Special Topics for Embedded Programming

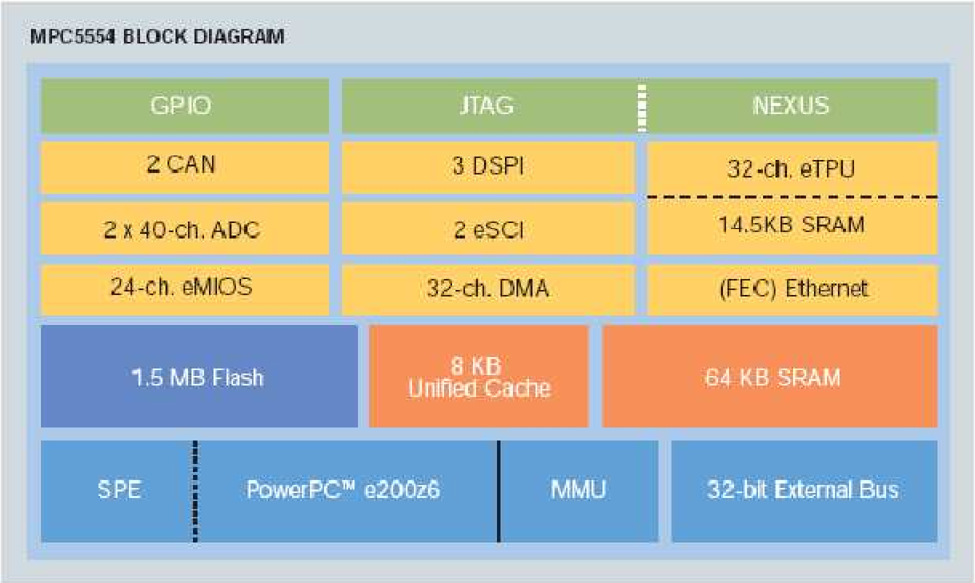
Reference: The C Programming Language by Kernighan & Ritchie

Overview of Topics

- Microprocessor architecture
  - Peripherals
  - Registers
  - Memory mapped I/O
- C programming for embedded systems
- Lab 1: General Purpose I/O
  - Read data from input pins and write to output pins on the MPC5553
  - GPIO example code

