Components of a Microprocessor

Components of a Microprocessor

- Memory:
  - Storage of data
  - Storage of a program
  - Either can be temporary or “permanent” storage
- Registers: small, fast memories
  - General purpose: store arbitrary data
  - Special purpose: used to control the processor

Components of a Microprocessor

- Instruction decoder:
  - Translates current program instruction into a set of control signals
- Arithmetic logical unit:
  - Performs both arithmetic and logical operations on data
- Input/output control modules

Components of a Microprocessor

- Many of these components must exchange data with one-another
- It is common to use a ‘bus’ for this exchange

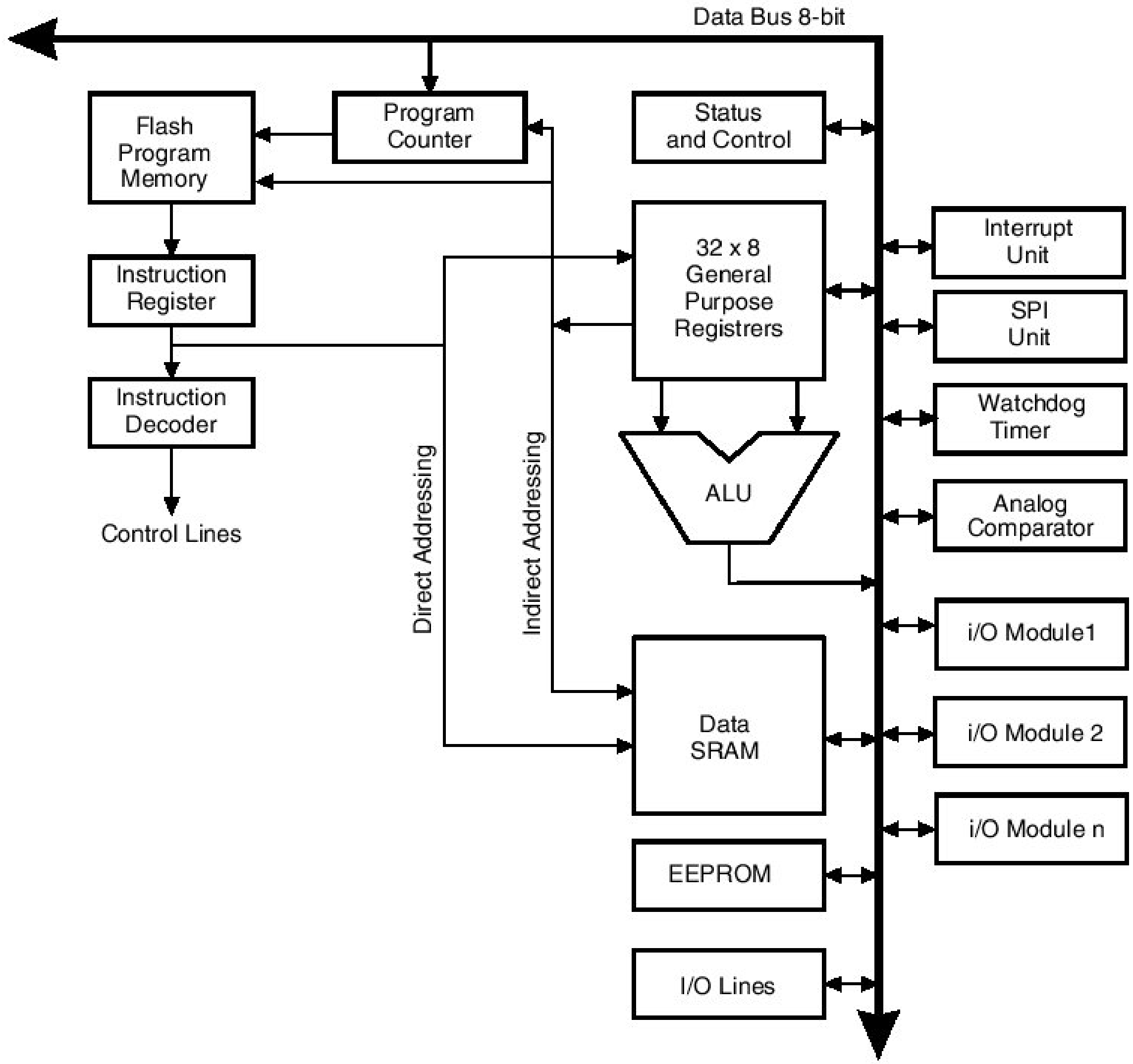
Buses

- In the simplest form, a bus is a single wire
- Many different components can be attached to the bus
- Any component can take input from the bus or place information on the bus

Buses

- At most one component may write to the bus at any one time
- In a microprocessor, which component is allowed to write is usually determined by the code that is currently executing

