer1A_Handler	NVIC_PRI5_R	15 – 13
0x00000098	38	22	Timer1B_Handler	NVIC_PRI5_R	23 – 21
0x0000009C	39	23	Timer2A_Handler	NVIC_PRI5_R	31 – 29
0x000000A0	40	24	Timer2B_Handler	NVIC_PRI6_R	7 – 5
0x000000A4	41	25	Comp0_Handler	NVIC_PRI6_R	15 – 13
0x000000A8	42	26	Comp1_Handler	NVIC_PRI6_R	23 – 21
0x000000AC	43	27	Comp2_Handler	NVIC_PRI6_R	31 – 29
0x000000B0	44	28	SysCtl_Handler	NVIC_PRI7_R	7 – 5
0x000000B4	45	29	FlashCtl_Handler	NVIC_PRI7_R	15 – 13
0x000000B8	46	30	GPIOPortF_Handler	NVIC_PRI7_R	23 – 21
0x000000BC	47	31	GPIOPortG_Handler	NVIC_PRI7_R	31 – 29
0x000000C0	48	32	GPIOPortH_Handler	NVIC_PRI8_R	7 – 5
0x000000C4	49	33	UART2_Handler	NVIC_PRI8_R	15 – 13
0x000000C8	50	34	SSI1_Handler	NVIC_PRI8_R	23 – 21
0x000000CC	51	35	Timer3A_Handler	NVIC_PRI8_R	31 – 29
0x000000D0	52	36	Timer3B_Handler	NVIC_PRI9_R	7 – 5
0x000000D4	53	37	I2C1_Handler	NVIC_PRI9_R	15 – 13
0x000000D8	54	38	Quadrature1_Handler	NVIC_PRI9_R	23 – 21
0x000000DC	55	39	CAN0_Handler	NVIC_PRI9_R	31 – 29
0x000000E0	56	40	CAN1_Handler	NVIC_PRI10_R	7 – 5
0x000000E4	57	41	CAN2_Handler	NVIC_PRI10_R	15 – 13
0x000000E8	58	42	Ethernet_Handler	NVIC_PRI10_R	23 – 21
0x000000EC	59	43	Hibernate_Handler	NVIC_PRI10_R	31 – 29
0x000000F0	60	44	USB0_Handler	NVIC_PRI11_R	7 – 5
0x000000F4	61	45	PWM3_Handler	NVIC_PRI11_R	15 – 13
0x000000F8	62	46	uDMA_Handler	NVIC_PRI11_R	23 – 21
0x000000FC	63	47	uDMA_Error	NVIC_PRI11_R	31 – 29

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Nested Vectored Interrupt Controller (NVIC)

- Priorities (global level in **BASEPRI**)

Address	31 – 29	23 – 21	15 – 13	7 – 5	Name
0xE000E400	GPIO Port D	GPIO Port C	GPIO Port B	GPIO Port A	NVIC_PRI0_R
0xE000E404	SSI0, Rx Tx	UART1, Rx Tx	UART0, Rx Tx	GPIO Port E	NVIC_PRI1_R
0xE000E408	PWM Gen 1	PWM Gen 0	PWM Fault	I2C0	NVIC_PRI2_R
0xE000E40C	ADC Seq 1	ADC Seq 0	Quad Encoder	PWM Gen 2	NVIC_PRI3_R
0xE000E410	Timer 0A	Watchdog	ADC Seq 3	ADC Seq 2	NVIC_PRI4_R
0xE000E414	Timer 2A	Timer 1B	Timer 1A	Timer 0B	NVIC_PRI5_R
0xE000E418	Comp 2	Comp 1	Comp 0	Timer 2B	NVIC_PRI6_R
0xE000E41C	GPIO Port G	GPIO Port F	Flash Control	System Control	NVIC_PRI7_R
0xE000E420	Timer 3A	SSI1, Rx Tx	UART2, Rx Tx	GPIO Port H	NVIC_PRI8_R
0xE000E424	CAN0	Quad Encoder 1	I2C1	Timer 3B	NVIC_PRI9_R
0xE000E428	Hibernate	Ethernet	CAN2	CAN1	NVIC_PRI10_R
0xE000E42C	uDMA Error	uDMA Soft Tfr	PWM Gen 3	USB0	NVIC_PRI11_R
0xE000ED20	SysTick	PendSV	--	Debug	NVIC_SYS_PRI3_R

- Interrupt enable
  - **NVIC_EN0_R** and **NVIC_EN1_R**

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SysTick Timer

Address	31-24	23-17	16	15-3	2	1	0	Name
$E000E010	0	0	COUNT	0	CLK_SRC	INTEN	ENABLE	NVIC_ST_CTRL_R
$E000E014	0	24-bit RELOAD value						NVIC_ST_RELOAD_R
$E000E018	0	24-bit CURRENT value of SysTick counter						NVIC_ST_CURRENT_R

- Timer/Counter
  - 24-bit counter decrements at bus clock frequency
    - With 80 MHz bus clock, decrements every 12.5 ns
  - Counting is from $n \rightarrow 0$
    - Setting *n* appropriately will make the counter a modulo *n*+1 counter:
      - next_value = (current_value-1) mod (n+1)
      - Sequence: n,n-1,n-2,n-3… 2,1,0,n,n-1…
- Initialization
  1. Clear *ENABLE* to stop counter
  2. Specify the *RELOAD* value
  3. Clear the counter via **NVIC_ST_CURRENT_R**
  4. Set *CLK_SRC*=1 and specify interrupt action via *INTEN*