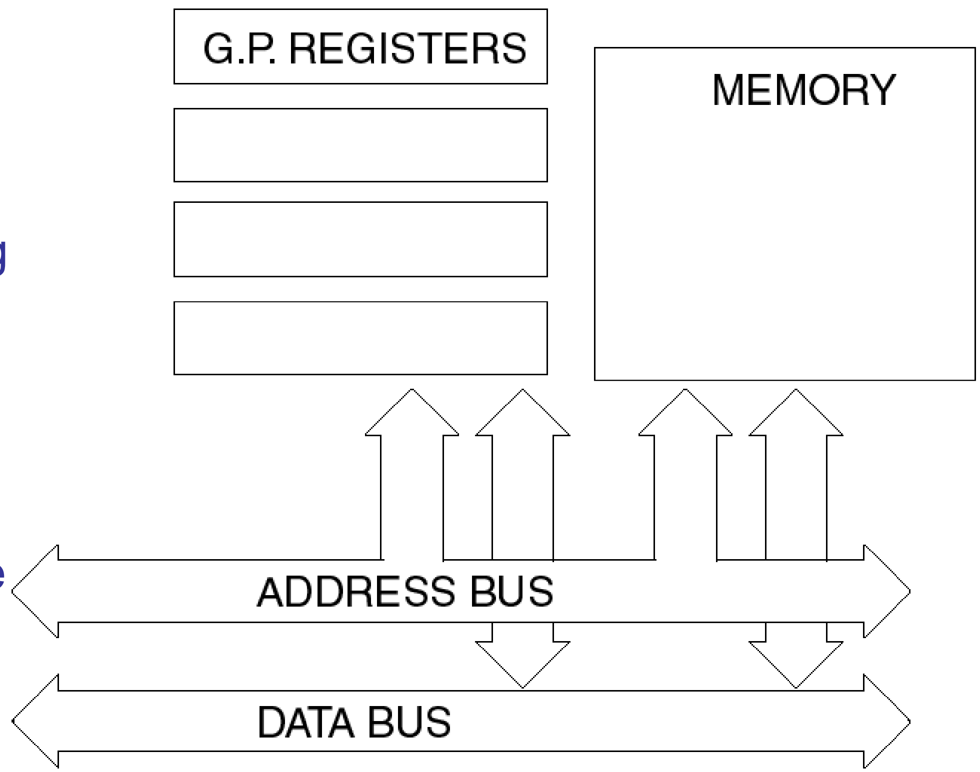
Freescale MPC55xx Architecture

- 132 MHz 32-bit PowerPC, Temperature range: -40 to 125ºC
- 1.5 MB of embedded Flash
- 64 KB on-chip static RAM
- 8 KB of cache
- 210 selectable-priority interrupt sources
- 3 DSPI (serial peripheral interface)
- 2 eSCI (serial communications)
- GPIO
- 2 x 40-ch. ADC
- 24-ch. eMIOS
- 2 CAN
- 32-ch. eTPU
- Direct Memory Access (DMA)



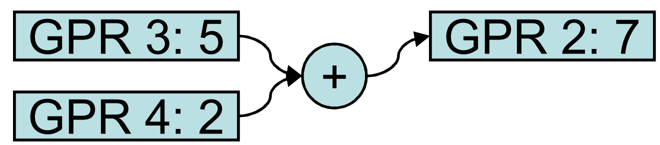
Microprocessor Architecture

- Microprocessor memory has location (“address”) and contents (the data stored at a specific address in memory)
- Data are accessed by specifying a location on the address bus, and reading the contents of the specified address on the data bus
- Registers are memory locations used for calculations, to initialize the processor or check its status, or to access peripheral devices.
  - General purpose registers
  - Special purpose registers



General Purpose Registers

- Hold data values before and after calculations
- C compilers automatically use these registers as resources to load/store data & perform calculations



Special Purpose Registers: Memory Mapped I/O

- Access peripherals by writing to and reading from memory
- Each peripheral has a fixed range of memory addresses assigned to it
  - These are "memory-mapped registers," used for interacting with peripherals
- Memory locations can be:
  - Peripheral configuration registers
  - Peripheral status registers
  - inputs from the hardware
  - outputs to the hardware

Table 21-2. Module Memory Map

Address	Register Name	Register Description	Size (bits)
Base 0xFFFB_0000 (A) 0xFFFB_4000 (B)	ESCIx_CR1	eSCI control register 1	32
Base + 0x04	ESCIx_CR2	eSCI control register 2	16
Base + 0x06	ESCIx_DR	eSCI data register	16
Base + 0x08	ESCIx_SR	eSCI status register	32
Base + 0x0C	ESCIx_LCR	LIN control register	32
Base + 0x10	ESCIx_LTR	LIN transmit register	32
Base + 0x14	ESCIx_LRR	LIN receive register	32
Base + 0x18	ESCIx_LPR	LIN cyclic redundancy check polynomial register	32

C Programming for Embedded Systems

Primitive Data Types, Data Declaration

- Integer data types
  - Have both size and sign
  - char (8-bit)
  - short (16-bit)
  - int (32-bit)
  - long (32-bit)
  - signed (positive and negative)
  - unsigned (positive only)
- Floating-point types
  - Only have size
  - Can always be positive or negative
  - float (32-bit)
  - double (64-bit)
- Data declarations should be at the top of a code block

```
{
/* Top of Code Block
*/
signed char A;
char input;
unsigned short var;
int output;
unsigned long var2;

float realNum;
double realNum2;

.
}
```