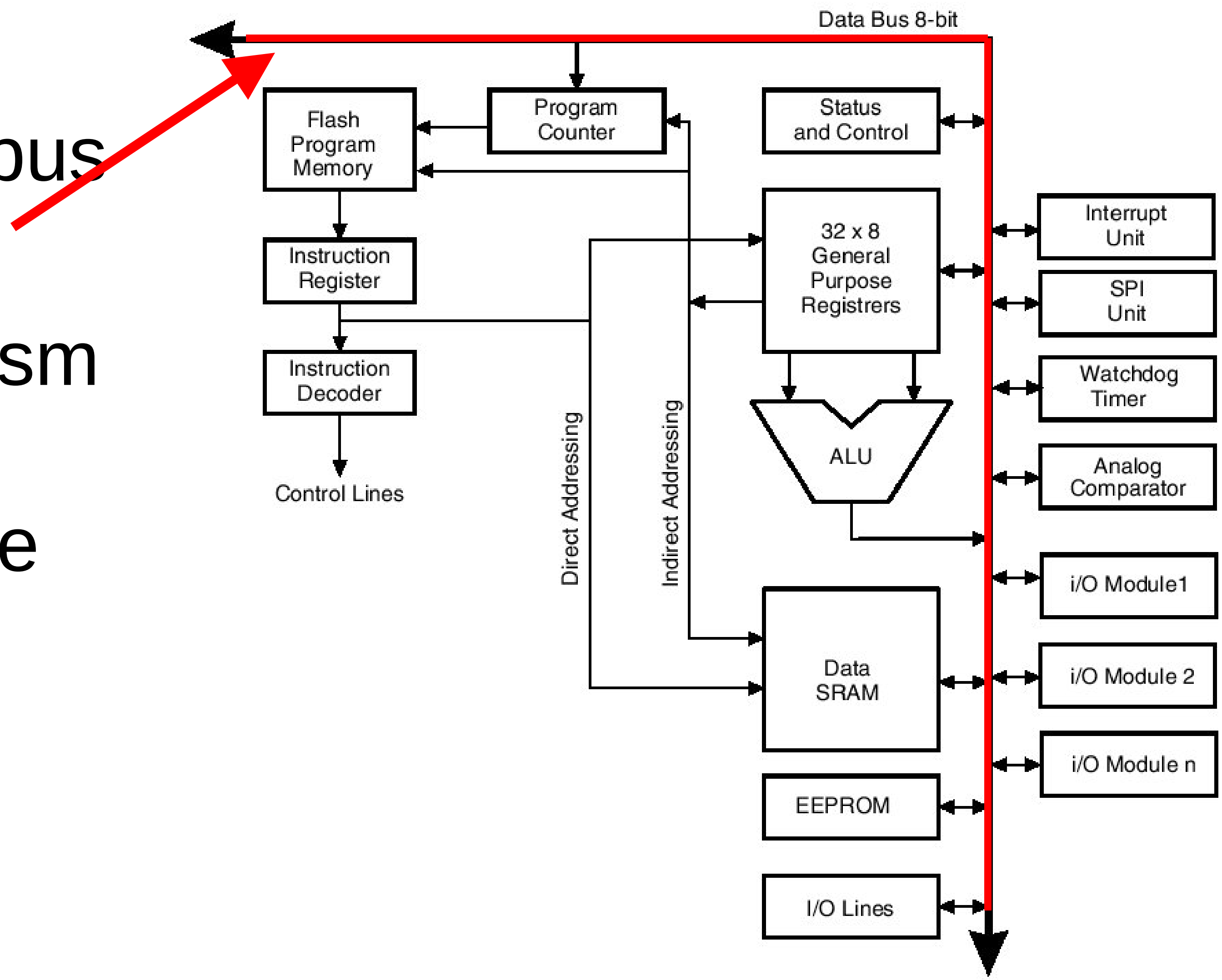
Atmel Mega2560 Architecture



Atmel Mega2560

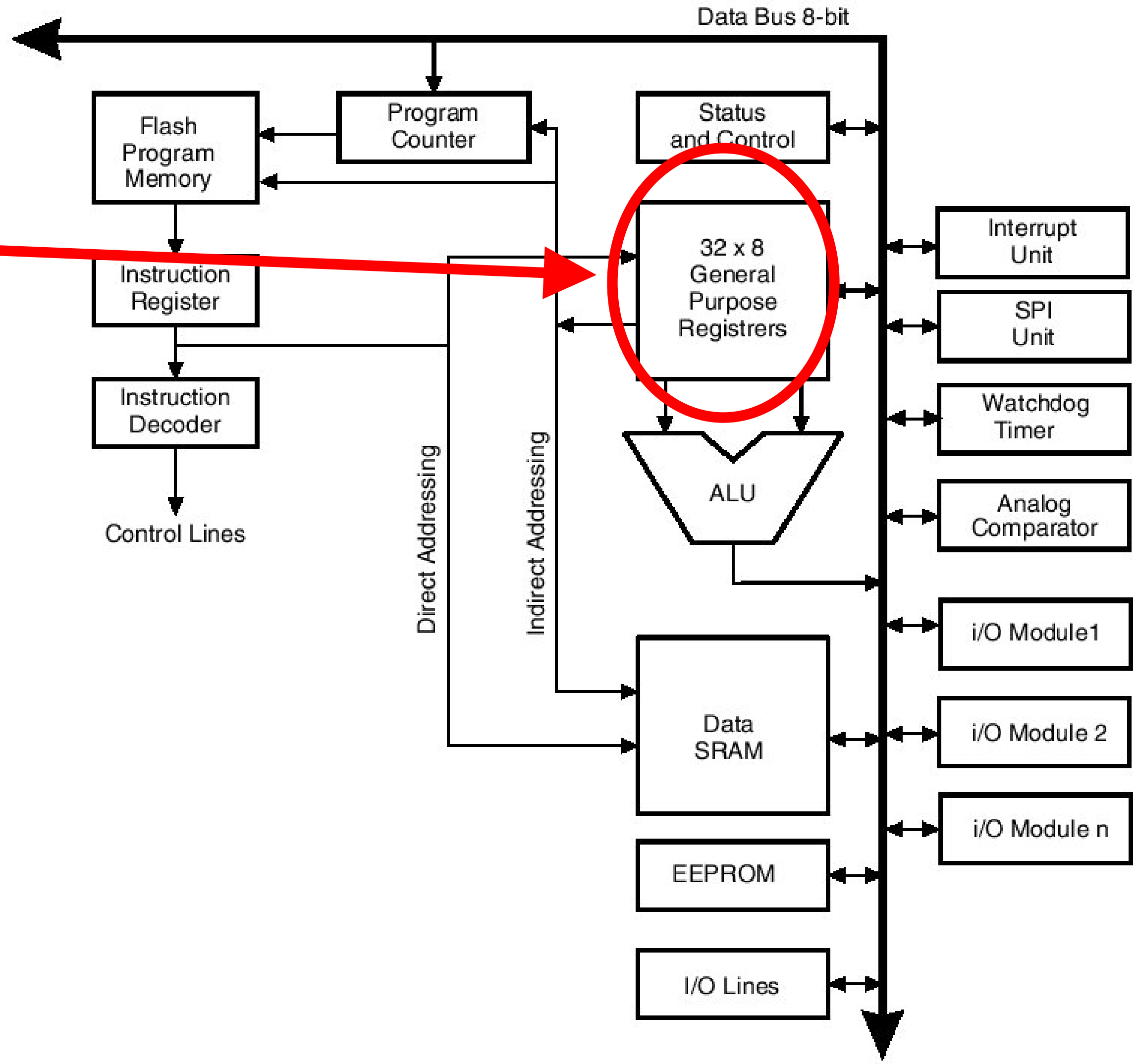
8-bit data bus

- Primary mechanism for data exchange



Atmel Mega2560

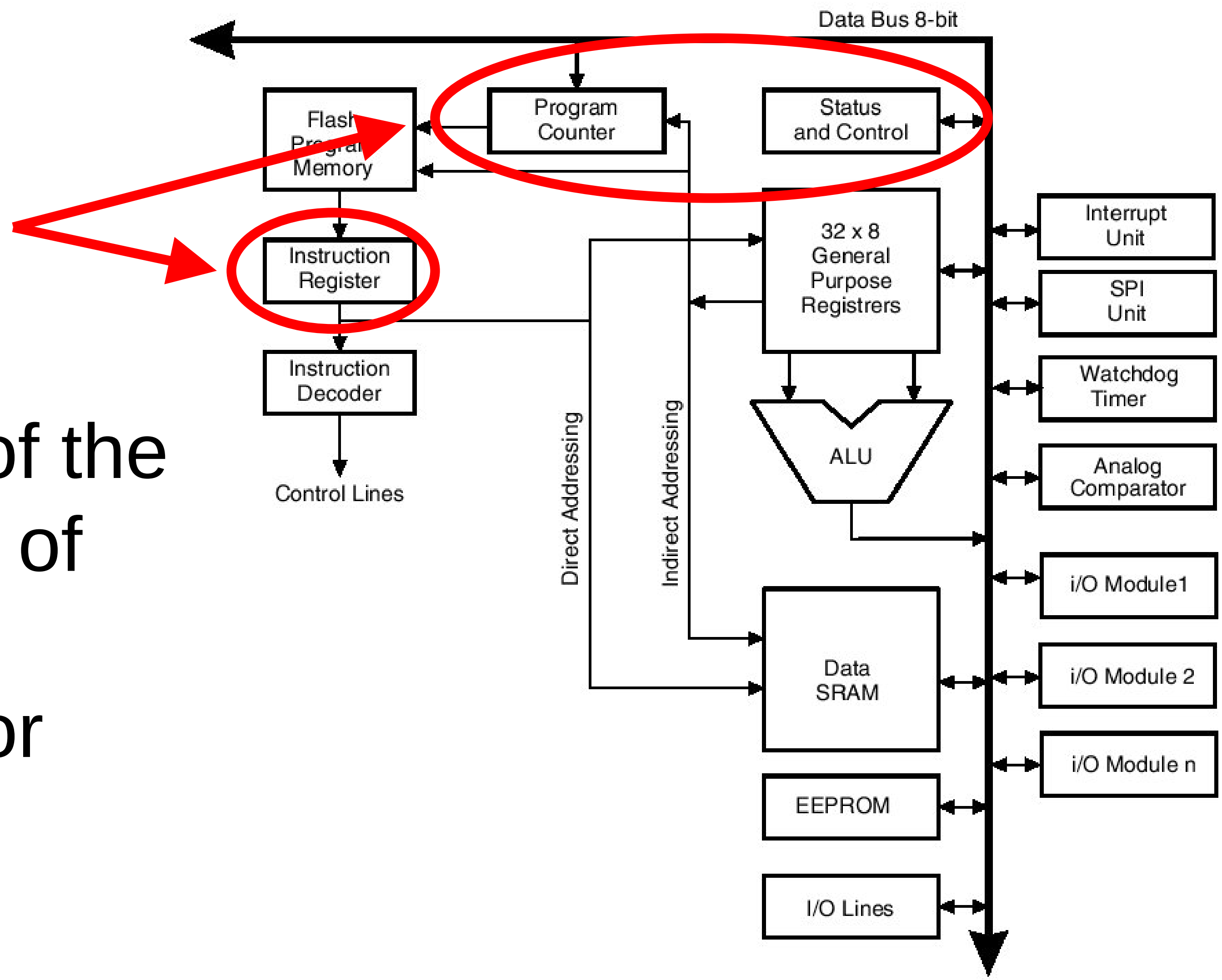
32 general purpose registers
- 8 bits wide
- 3 pairs of registers can be combined to give us 16 bit registers



Atmel Mega2560

Special purpose registers

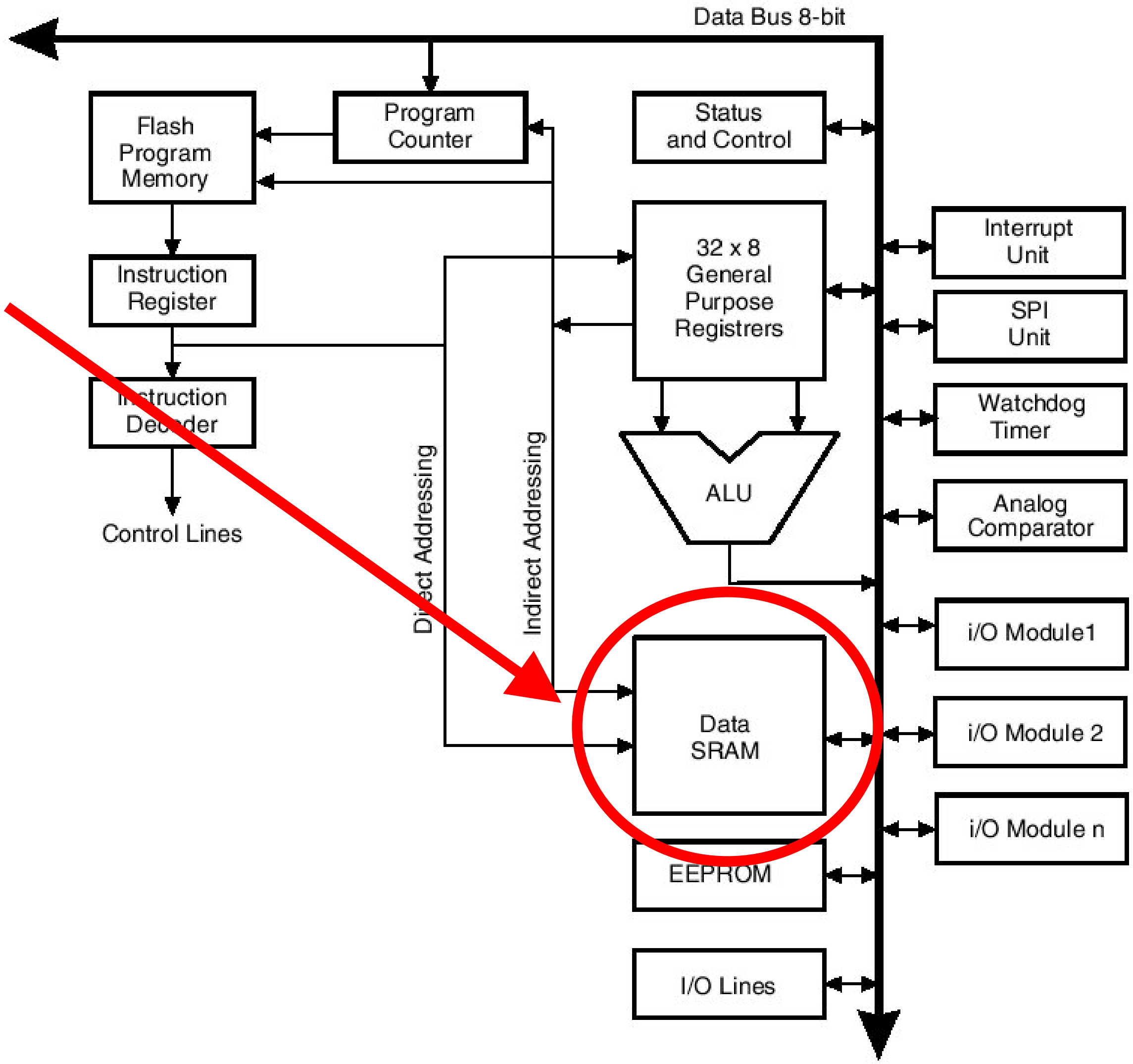
- Control of the internals of the processor



Atmel Mega2560

Random Access Memory (RAM)

- 8 KByte in size

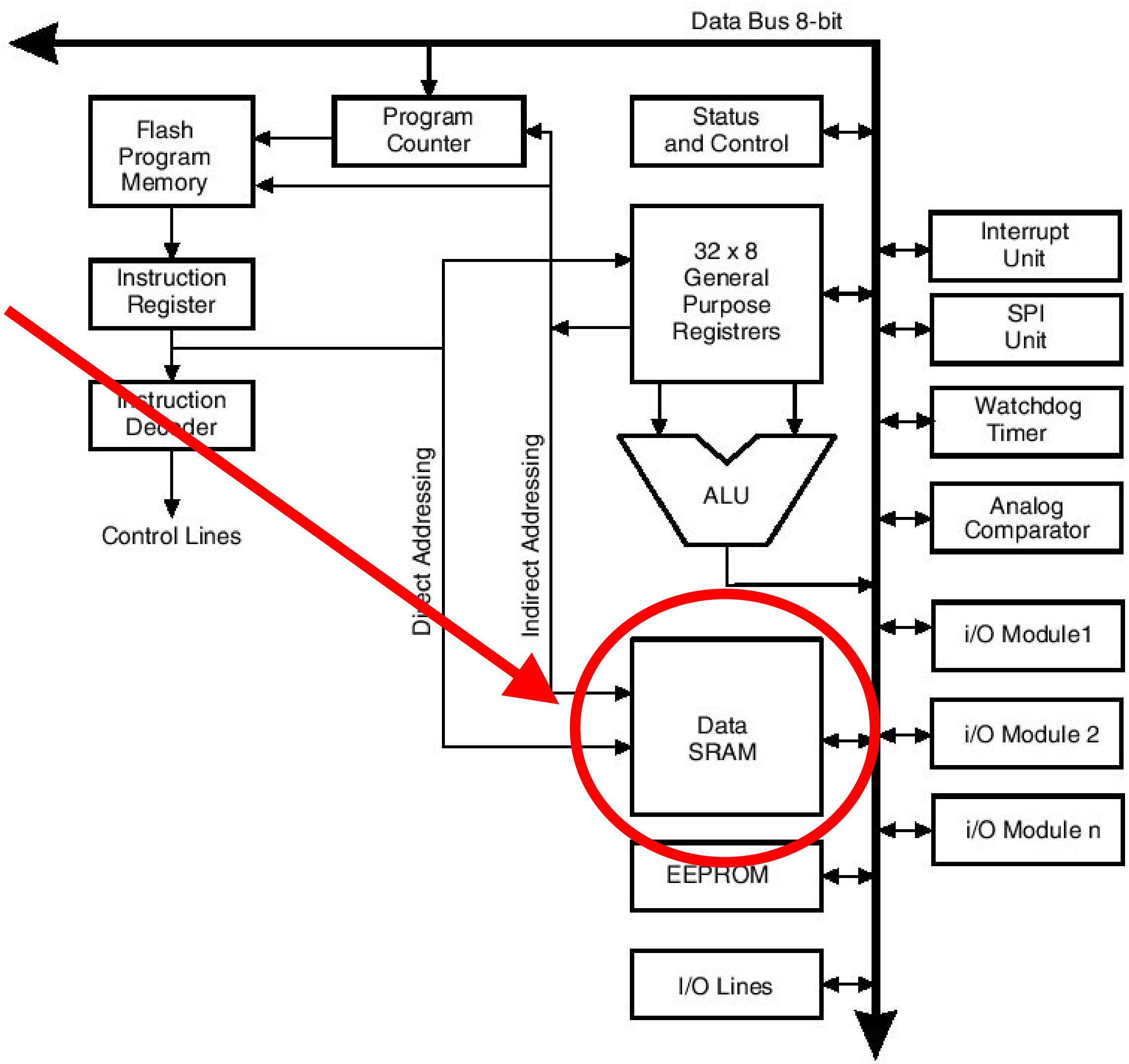


Atmel Mega2560

Random Access Memory (RAM)