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System Tick (Initialization)

```
void SysTick_Init(unsigned long period) {     volatile unsigned long delay;
  SYSCTL_RCGC2_R |= SYSCTL_RCGC2_GPIOD; // activate port D
  Counts = 0;  delay = SYSCTL_RCGC2_R;   // init, allow time to finish
  GPIO_PORTD_DIR_R |= 0x01;      // make PD0 output
  GPIO_PORTD_DEN_R |= 0x01;     // enable digital I/O on PD0

  NVIC_ST_CTRL_R = 0;               // disable SysTick during setup
  NVIC_ST_RELOAD_R = period - 1; // reload value
  NVIC_ST_CURRENT_R = 0;         // any write to current clears it
                                             // Systick=priority 2
  NVIC_SYS_PRI3_R =  (NVIC_SYS_PRI3_R&0x00FFFFFF)|0x40000000;
  NVIC_ST_CTRL_R = NVIC_ST_CTRL_ENABLE+NVIC_ST_CTRL_CLK_SRC
                           +NVIC_ST_CTRL_INTEN;
  EnableInterrupts();
}
```

PeriodicSysTickInts_4C123

System Tick

```
#define GPIO_PD0  (*((volatile unsigned long *) 0x40007004))

void SysTick_Handler(void) {
  GPIO_PD0 = GPIO_PD0^0x01;
  Counts = Counts + 1;
}

void main(void){
…
 SysTick_Init(50000);        // 1msec, assuming 50 MHz bus clock
…
}
```

Reset debugger:
- stop in ISR and
- single step through ISR
- look at assembly code

PeriodicSysTickInts_4C123

Other Peripherals (Lab 1)

- Serial I/O (UART)
  - `UARTInts_4C123`
- Analog-to-digital conversion (ADC)
  - `ADCSWTrigger_4C123`
- LCD display (ST7735) via GPIO
  - `ST7735_4C123`
- General-purpose timers
  - `PeriodicTimer2AInts_4C123` (Timer2A)

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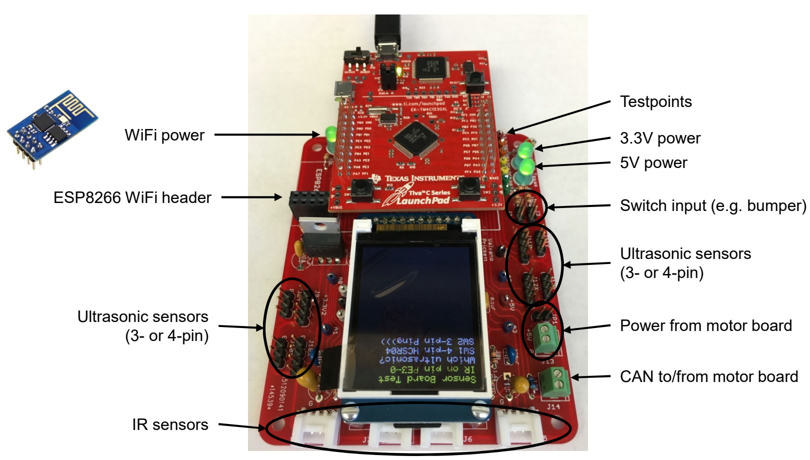
Sensor Board (Labs 1-7)



- **Reference material**
  - **Schematic:** http://www.ece.utexas.edu/~gerstl/ee445m_s16/resources/Robot_Sensor_v3.pdf
  - **PCB layout:** http://www.ece.utexas.edu/~gerstl/ee445m_s16/resources/sensor_top3.png

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Terminal I/O

- UART0 connected to USB serial port
- How to do terminal input/output?
  1. Write your own, like **`UARTInts`**
  2. Use *sprintf*() to create strings then output string
  3. Retarget and link to standard library
     - Output using stdlib function *printf*()
       - *fputc*() & *_ttywrch*() mapped to Your_*UART_OutChar*()
     - Input using stdlib function *getchar*()
       - *fgetc*() mapped to *Your_UART_InChar*()

Stdio Retargeting

```
int fputc(int ch, FILE *f){
  UART_OutChar(ch);
  return (1);
}

int fgetc (FILE *f){
  return (UART_InChar());
}

int ferror(FILE *f){
  /* Your implementation of ferror */
  return EOF;
}
```

retarget.c in C:\Keil_v5\ARM\Startup

Starter Code and Driver Lib

- How much code to reuse?
  - Starter files (Valvano) & **`driverlib`** (TI) will have fewer bugs than any you or I write
  - You will have to certify all code working in parallel environment (critical sections)
  - Most students will want to fit code into 32k
  - All students must understand everything

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Lab 1 Starter Project

- **`RTOS_Lab1_Interpreter`** project
  - Application/user code (**`Lab1.c`**)
- **`RTOS_Labs_common`** code
  - Command line (**`Interpreter.c`**) to be developed
  - OS kernel (**`OS.c`**, **`osasm.s`**) developed in labs
  - Drivers to be developed (**`ST7735.c`**, **`ADC.c`**)
  - Custom copies of standard drivers (**`UART0Int.c`**)
- Standard drivers (from **`inc`** directory)
  - Timers, ADC, …

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Summary

- Setup Laptop & Keil
- Learn ARM assembly language
- Get your board & display
- Get familiar with TM4C123 microcontoller
- Get started on Lab 1!
  - If you can finish Lab 1 by yourself, you will be fine in this class…