Freescale Defined Types

- See freescale/typedefs.h
  - `typedef signed char int8_t;`
  - `typedef unsigned char uint8_t;`
  - `typedef volatile signed char vint8_t;`
  - `typedef volatile unsigned char vuint8_t;`
  - `typedef signed short int16_t;`
  - `typedef unsigned short uint16_t;`
  - …

Functions and Function Prototypes

- Function Prototype declares name, parameters and return type prior to the functions actual declaration
- Information for the compiler; does not include the actual function code
- You will be given function prototypes to access peripherals
- Pro forma: `RetType FcnName (ArgType ArgName, … );`

```
int Sum (int a, int b);     /* Function Prototype */
void main()
{
        c = Sum ( 2, 5 );          /* Function call */
}
        int Sum (int a, int b)    /* Function Definition */
                {
            return ( a + b );
                }
```

C vs. C++

- C++ language features cannot be used
  - No `new, delete, class`
  - Comment with `/* */` , not `//`
- Variables must be declared at top of code blocks

```
{
int j;
double x;

/* code */
int q;                  /* only in C++, not in C */
/* code */
}
```

Useful Features for Embedded Code

- Type Qualifiers
  - Volatile
  - Static
- Pointers
- Structures
- Unions
- Bit Operations
- Integer Conversions

Volatile Type Qualifier

- Variables that tend to be reused repeatedly in different parts of the code are often identified by compilers for optimization.
  - These variables are often stored in an internal register that is read from or written to whenever the variable is accessed in the code.
  - This optimizes performance and can be a useful feature
- Problem for embedded code: Some memory values may change without software action!
  - Example: Consider a memory-mapped register representing a DIP-switch input
  - Register is read and saved into a general-purpose register
  - Program will keep reading the same value, even if hardware has changed
- Use `volatile` qualifier:
  - Value is loaded from or stored to memory every time it is referenced
  - Example: `volatile unsigned char *GPIO_pointer;`

Static Type Qualifier

- Variables local to functions are destroyed when the function returns a value and exits (they have *local scope*)
- In embedded code we often want a variable to retain its value between function calls
  - Consider a function that senses a change in the crankshaft angle: The function needs to know the previous angle in order to compute the difference
- If a local variable within a function is declared static, it is stored in the “heap” (a dedicated pool of memory) instead of the function “stack” (a temporary storage) and will thus retain its value between subsequent function calls
- When used with global variables and functions, static limits the scope of the variable to its file.
- Example: `static int x = 2 ;`

Pointers

- Every variable has an *address* in memory and a *value*
- A pointer is a variable that stores an address
  - The value of a pointer is the location of another variable
- The size of a pointer variable is the size of an address
  - 4 bytes (32 bits) for the MPC5553
- Two operators used with pointers
  - **`&`** operator returns the address of a variable
  - **`*`** is used to "de-reference" a pointer (*i.e.*, to access the *value* at the *address* stored by a pointer

Pointer Example

Address	Value	Variable
0x100	5	x
0x104	5	y
0x108	0x100	ptr

```
int x, y;             /* x is located at address 0x100 */
int *ptr;             /* This is how to declare a pointer */

x = 5;
ptr = &x;             /* The value of ptr is now 0x100 */
y = *ptr;             /* y now has the value 5 */
*ptr = 6;             /* The value at address 0x100 is 6 */
```

More Pointer Examples

- Declare a pointer,

```
volatile int     *p;
```

- Assign the address of the I/O memory location to the pointer,

```
p = (volatile int*) 0x30610000;
/* 4-byte long, address of some memory-
mapped register */
```

- Output a 32-bit value by setting the value of bytes at 0x30610000,

```
*p = 0x7FFFFFFF;   /* Turn on all but
the highest bit */
```