- 8 KByte in size

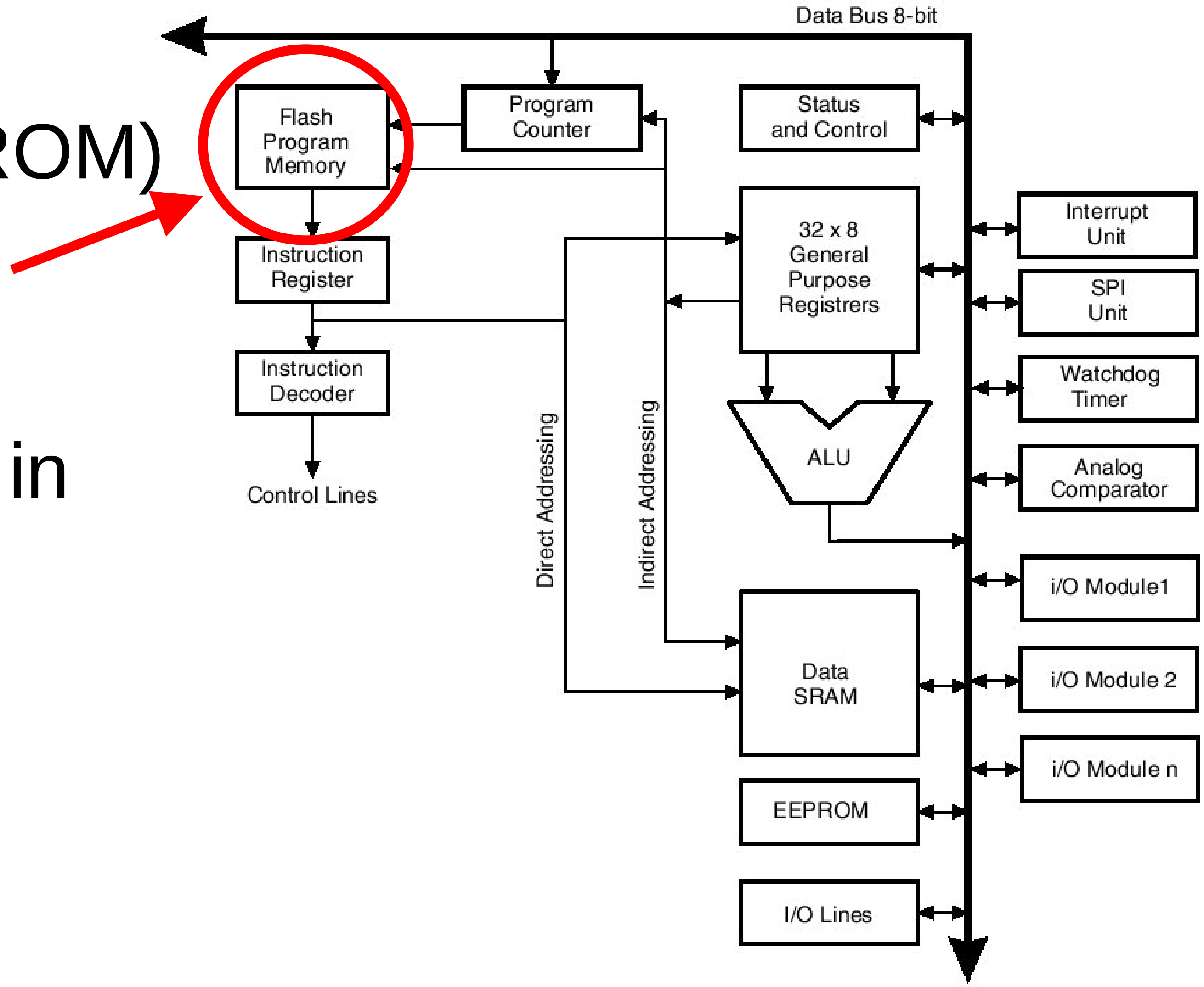
Note: in high-end processors, RAM is a separate component



Atmel Mega2560

Flash (EEPROM)

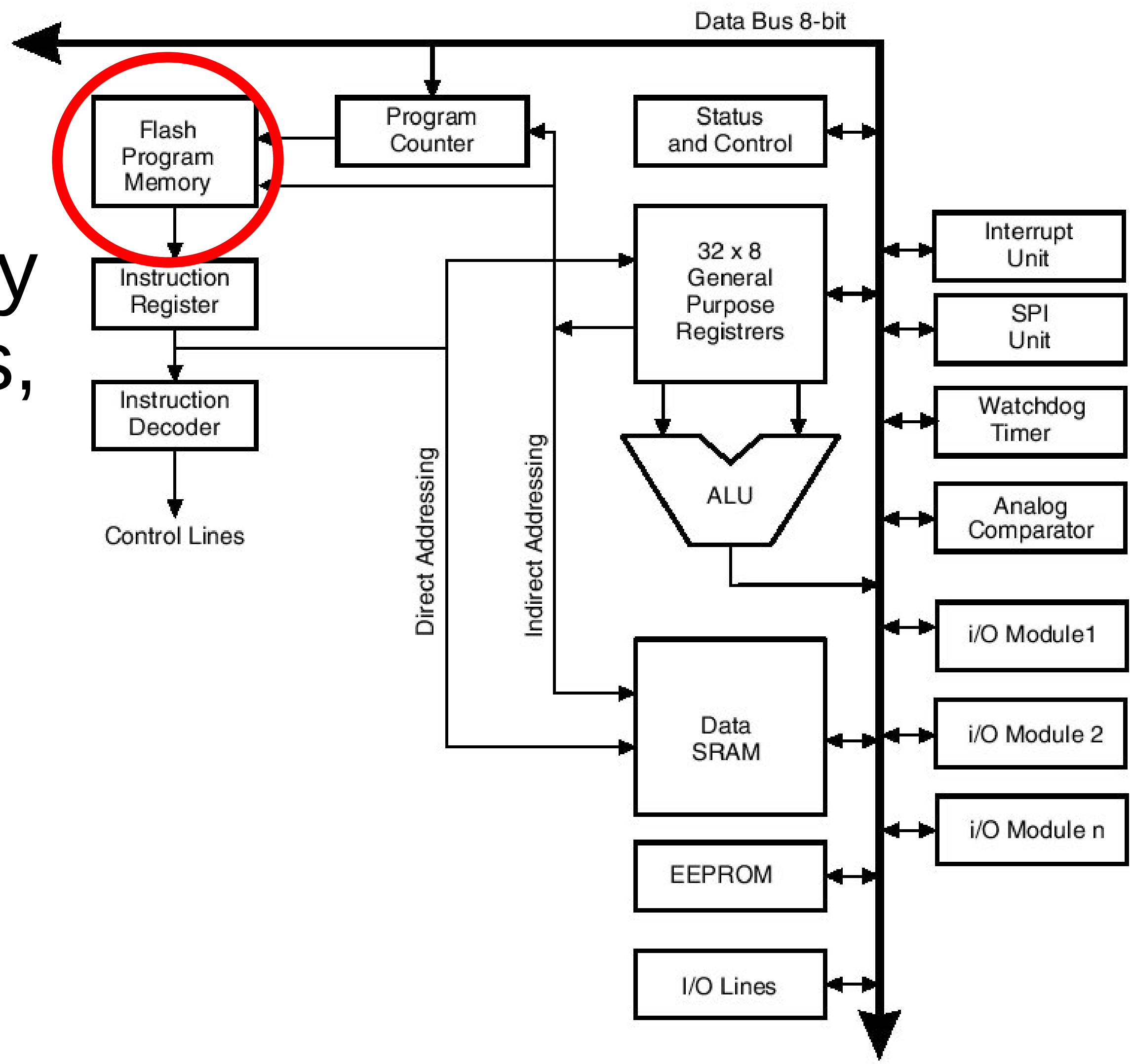
- Program storage
- 256 KByte in size



Atmel Mega2560

Flash (EEPROM)

- In this and many microcontrollers, program and data storage is separate
- Not the case in our general purpose computers



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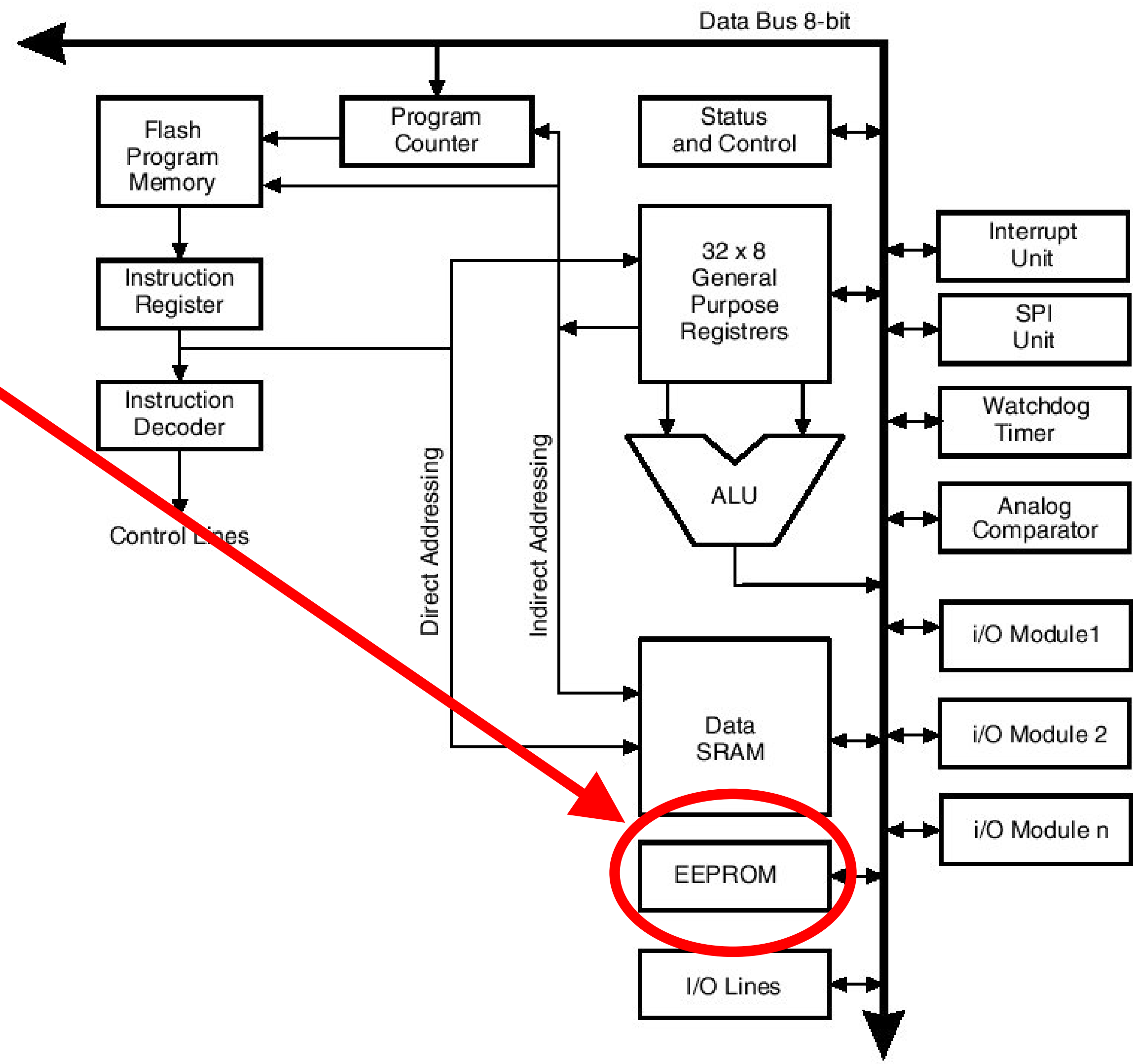
EEPROM

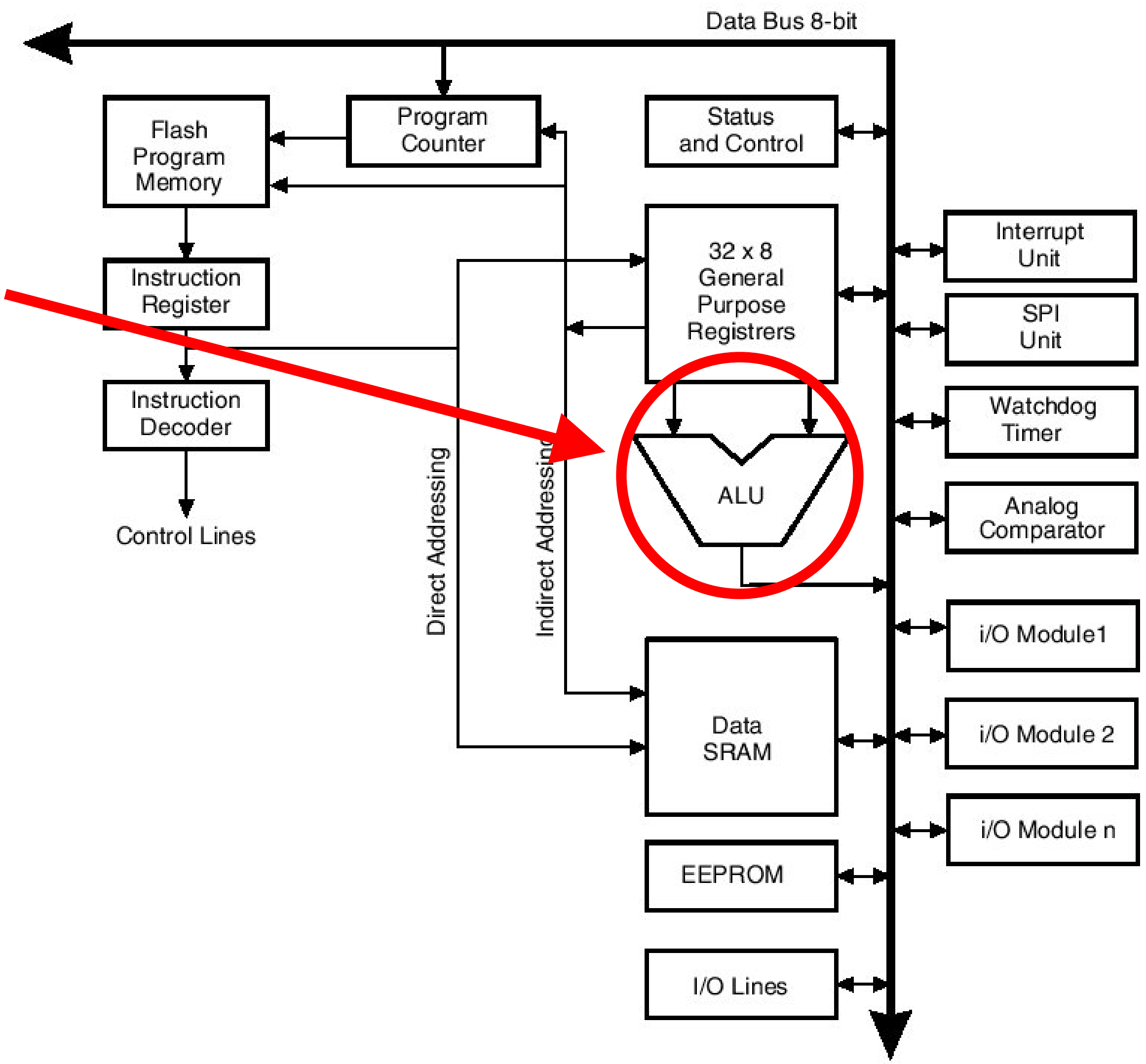
- Permanent data storage



Atmel Mega2560

Arithmetic Logical Unit

- Data inputs from registers
- Control inputs not shown (derived from instruction decoder)