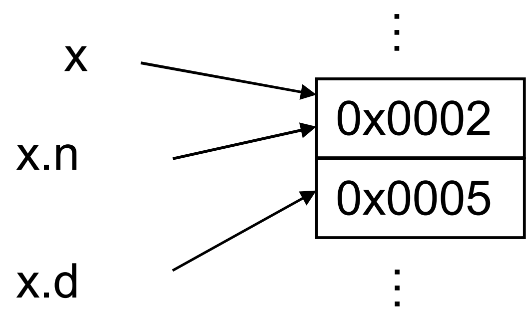
- Alternatively,

```
*((volatile unsigned
short*)(0x30610000)) = 0x7FFF;
```

Structures

- A `struct` holds multiple variables
  - Divides range of memory into pieces that can be referenced individually
  - The following structure creates a variable `x` of type `rational` with members `n` and `d`

```
struct rational { short n;
 short d; } x;
x.n = 2;
x.d = 5;
```



- Recall: We can treat a peripheral’s memory map as a range of memory.
- Result: We can use a structure and its member variables to access peripheral registers.

Structures

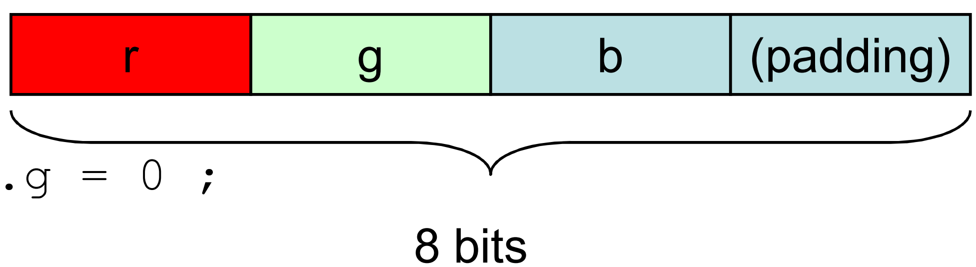
- Access structure member variables using "." and "->"
  - . is used with structures
  - -> is used with pointers-to-structures
- Example
  - `bob` is a variable of type `student`
  - Assign `firstnm`, `lastnm` and `age`
  - Increment `age`

```
/* Definition */
struct student{
   char firstnm[32];
   char lastnm[32];
   int age;
};
void main()
{
  struct student bob;
  struct student *pbob;

  bob.age = 20;
  strcpy(bob.firstnm, "Bob");
  strcpy(bob.lastnm, "Smith");

  pbob = &bob;
  pbob->age++;
  /* same as (*pbob).age++ */
};
```

Structure bit-fields

Number of bits per data member in structures is specified with ":n"

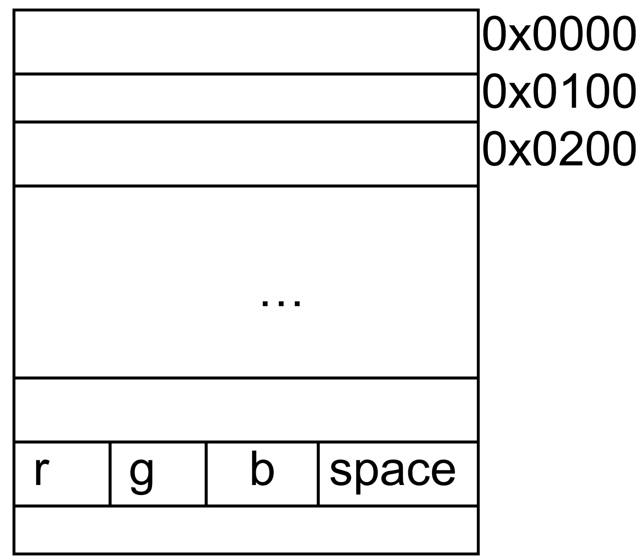
```
struct RGB_color{
  unsigned char r:2; /* 2-bits */
  unsigned char g:2;
  unsigned char b:2;
  /* padding */
  unsigned char:2;  /*don't need to explicitly do this. */
};
```




```
/* reset g */
struct RGB_color clr; clr.g = 0 ;
```

Bit-Fields Diagram

- But what if we want to access r,g & b all at the same time?