Collections of Bits

- 8 bits: a “byte”
- 4 bits: a “nybble”

- “words”: can be 8, 16, or 32 bits (depending on the processor)

Collections of Bits

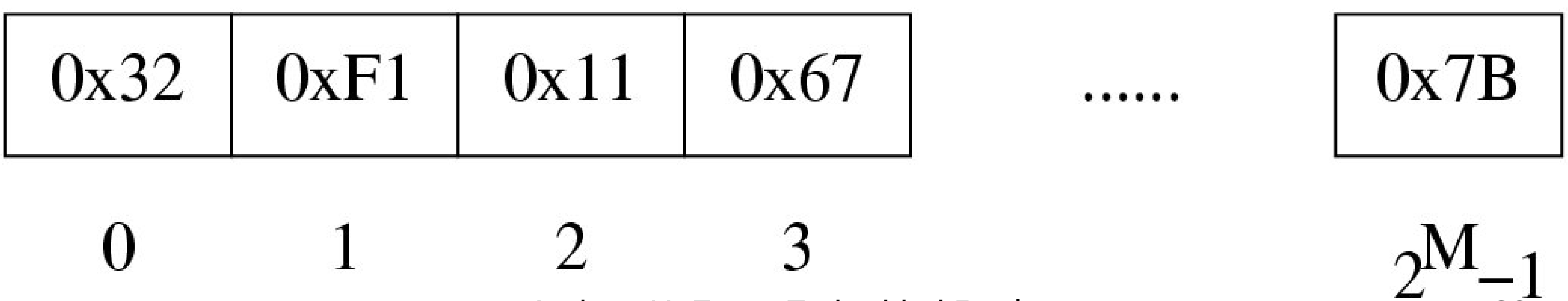
- A data bus typically captures a set of bits simultaneously
- Need one wire for each of these bits
- In the Atmel Mega2560 (and Mega8): the data bus is 8-bits “wide”
- In your home machines: 32 or 64 bits

Memory

What are the essential components of a memory?

A Memory Abstraction

- We think of memory as an array of elements – each with its own address
- Each element contains a value
  - It is most common for the values to by 8-bits wide (so a byte)



A Memory Abstraction

- We think of memory as an array of elements – each with its own address
- Each element contains a value
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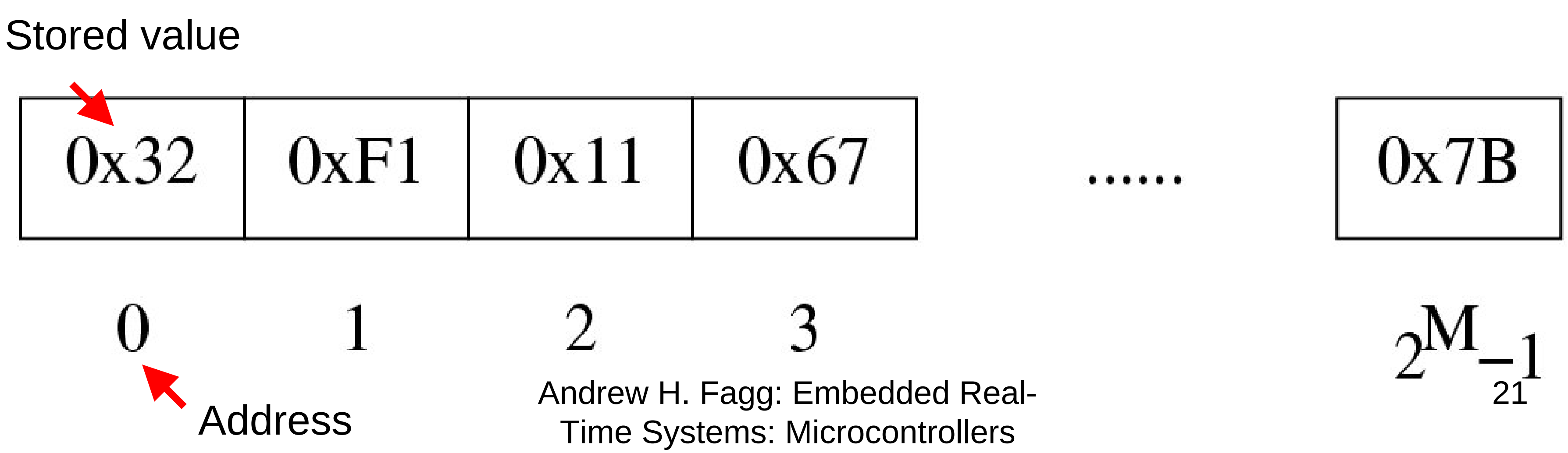


Memory Operations

Read

```
foo(A+5);
```

reads the value from the memory location referenced by the variable ‘A’ and adds the value to 5. The result is passed to a function called `foo();`

Memory Operations

Write

```
A = 5;
```

writes the value 5 into the memory location referenced by ‘A’

Types of Memory

Random Access Memory (RAM)

- Computer can change state of this memory at any time
- Once power is lost, we lose the contents of the memory

- This will be our data storage on our microcontrollers

Types of Memory

Read Only Memory (ROM)

- Computer **cannot** arbitrarily change state of this memory
- When power is lost, the contents are maintained

Types of Memory

Erasable/Programmable ROM (EPROM)

- State can be changed under very specific conditions (usually not when connected to a computer)

- Our microcontrollers have an Electrically Erasable/Programmable ROM (EEPROM) for program storage

Machine-Level Programs

Machine-level programs are stored as sequences of ***atomic*** machine instructions

- Stored in program memory
- Execution is generally sequential (instructions are executed in order)
- But – with occasional “jumps” to other locations in memory

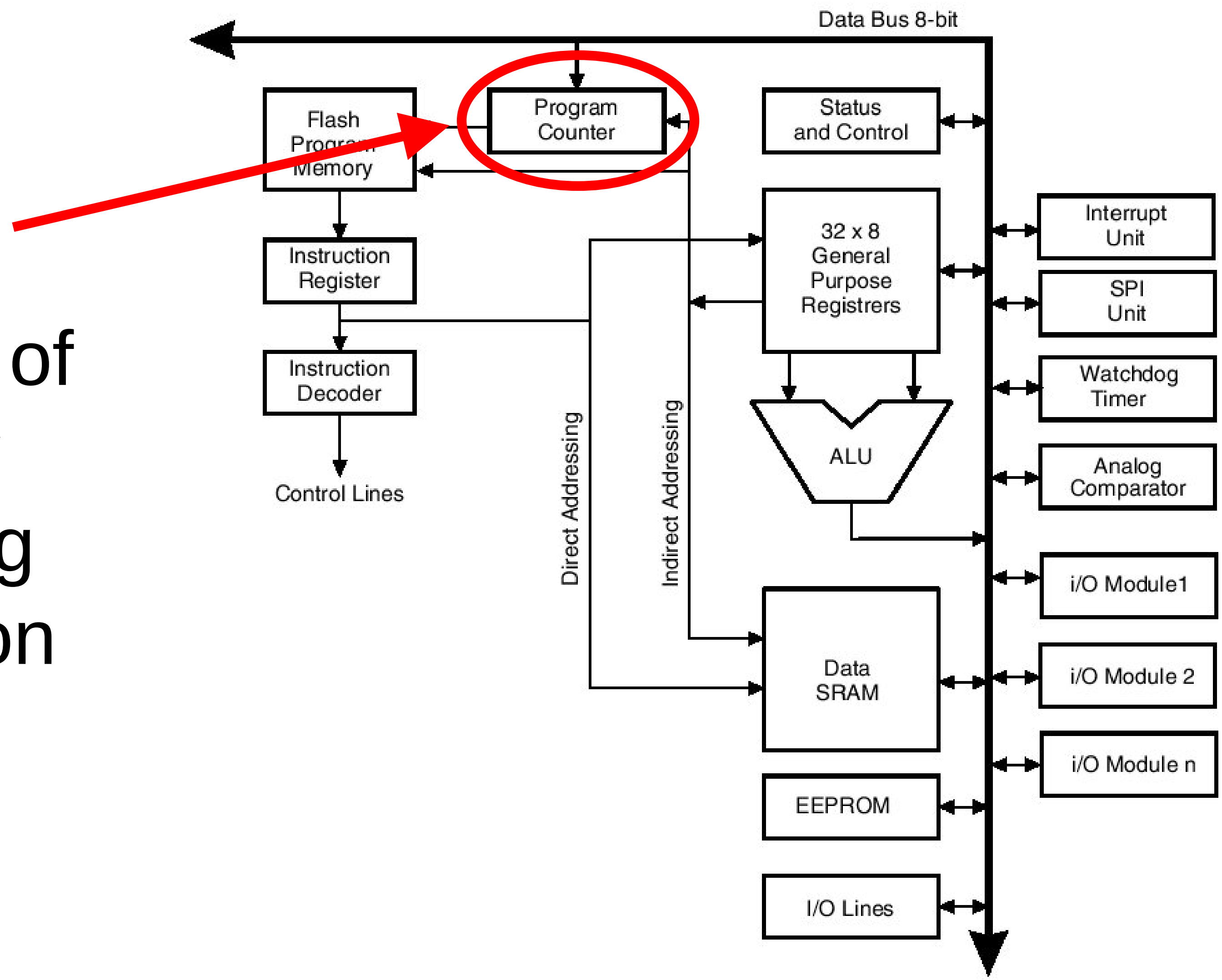
Types of Instructions

- Memory operations: transfer data values between memory and the internal registers
- Mathematical operations: ADD, SUBTRACT, MULT, AND, etc.
- Tests: value == 0, value > 0, etc.
- Program flow: jump to a new location, jump conditionally (e.g., if the last test was true)