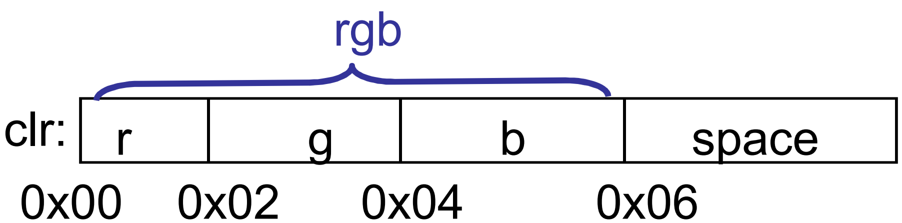
Unions

- Multiple ways to view memory locations
- Unions contain member variables
  - Member variables **share same memory**
  - All variables are overlaid on each other
- Changing one member results in the other members being changed
- Union is as long as longest member

Two ways
To read the
Same memory
location

Memory Location 0x0716			
rgb: 6			padding
r : 2	g : 2	b : 2	padding

Unions




```
union RGB_color{
    struct {
      unsigned char r:2,g:2,b:2;
      unsigned char:2;
    };
    struct {
      unsigned char rgb:6;
      unsigned char:2;
  }};
union RGB_color clr;
```

Pros & Cons of Using Structures

- Pros
  - Readable code
  - Simple way to set or clear individual bits
- Cons
  - Relies on the compiler implementation
  - Assembly code for a simple bit-write is much longer than if registers were directly written to

Constants and Bit Operations

Tools for Manipulating Values

Integer Constants

- Binary constant: 0b*number*
  - Example: `0b10110000`
- Octal constant: 0*number* (prefix is a zero)
  - Example: `0775`
- Hexadecimal constant: 0x*number*
  - Example: `0xffff` or `0xFFFF`

Bit Operations

- Bit-shifts
  - Right shift: `num >> shift` `0b1001 >> 2 → 0b0010`
  - Left shift: `num << shift` `0b0011 << 2 → 0b1100`
- Masking
  - Bit-or: `num | mask` `0b0001 | 0b1000 → 0b1001`
  - Bit-and: `num & mask` `0b1001 & 0b1000 → 0b1000`
- Complement
  - Not: `~ num` `~ 0b0101 → 0b1010`
- Set bits
  - set the 5th bit `x = x | (1 << 4);`
  - set the 5th bit `x |= (1 << 4);`
- Clear bits
  - clear 5th and 6th bit `x = x & ~(0b11 << 4);`
  - clear 5th and 6th bit `x &= ~(0b11 << 4);`

Type Conversions

- Explicit Casts
  - For specifying the new data type
  - Syntax: `(type-name)expression`
  - Example: `(int)largeVar`
- Integral Promotion
  - Before basic operation (`+ - * /`), both operands converted to same type
  - The smaller type is “promoted” (increased in size) to the larger type
  - Value of promoted type is preserved
- Implicit Casts
  - Assigning a value into a different type
  - Widening conversion – preserve value of expression

```
short x = 10;  long y = x;
```

  - Narrowing conversions – do NOT preserve value

```
unsigned long x = 257;
unsigned char y = x;
```

Integer Division

- When dividing two numbers, may receive unexpected results
- If both operands are integers, then result is integer
  - Expected result of division is truncated to fit into an integer
- If one operand is floating-point, then result is floating-point
  - Integer operand is promoted to floating-point
  - Receive expected result

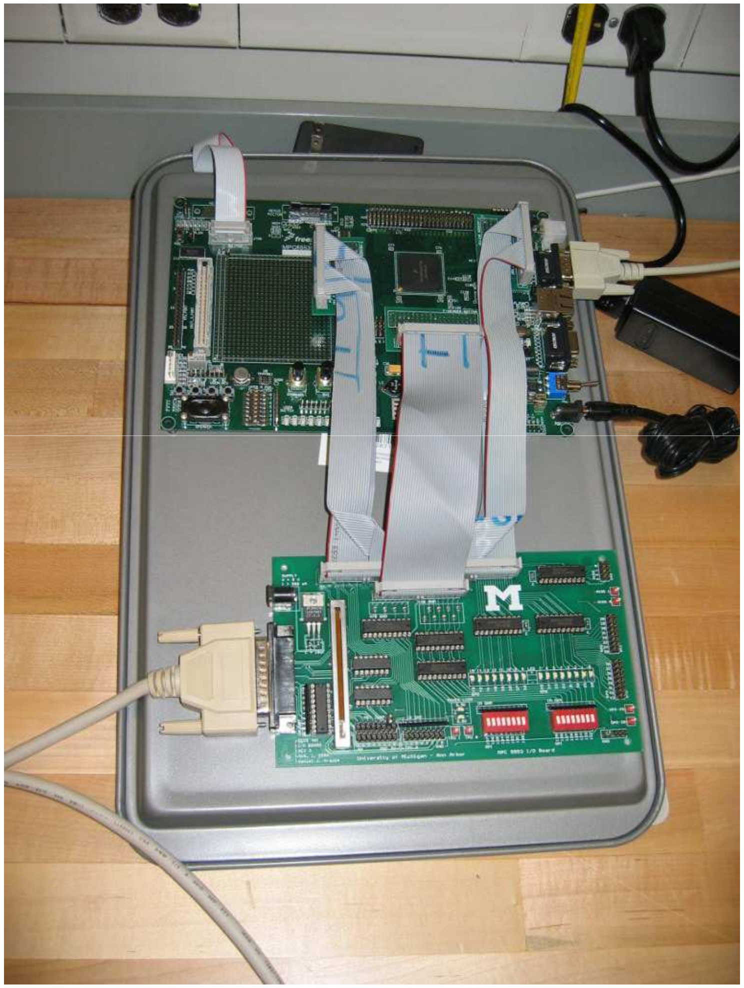
```
/* floating-point results */
(5.0 / 2.0) →  2.5  /* no promotion, result is float */
(5.0 / 2)  →  2.5   /* operand 2 promoted to float */
(5 / 2.0)  →  2.5   /* operand 5 promoted to float */

/* integer-valued results */
(5 / 2)  →  2 /* no promotion, result is integer */
```

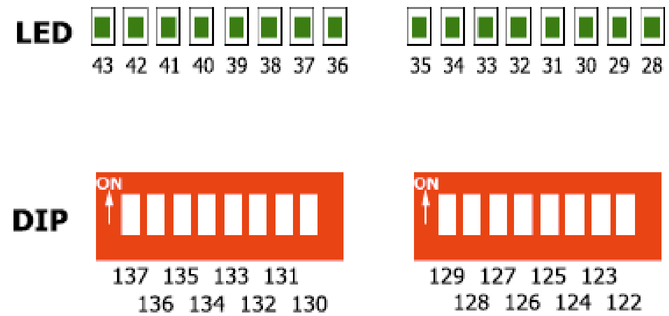
Lab 1
Familiarization and Digital I/O

Lab 1

- Program the MPC5553 for Digital I/O.
  - Write C code that performs low-level bit manipulation and writes to memory mapped registers
  - Write a simple program (lab1.c) to add two 4-bit numbers specified on the DIP switches on the interface board and echo the results onto the LED display
  - Modify your program to use serial interface and keyboard instead of DIP switches
- MPC5553/MPC5554 Microcontroller Reference Manual (on website – very large: do not print!)
  - Chapter 6, Section 6.1.3 System Integration Unit (SIU)
  - Chapter 6, Section 6.3, Memory Map/Register Definition

Lab 1 GPIO





MPC5553 Pad Connections to Interface Board

Interface board connects to pads 122 through 137 for input from DIP switches, and 28 through 43
for output to LEDs.