Mega2560: Decoding Instructions

Program counter

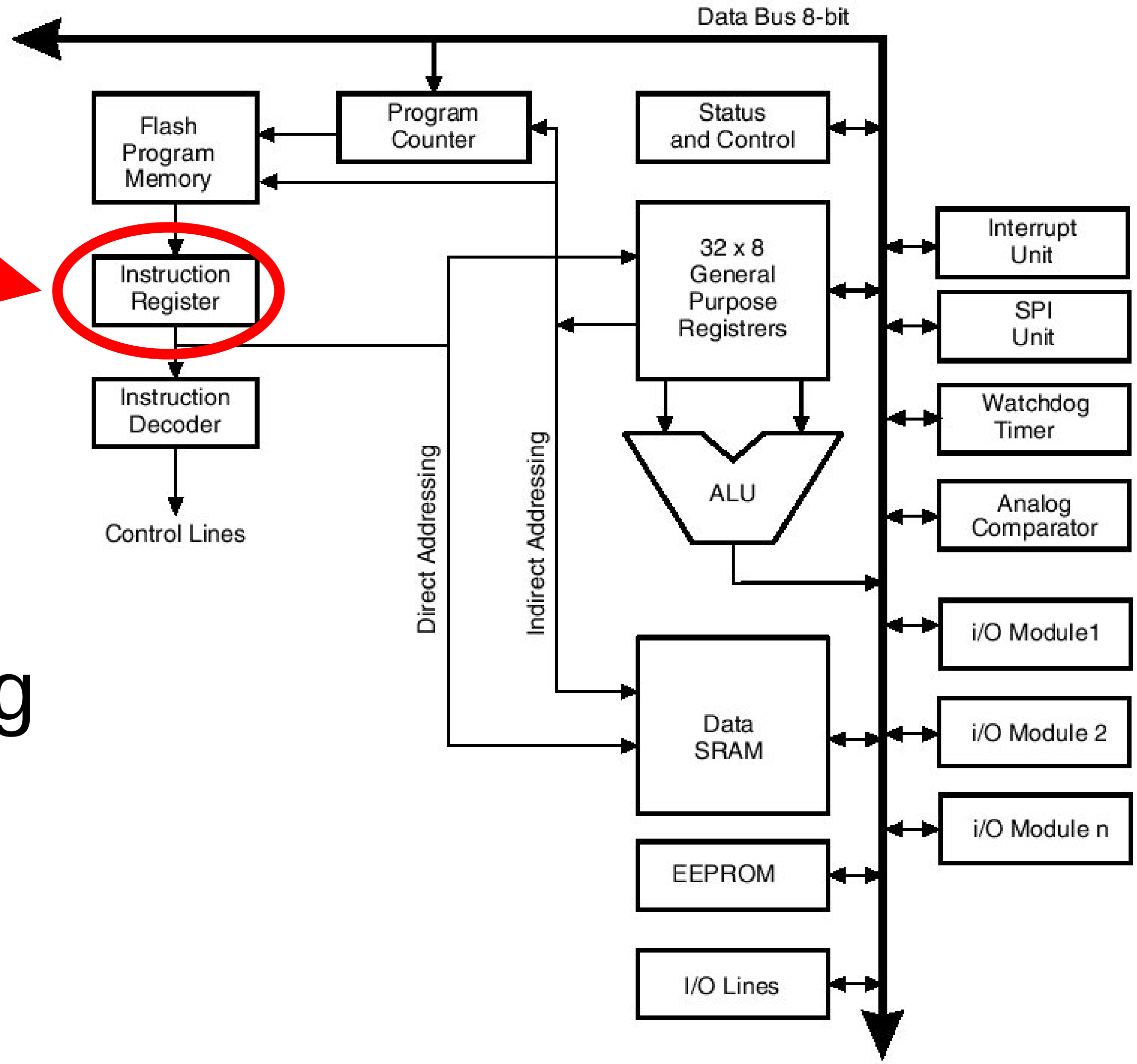
- Address of currently executing instruction



Mega2560: Decoding Instructions

Instruction register

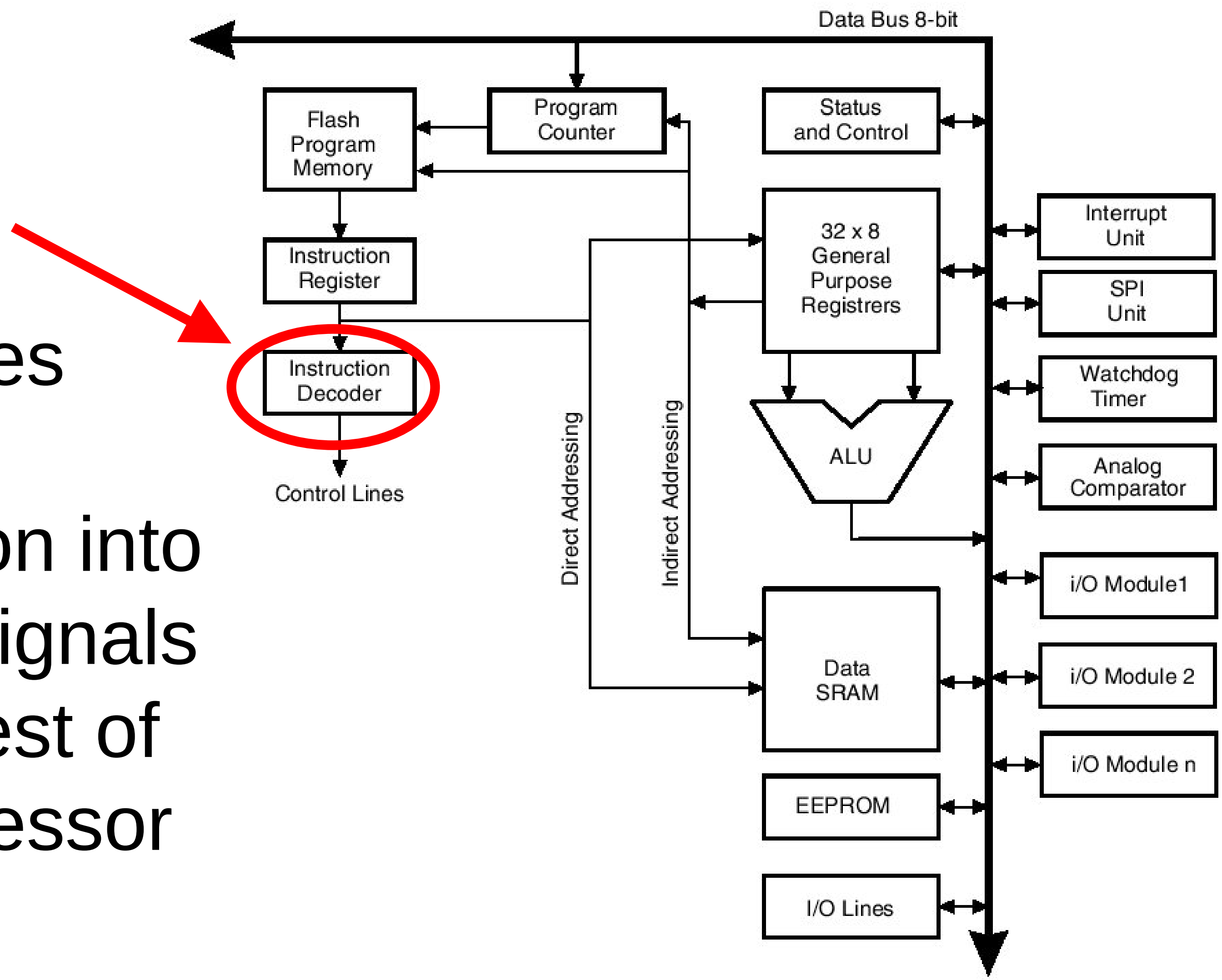
- Stores the machine-level instruction currently being executed



Atmel Mega2560

Instruction decoder

- Translates current instruction into control signals for the rest of the processor



Some Mega2560 Memory Operations

We refer to this as "Assembly Language"

LDS Rd, k

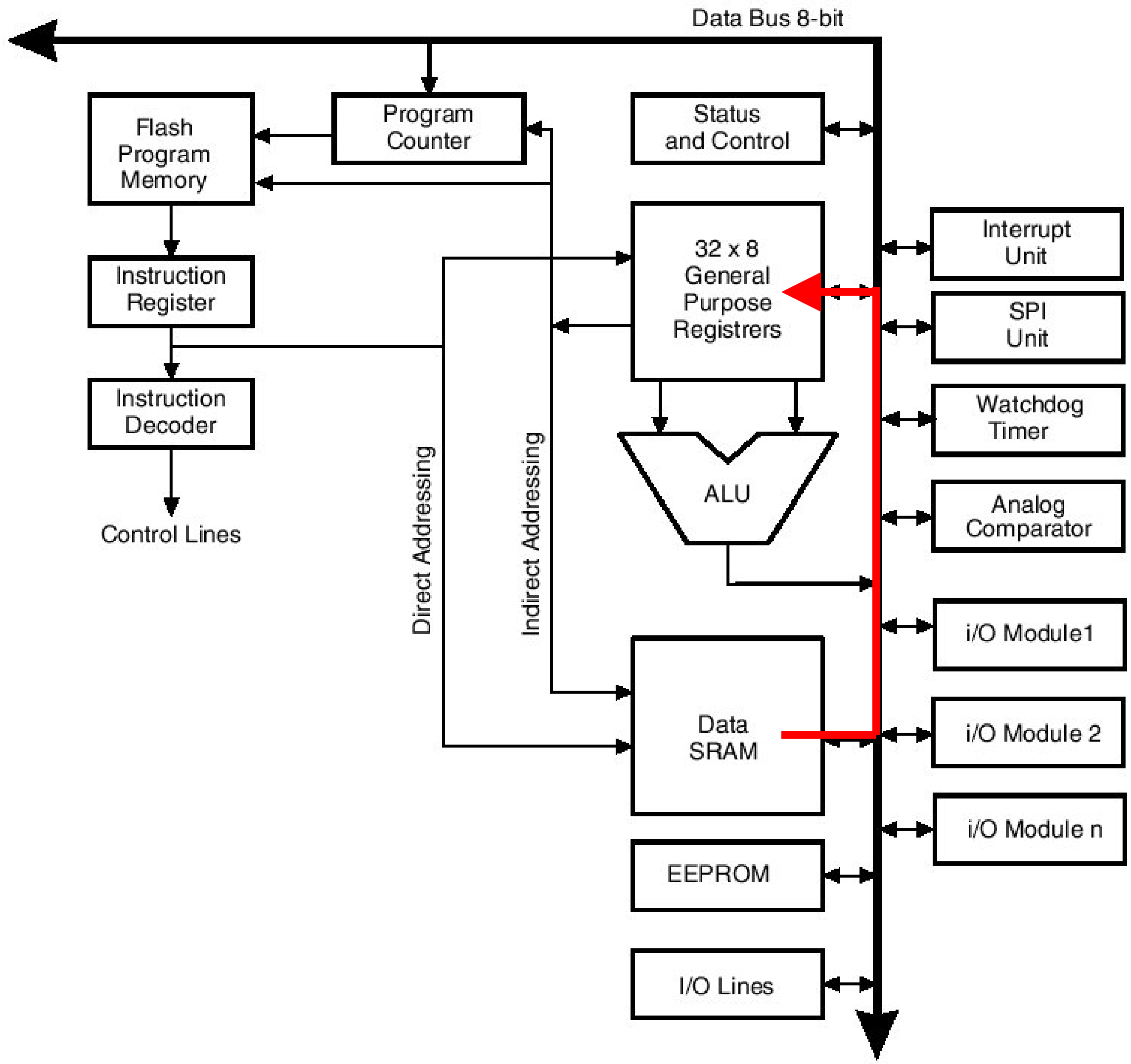
- Load SRAM memory location k into register Rd
- Rd <- (k)