Lab 1 GPIO

- Three registers for each pin
  - Pad Configuration register (PCR)
  - General Purpose Data Input register (GPDI)
  - General Purpose Data Output register (GPDO)
  - Many other SIU registers
  - Most pins have alternate function (connected to other peripherals)
  - See SIU memory map, Table 6.2

Table 6-2. SIU Address Map

Address	Register Name	Register Description	Size (bits)
Base (0xC3F9_0000)	—	Reserved	—
Base + 0x4	SIU_MIDR	MCU ID register	32
Base + 0x8	—	Reserved	—
Base + 0xC	SIU_RSR	Reset status register	32
Base + 0x40–Base + 0x20C	SIU_PCR0–SIU_PCR230	Pad configuration registers 0–230	16
Base + 0x20E–Base + 0x5FF	—	Reserved	—
Base + 0x600–Base + 0x6D5	SIU_GPDO0–SIU_GPDO213	GPIO pin data output registers 0–213	8
Base + 0x6D6–Base + 0x7FF	—	Reserved	—
Base + 0x800–Base + 0x8D5	SIU_GPDI0–SIU_GPDI213	GPIO pin data input registers 0–213	8
Base + 0x8D6–	—	Reserved	—

Memory Map Table 6.2

GPIO Registers

- For each pin:
  - Pad Configuration Register (PCR) (6.3.1.12)
    - Set pin purpose
    - Turn on/off voltage buffers
  - Data Input Register (GPDI) (6.3.1.14)
    - Read voltage on pin
    - On is 1, off is 0
  - Data Output Register (GPDO) (6.3.1.13)
    - Set voltage on pin
    - On is 1, off is 0

SIU_BASE+0xAC

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R	0	0	0	PA[1]			OBE[2]	IBE[3]	DSC		ODE[4]	HYS[5]	0	0	WPE[6]	WPS[6]
W																
RESET:	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	1

	0	1	2	3	4	5	6	7
R	0	0	0	0	0	0	0	PDI*n*
W								
Reset	0	0	0	0	0	0	0	0
Reg Addr	SIU_BASE + 0x800 + *n*							

Figure 6-129. GPIO Pin Data Input Register 0–213 (SIU_GPDI*n*)

	0	1	2	3	4	5	6	7
R	0	0	0	0	0	0	0	0
W								PDO*n*
Reset	0	0	0	0	0	0	0	0
Reg Addr	SIU_BASE + 0x600 + *n*							

Figure 6-128. GPIO Pin Data Output Register 0–213 (SIU_GPDO*n*)

SIU Pad Configuration Register

SIU_BASE+0xEA

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
R	0	0	0	0	PA[1]		OBE[2]	IBE[3]	0	0	ODE	HYS	SRC		WPE	WPS
W																
RESET:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1

- Section 6.3.1.12, Table 6-15. SIU_PCR Field Descriptions
- **PA**: Pin assignment (selects the function of a multiplexed pad)
- **OBE**: Output buffer enable
- **IBE**: Input buffer enable
- DSC: Drive strength control
- ODE: Open drain output enable
- HYS: Input hysteresis enable
- SRC: Slew rate control
- **WPE**: Weak pull up/down enable (*Disable* pull up)
- WPS: Weak pull up/down select

SIU Pad Configuration Register

```
typedef union siu_pcr_u {
   /* Pad Configuration Registers */
   volatile unsigned short REG;
   struct {
        volatile unsigned short :3;
        volatile unsigned short PA:3;
        volatile unsigned short OBE:1;
        volatile unsigned short IBE:1;
        volatile unsigned short DSC:2;
        volatile unsigned short ODE:1;
        volatile unsigned short HYS:1;
        volatile unsigned short SRC:2;
        volatile unsigned short WPE:1;
        volatile unsigned short WPS:1;
   } FIELDS;
} SIU_PCR;
```

- Union accesses entire register or individual bit fields
- Provide one union generic enough to suit any SIU pad
- There are over 200 configuration registers!
  - Address each configuration register by declaring your union as a pointer
  - Use pointer indexing (I.e.: `padptr[122]`) to access a specific register

MPC5553 Register Definitions

```
/**********************************************/
/* FILE NAME: mpc5553.h
   COPYRIGHT (c) Freescale 2005 */
/* VERSION:  1.5
   All Rights Reserved     */
/*
   */
/* DESCRIPTION:
   */
/* This file contains all of the
   register and bit field definitions
   for    */
/* MPC5553.
   */
/*========================================*/


/*>>>>NOTE! this file is auto-generated
   please do not edit it!<<<<*/
```

- freescale/mpc553.h has registers, bit field definitions
  - Don’t have to write your own structure (except for lab #1)
- Register addresses at the bottom of mpc553.h
- Register definitions use freescale/typedefs.h

Read and Write GPIO

```
#include<eecs461.h>            /* Typedefs and processor initialization */
#include "my_siu_pcr.h"        /* Your SIU PCR configuration goes here */
void main()
{
          int i;
          unsigned char op1, op2;
          int result;
          int temp;
          volatile SIU_PCR *siu_pcr_ptr;          /* pointers to registers */
          volatile unsigned char *siu_gpdi_ptr;
          volatile unsigned char *siu_gpdo_ptr;

          siu_pcr_ptr =  (SIU_PCR*)(0Xc3f90040);        /* SIU_BASE + 0X40 for pcr */
          siu_gpdo_ptr = (unsigned char*)(0Xc3f90600);  /* SIU_BASE + 0X600 for gpdo */
          siu_gpdi_ptr = (unsigned char*)(0Xc3f90800);  /* SIU_BASE + 0X800 for gpdi */
                                                         /* See Table 6.2 */
```

Read and Write GPIO (continued)

```
/* configure input dipswitches */
        for(i=122; i<130; i++)
        {
                siu_pcr_ptr[i].FIELDS.PA = 0;  /* GPIO */
                siu_pcr_ptr[i].FIELDS.IBE = 1; /* Input */
                siu_pcr_ptr[i].FIELDS.WPE = 0; /* Weak pull up disabled */
        }

/* configure output leds */
        for(i=28; i<33; i++)
        {
                siu_pcr_ptr[i].FIELDS.PA = 0;  /* GPIO */
                siu_pcr_ptr[i].FIELDS.OBE = 1; /* Output */
                siu_pcr_ptr[i].FIELDS.WPE = 0;
        }
    init_EECS461(1); /* Call this function with lab number = 1 to init processor */
```

Read and Write GPIO (continued)

```
while(1)
        {
                /* get the number contained on DIP 126-129 and 122-125 */
                        /* read the bit
                           shift left 1
                           read the next bit and continue */
                 /* calculate the sum */
                /* display the result  on LED 28-32 */
                        /* write result LSB
                           shift right 1
                           write the next bit and continue */
        }
```

Read Serial Port and Write GPIO

- Use keyboard input instead of DIP switches
  - Input 2 digits (0-9), calculate sum and output binary result to LEDs
  - `serial.c, serial.h` provided
- ASCII to binary conversion

ASCII	Binary	Decimal
`011 0001`	`0001`	`1`
`011 0010`	`0010`	`2`
… …	…	
`011 1001`	`1001`	`9`

```
Binary = ASCII & 0xF
```

Lab 1 GPIO

- Read the lab 1 documentation
- Organize your file structure as described in section 2.3
- Pre-lab
  - Read the manual and answer the questions
- In-lab
- Post-lab
  - Summarize the concepts learned in lab 1