STS Rd, k

- Store value of Rd into SRAM location k
- (k) <- Rd

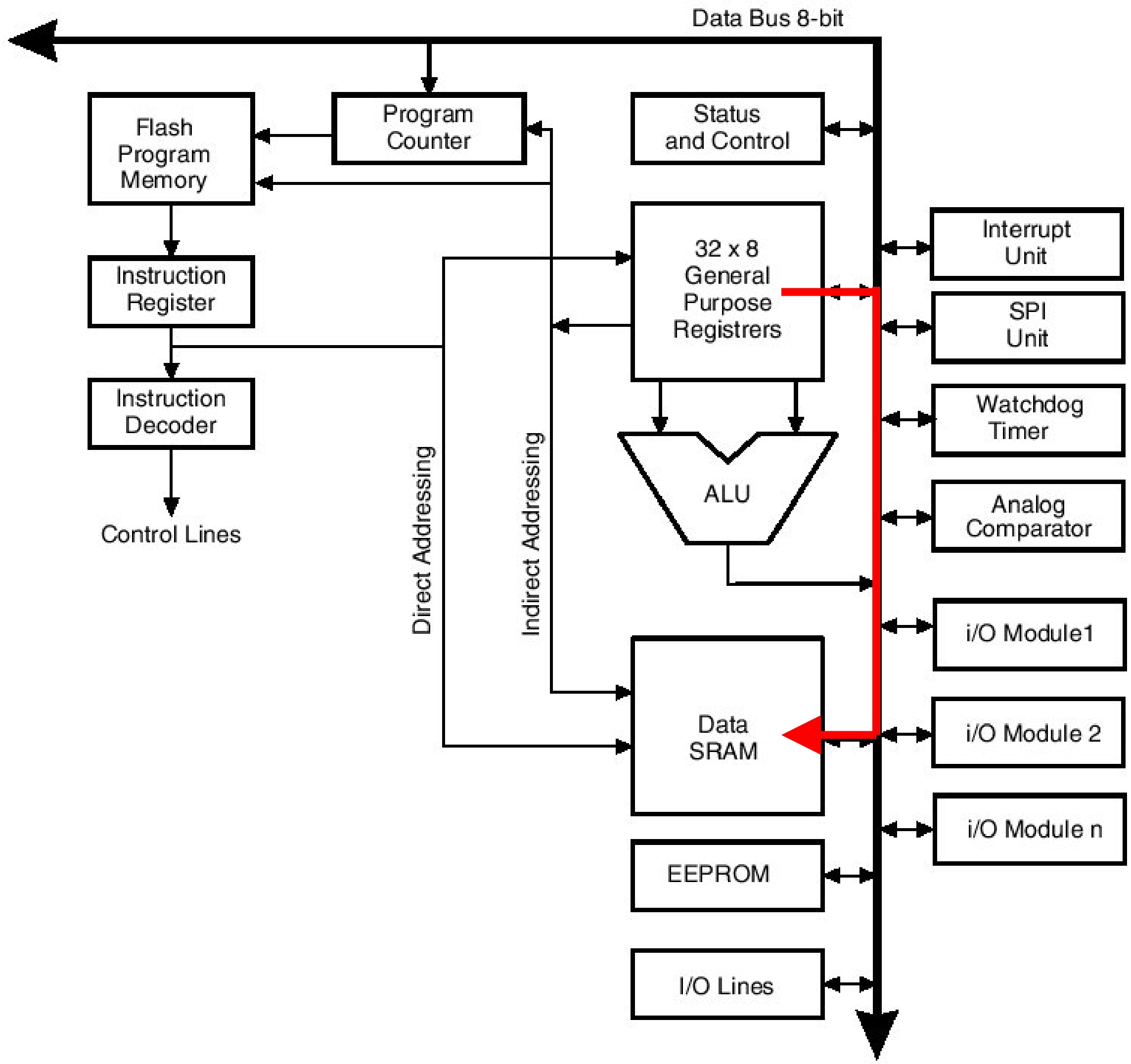
Load SRAM Value to Register

LDS Rd, k



Store Register Value to SRAM

STS Rd, k



Some Mega2560 Arithmetic and Logical Instructions

ADD Rd, Rr

- Rd and Rr are registers
- Operation: Rd <- Rd + Rr

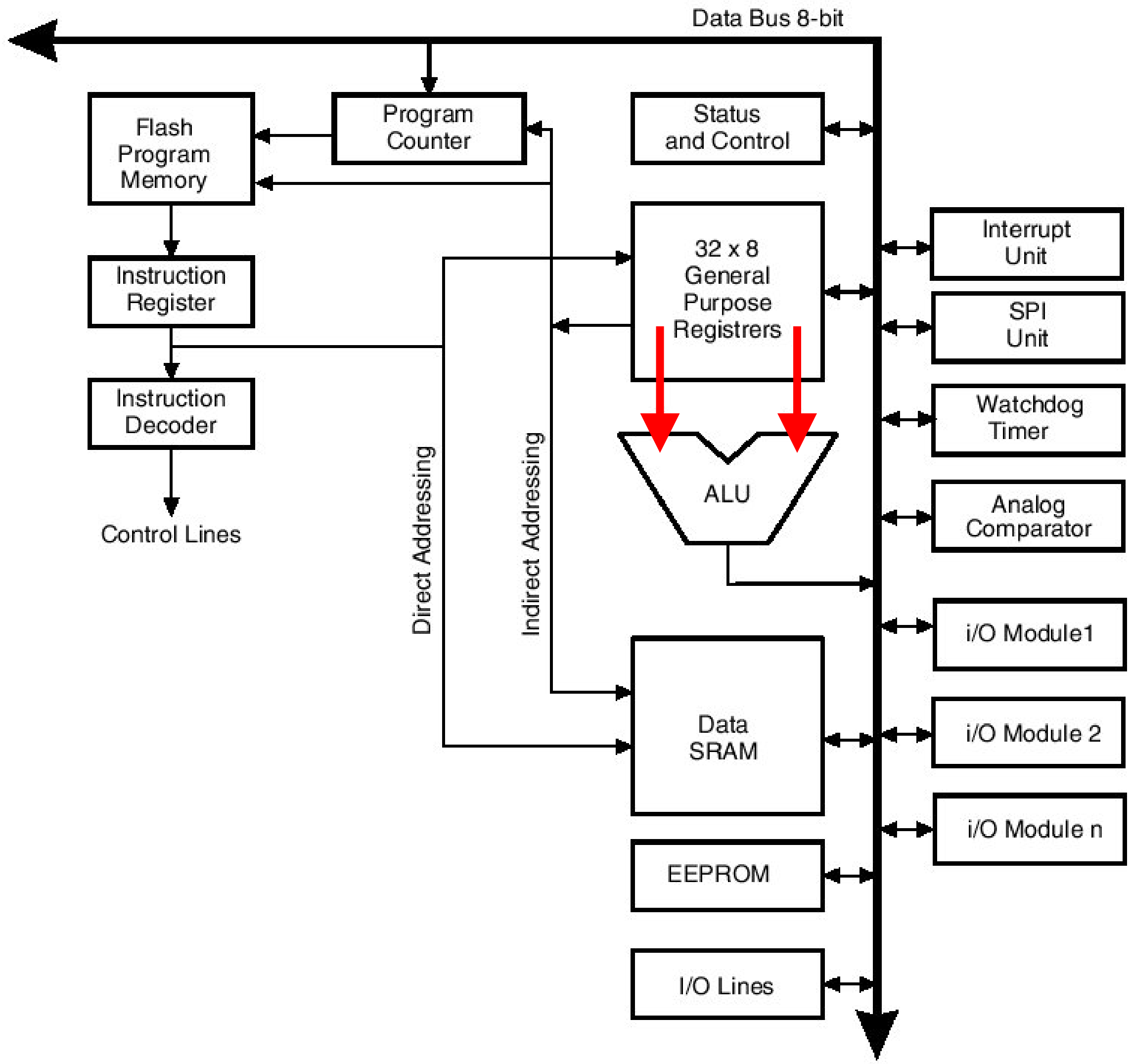
ADC Rd, Rr

- Add with carry
- Rd <- Rd + Rr + C

Add Two Register Values

ADD Rd, Rr

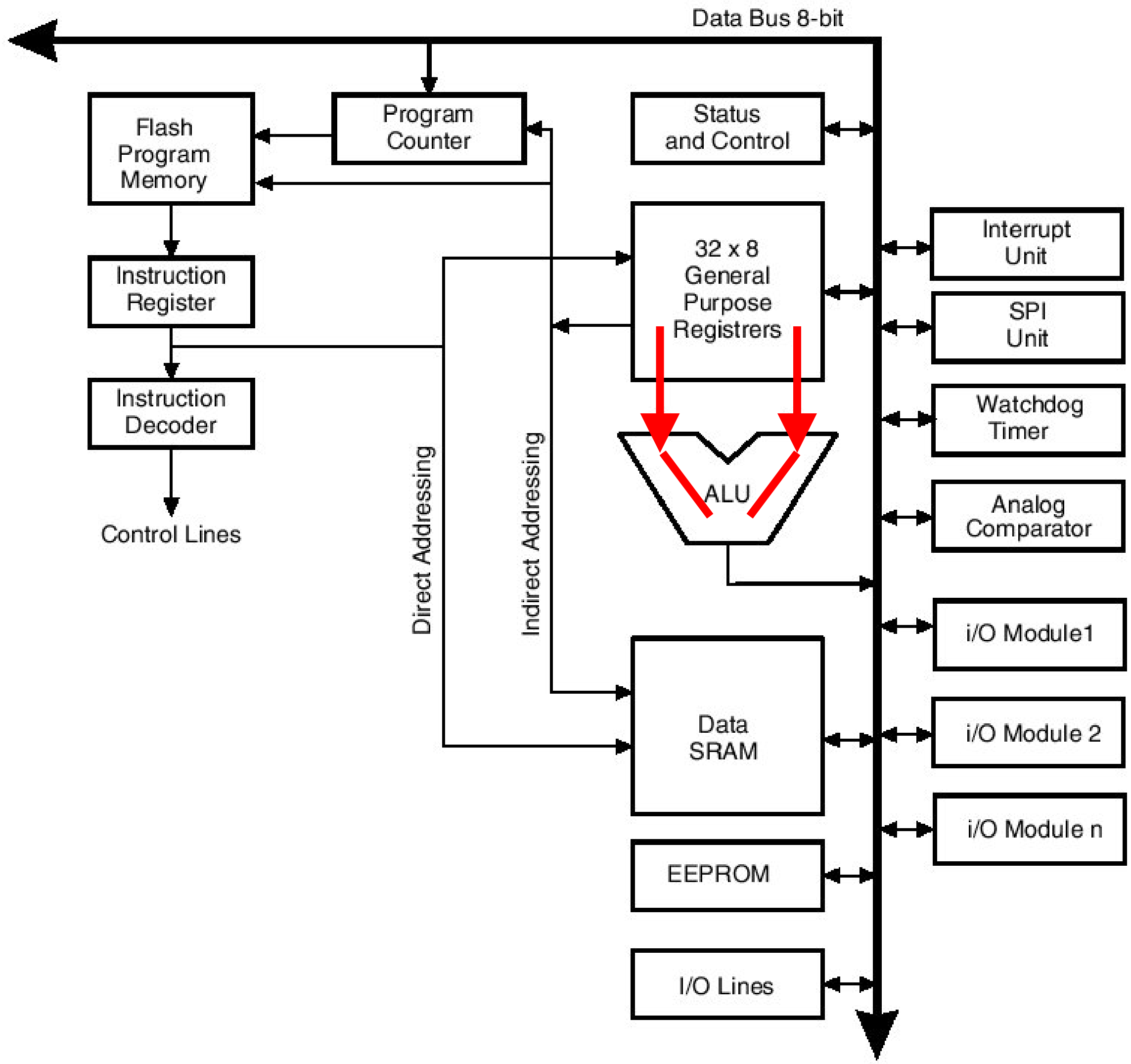
- Fetch register values



Add Two Register Values

ADD Rd, Rr

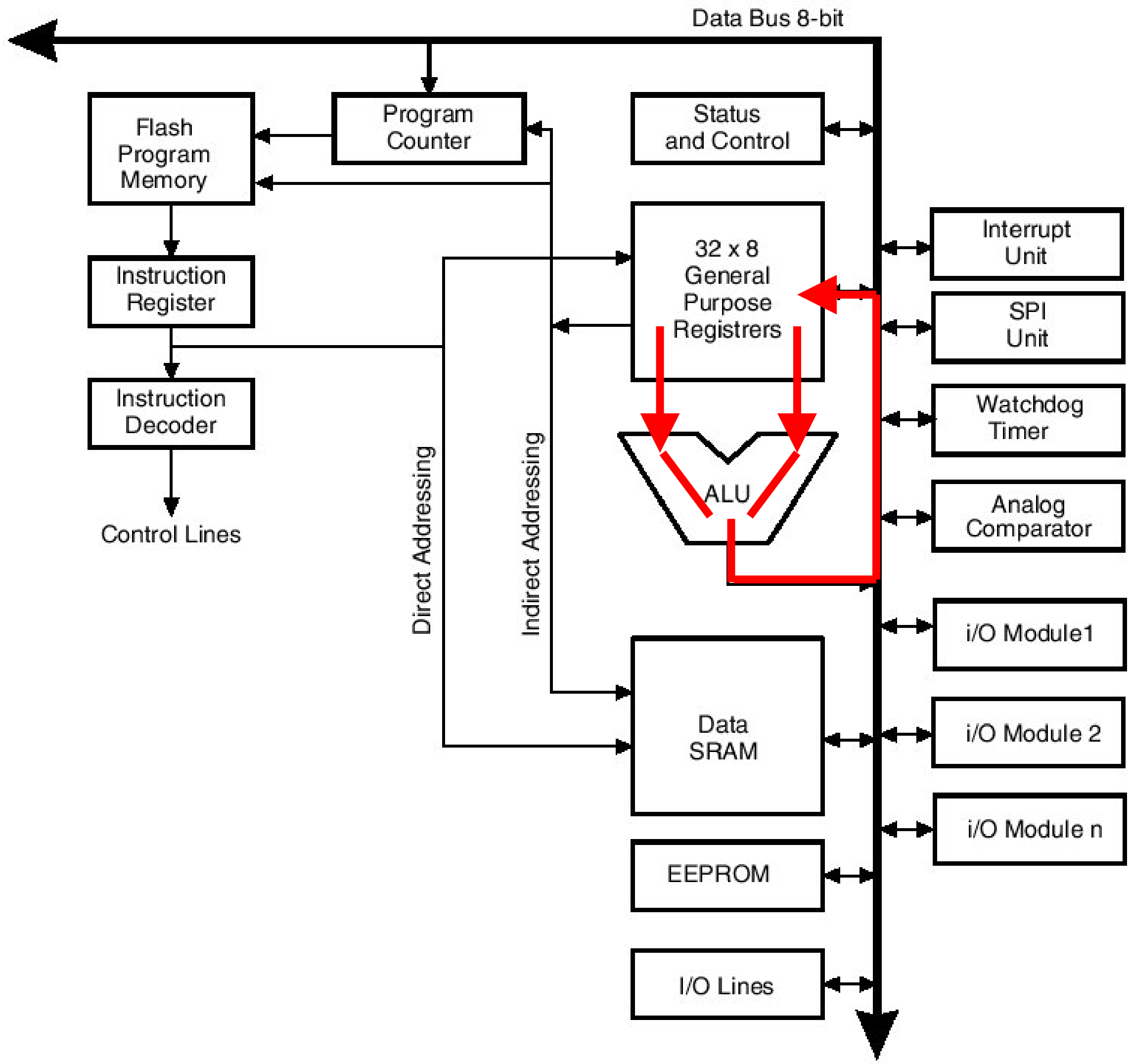
- Fetch register values
- ALU performs ADD



Add Two Register Values

ADD Rd, Rr

- Fetch register values
- ALU performs ADD
- Result is written back to register via the data bus



Some Mega2560 Arithmetic and Logical Instructions

NEG Rd: take the two’s complement of Rd

AND Rd, Rr: bit-wise AND with a register

ANDI Rd, K: bit-wise AND with a constant

EOR Rd, Rr: bit-wise XOR

INC Rd: increment Rd

MUL Rd, Rr: multiply Rd and Rr (unsigned)

MULS Rd, Rd: multiply (signed)

Some Mega8 Test Instructions

CP Rd, Rr

- Compare Rd with Rr

TST Rd

- Test for if register Rd is zero or a negative number

Some Program Flow Instructions

RJMP k

- Change the program counter by k+1
- PC <- PC + k + 1

BRGE k

- Branch if greater than or equal to
- If last compare was greater than or equal to, then PC <- PC + k + 1

Connecting Assembly Language to C

- Our C compiler is responsible for translating our code into Assembly Language
- Today, we rarely program in Assembly Language
  - Embedded systems are a common exception
  - Also: it is useful in some cases to view the assembly code generated by the compiler

An Example

A C code snippet:

```
if(B < A) {
   D += A;
}
```

An Example

A C code snippet:

```
if(B < A) {
   D += A;
}
```

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3
……..
```

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Load the contents of memory location A into register 1

The Assembly :

```
LDS R1 (A)    ← PC
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3
……..
```

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Load the contents of memory location B into register 2

The Assembly :

LDS R1 (A)

LDS R2 (B) ← **PC**

CP R2, R1

BRGE 3

LDS R3 (D)

ADD R3, R1

STS (D), R3

……..

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Compare the contents of register 2 with those of register 1

This results in a change to the status register

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1      ← PC
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3
……..
```

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Branch If Greater Than or Equal To: jump ahead 3 instructions if true

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3          ← PC
LDS R3 (D)
ADD R3, R1
STS (D), R3
……..
```

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3
……..
```

if true

PC

Branch if greater than or equal to will jump ahead 3 instructions if true

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Not true: execute the next instruction

if not true

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)      ← PC
ADD R3, R1
STS (D), R3
……..
```

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Load the contents of memory location D into register 3

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)      <- PC
ADD R3, R1
STS (D), R3
……..
```

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Add the values in registers 1 and 3 and store the result in register 3

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1   <- PC
STS (D), R3
........
```

An Example

A C code snippet:

```
if(B < A) {
    D += A;
}
```

Store the value in register 3 back to memory location D

The Assembly :

```
LDS R1 (A)
LDS R2 (B)
CP R2, R1
BRGE 3
LDS R3 (D)
ADD R3, R1
STS (D), R3   ← PC
……..
```

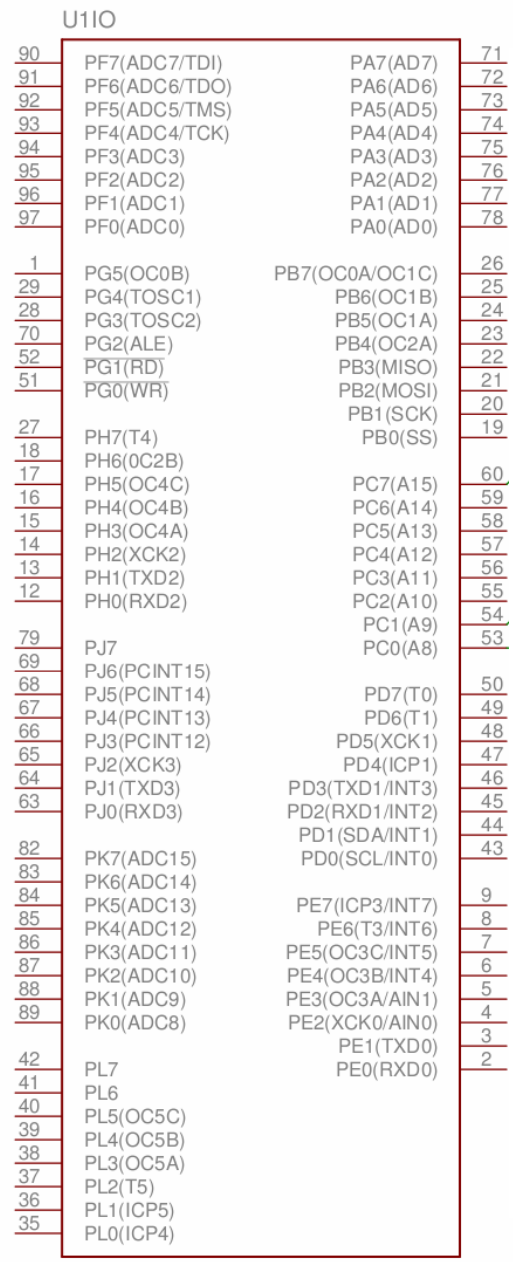
The Important Stuff

Instructions are the “atomic” actions that are taken by the processor

- One line of C code typically translates to a sequence of several instructions
- In the mega 2560, most instructions are executed in a single clock cycle

The high-level view is important here: don’t worry about the details of specific instructions

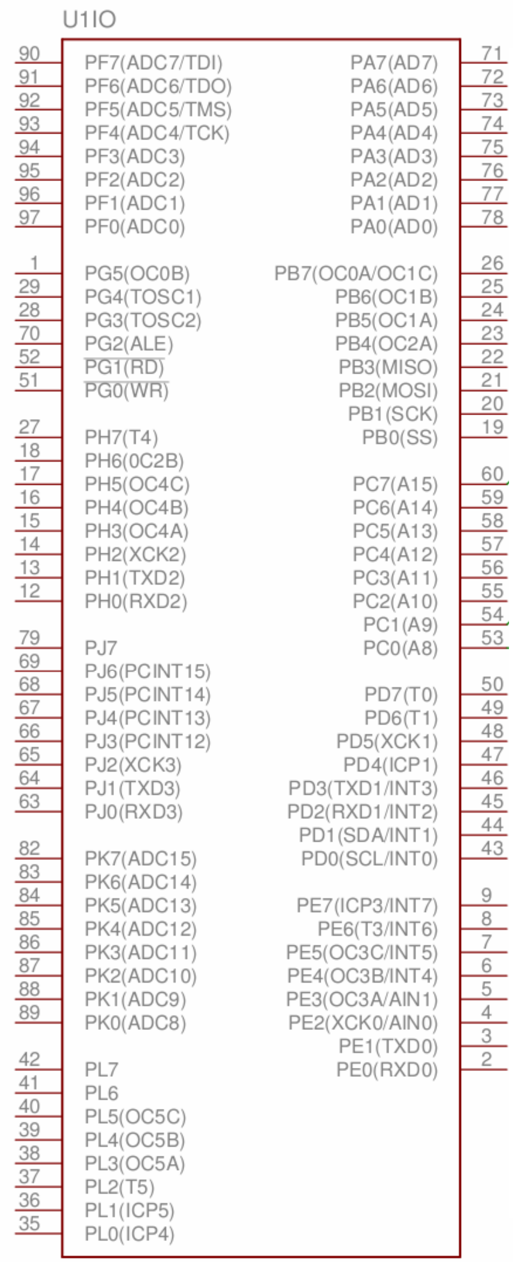
Atmel Mega2560



Atmel Mega2560

Pins are organized into 8-bit “Ports”:

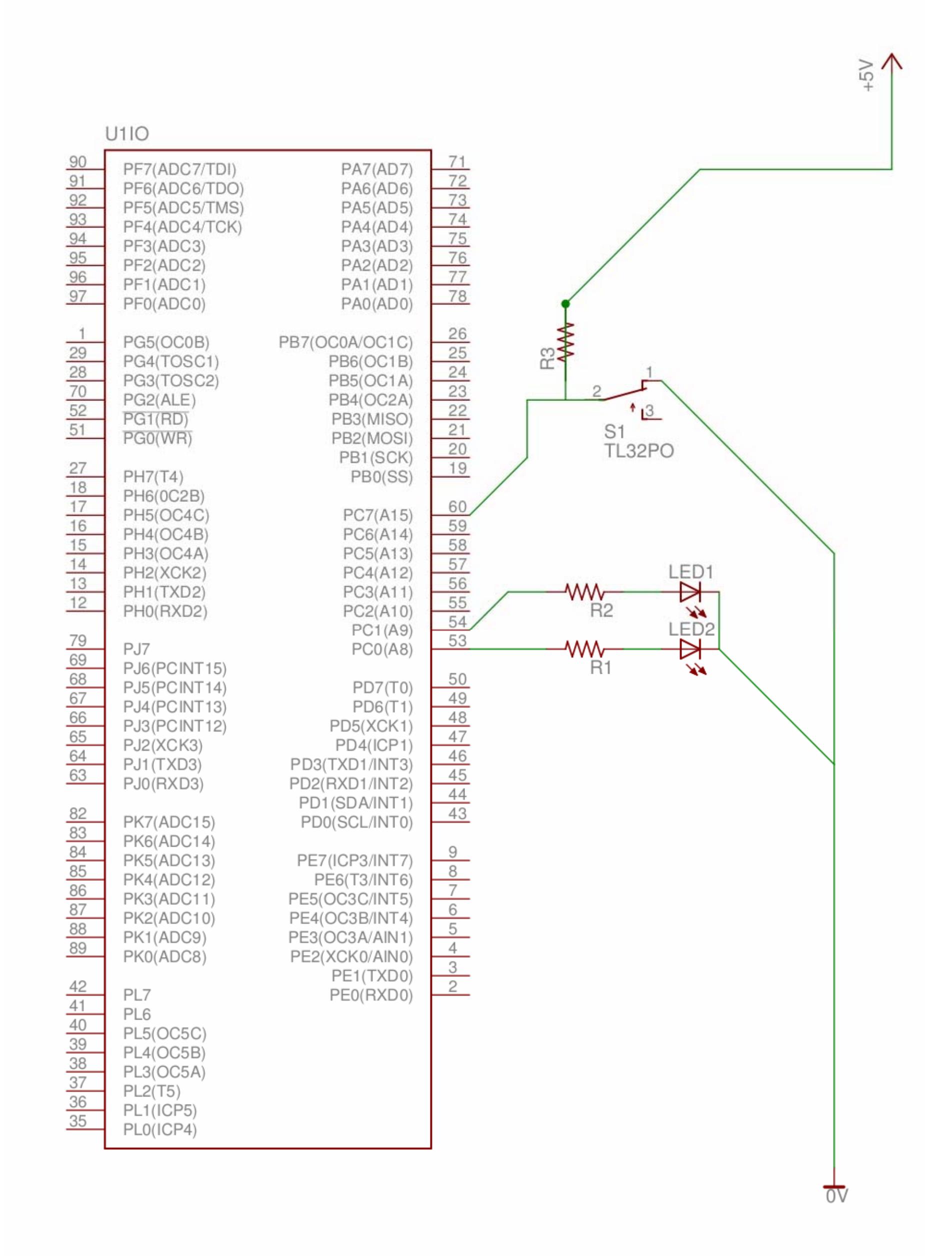
- A, B, C … L
  - But no “I”



Digital Input/Output

- Each port has three registers that control its behavior.
- For port B, they are:
  - DDRB: data direction register B
  - PORTB: port output register B
  - PINB: port input B

A First Circuit



Bit Manipulation

PORTB is a register

- Controls the value that is output by the set of port B pins
- But – all of the pins are controlled by this single register (which is 8 bits wide)

- In code, we need to be able to manipulate the pins individually

Bit-Wise Operators

If A and B are bytes, what does this code mean?

```
C = A & B;
```

Bit-Wise Operators

If A and B are bytes, what does this code mean?

```
C = A & B;
```

The corresponding bits of A and B are ANDed together

Bit-Wise Operators

0 1 0 1 1 1 1 0	A
1 0 0 1 1 0 1 1	B
?	C = A & B

Bit-Wise Operators

0 1 0 1 1 1 1 0 A

1 0 0 1 1 0 1 1 B

C = A & B

Bit-Wise Operators

0 1 0 1 1 1 1 0   A

1 0 0 1 1 0 1 1   B

---

0   C = A & B

Bit-Wise Operators

0 1 0 1 1 1 1 0	A
1 0 0 1 1 0 1 1	B
1 0	C = A & B

Bit-Wise Operators

0 1 0 1 1 1 1 0	A
1 0 0 1 1 0 1 1	B
0 0 0 1 1 0 1 0	C = A & B

Bit-Wise Operators

Other Operators:

- OR: |
- XOR: ^
- NOT: ~

Bit Manipulation

Given a byte A, how do we set bit 2 (counting from 0) of A to 1?

Bit Manipulation

Given a byte A, how do we set bit 2 (counting from 0) of A to 1?

```
A = A | 4;
```

Bit Manipulation

Given a byte A, how do we set bit 2 (counting from 0) of A to 0?

Bit Manipulation

Given a byte A, how do we set bit 2 (counting from 0) of A to 0?

```
A = A & 0xFB;
```

or

```
A = A & ~4;
```

Bit Shifting

```
uint8_t A = 0x5A;
uint8_t B = A << 2;
uint8_t C = A >> 5;
```

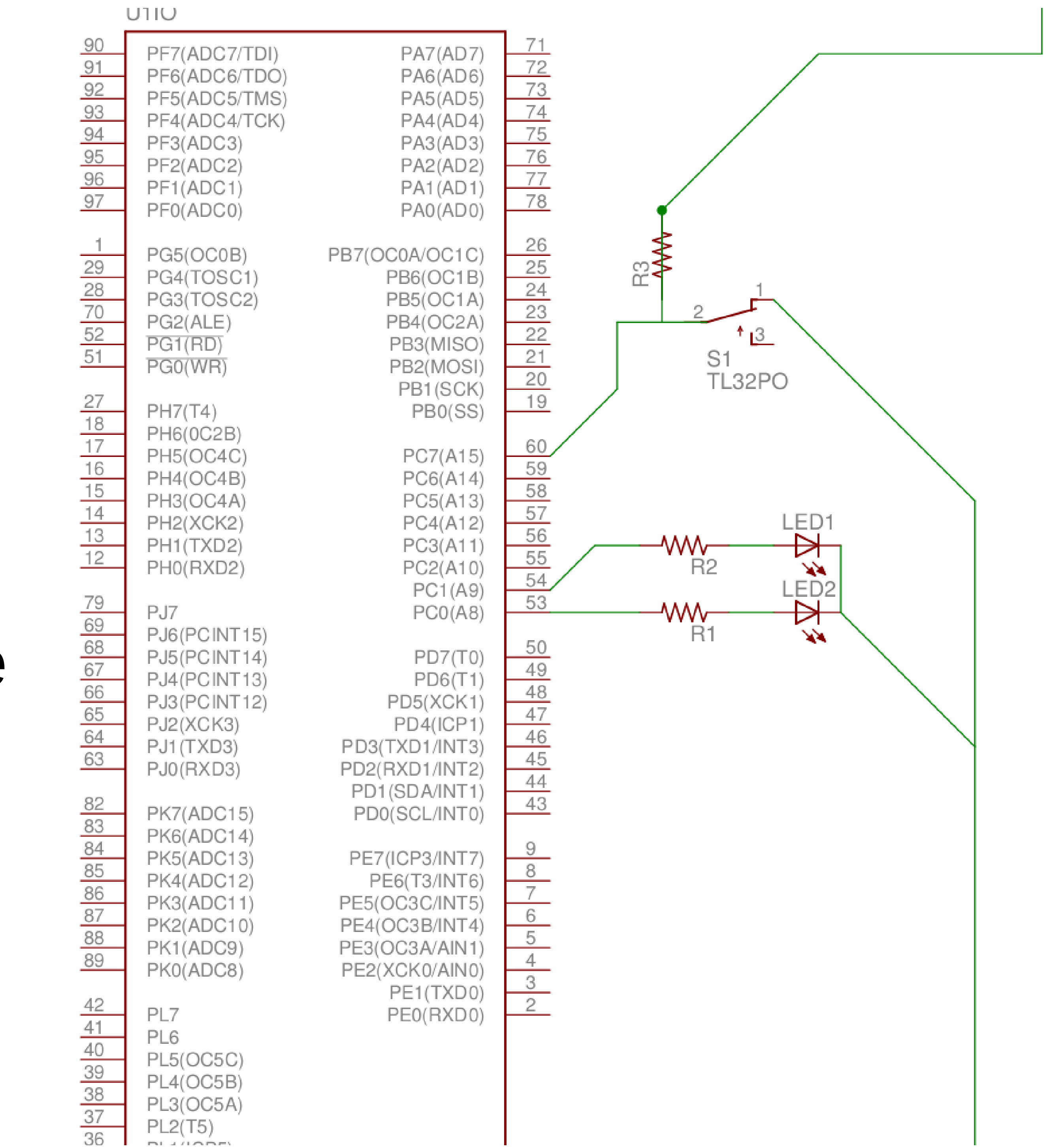
What are the values of B and C?

What mathematical operations have we performed?

A First Program

Flash the LEDs at a regular interval

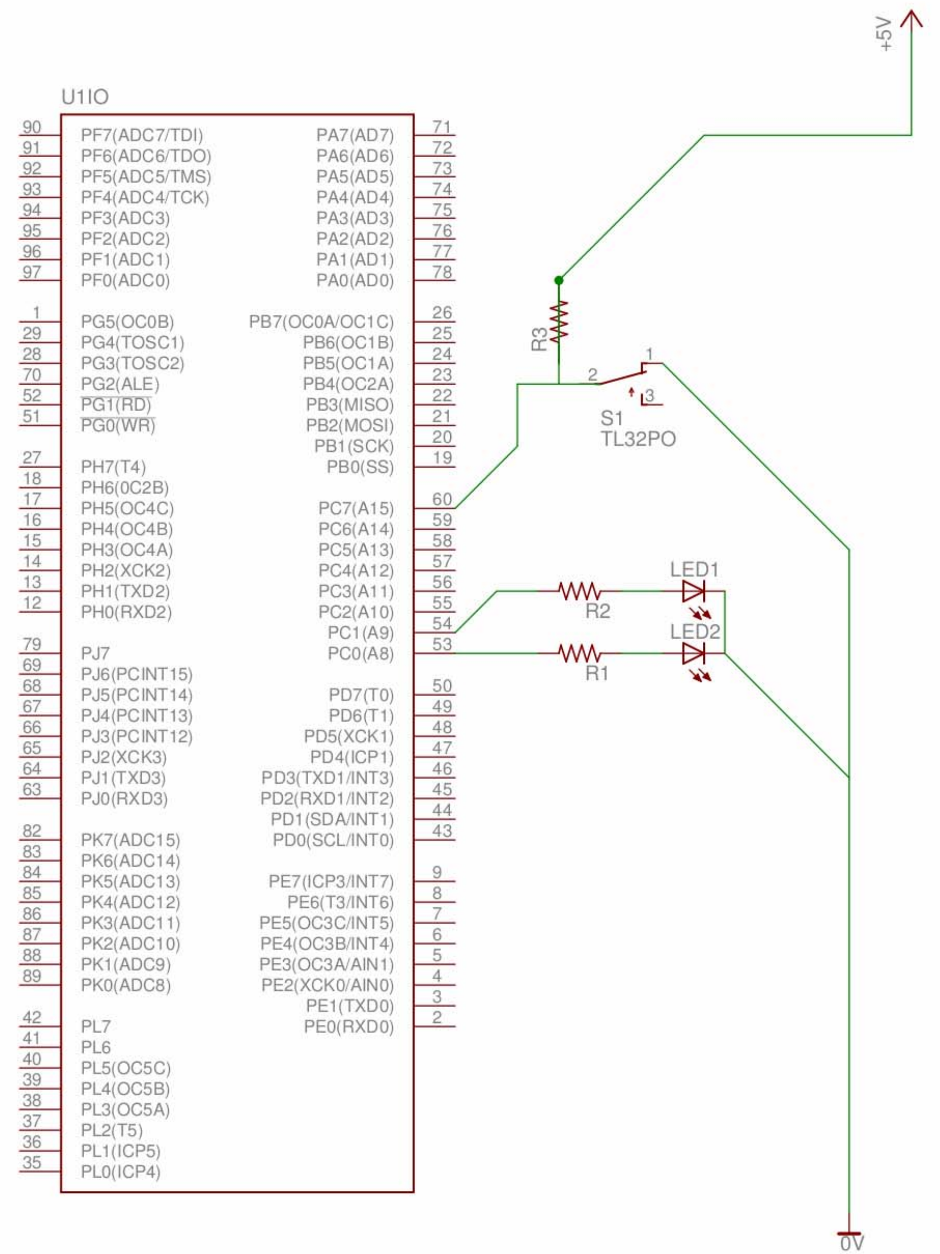
- How do we do this?



A First Program

How do we flash the LED at a regular interval?

- We toggle the state of PC0



A First Program

```
main() {
   DDRC = 1;   // Set port C pin 0 as an output

   while(1) {
        PORTC = PORTC | 0x1;
        delay_ms(500);
        PORTC = PORTC & ~0x1;
        delay_ms(500);
        }
}
```

A First Program

```
main() {
   DDRC = 1;   // Set port C pin 0 as an output

   while(1) {
        PORTC = PORTC ^ 0x1;   // XOR bit 0 with 1
        delay_ms(500);         // Pause for 500 msec
        }
}
```

A Second Program

```
main() {
   DDRC = 3;   // Set port C pins 0, and 1 as outputs

   while(1) {
        PORTC = PORTC ^ 0x1;   // XOR bit 0 with 1
        delay_ms(500);         // Pause for 500 msec
        PORTC = PORTC ^ 0x2;   // XOR bit 1 with 1
        delay_ms(250);
        PORTC = PORTC ^ 0x2;   // XOR bit 1 with 1
        delay_ms(250);
   }
}
```

What does this program do?

A Second Program

```
main() {
   DDRC = 3;   // Set port C pins 0, and 1 as outputs

   while(1) {
        PORTB = PORTC ^ 0x1;   // XOR bit 0 with 1
        delay_ms(500);         // Pause for 500 msec
        PORTB = PORTC ^ 0x2;   // XOR bit 1 with 1
        delay_ms(250);
        PORTB = PORTC ^ 0x2;   // XOR bit 1 with 1
        delay_ms(250);
   }
}
```

Flashes LED on PC1 at 1 Hz
on PC0: 0.5 Hz

Port-Related Registers

The set of C-accessible register for controlling digital I/O:

	Directional control	Writing	Reading
Port B	DDRB	PORTB	PINB
Port C	DDRC	PORTC	PINC
Port D	DDRD	PORTD	PIND

More Bit Masking

- Suppose we have a 3-bit number (so values 0 … 7)
- Suppose we want to set the state of B3, B4, and B5 with this number (B3 is the least significant bit)

  And: we want to leave the other bits undisturbed

- How do we express this in code?

Bit Masking

```
main() {
   DDRB = 0x38;   // Set pins B3, B4, B5  as outputs

       :
       :

  uint8_t val;  // A short is 8-bits wide

   val = command_to_robot;   // A value between 0 and 7

   PORTB = ????     //  Fill this in
}
```

Bit Masking

```
main() {
   DDRB = 0x38;   // Set pins B3, B4, B5  as outputs

        :
        :

  uint8_t val;  // A short is 8-bits wide

   val = command_to_robot;   // A value between 0 and 7

   PORTB = (PORTB & ~0x38)      // Set the current B3-B5 to 0s
        | ((val & 0x7)<<3);     // OR with new values (shifted
                                //  to fit within B3-B5
}
```

Reading the Digital State of Pins

Given: we want to read the state of PB6 and PB7 and obtain a value of 0 … 3

- How do we configure the port?
- How do we read the pins?
- How do we translate their values into an integer of 0 .. 3?

Reading the Digital State of Pins

```
main() {
   DDRB = 0x38;   // Set pins B3, B4, B5 as outputs
                  //   All others are inputs (suppose we care
                  //   about bits B6 and B7 only (so a 2-bit
                  //    number)
       :
       :

  unsigned short val, outval;  // A short is 8-bits wide

   val = ????  // Read the input value of B

   outval = ???  // Translate to a value of 0 … 3
}
```

Reading the Digital State of Pins

```
main() {
   DDRB = 0x38;    // Set pins B3, B4, B5 as outputs
                   //   All others are inputs (suppose we care
                   //   about bits B6 and B7 only (so a 2-bit
                   //    number)
       :
       :

  unsigned short val, outval;  // A short is 8-bits wide

   val = PINB;

   outval = (val & 0xC0) >> 6;
}
```

Putting It All Together

- Program development:
  – On your own laptop
  – We will use a C “crosscompiler” (avr-gcc and other tools) to generate code on your laptop for the mega8 processor
- Program download:
  – We will use “in circuit programming”: you will be able to program the chip without removing it from your circuit

Compiling and Downloading Code

Preparing to program:

- See the Atmel HOWTO (pointer from the schedule page)
- Windoze: Install AVR Studio and WinAVR
- OS X: Install OSX-AVR
  - We will use 'make' for compiling and downloading
- Linux: Install binutils, avr-gcc, avr-libc, and avrdude
  - Same as OS X