Microprocessors

Questions?

Quiz

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

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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;
}
```

The Assembly :

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

PC

Load the contents of memory location A into register 1

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
……..
```

PC

Load the contents of memory location B into register 2

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
……..
```

PC

Compare the contents of register 2 with those of register 1

This results in a change to the status register

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
……..
```

PC

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

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

The Assembly :

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

if not true

PC

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
……..
```

PC

Load the contents of memory location D into register 3

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
……..
```

PC

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

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

Take-Aways

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

- Many different component work together to execute a single instruction
- One line of C code typically translates into 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: you won’t be compiling programs on exams

Components of a Microprocessor

What are they?

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: temporarily 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: add, subtract, multiply, AND, OR …
- 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

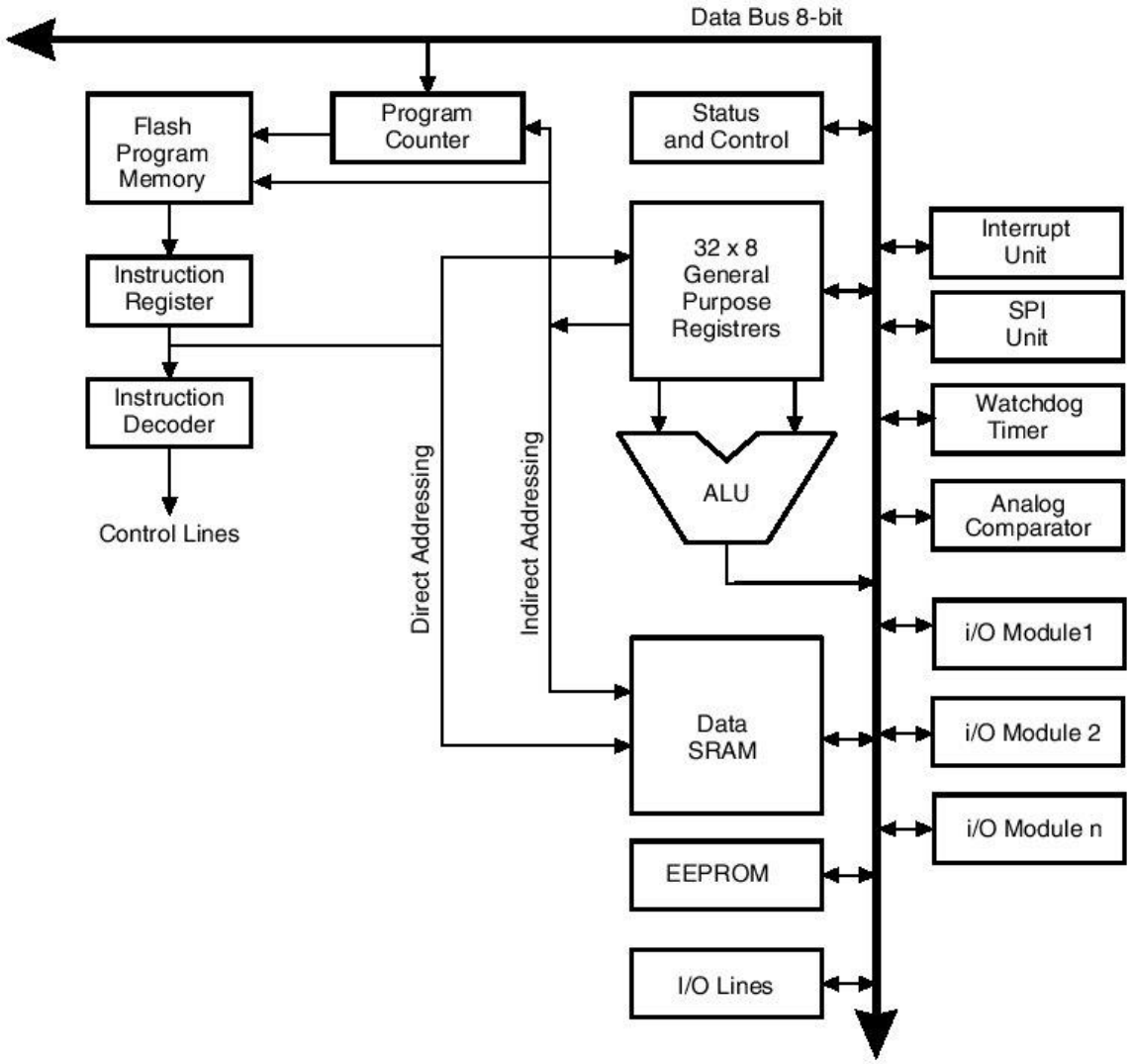
Buses

- 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

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: the data bus is 8-bits “wide”
- In your laptops: 32 or 64 bits

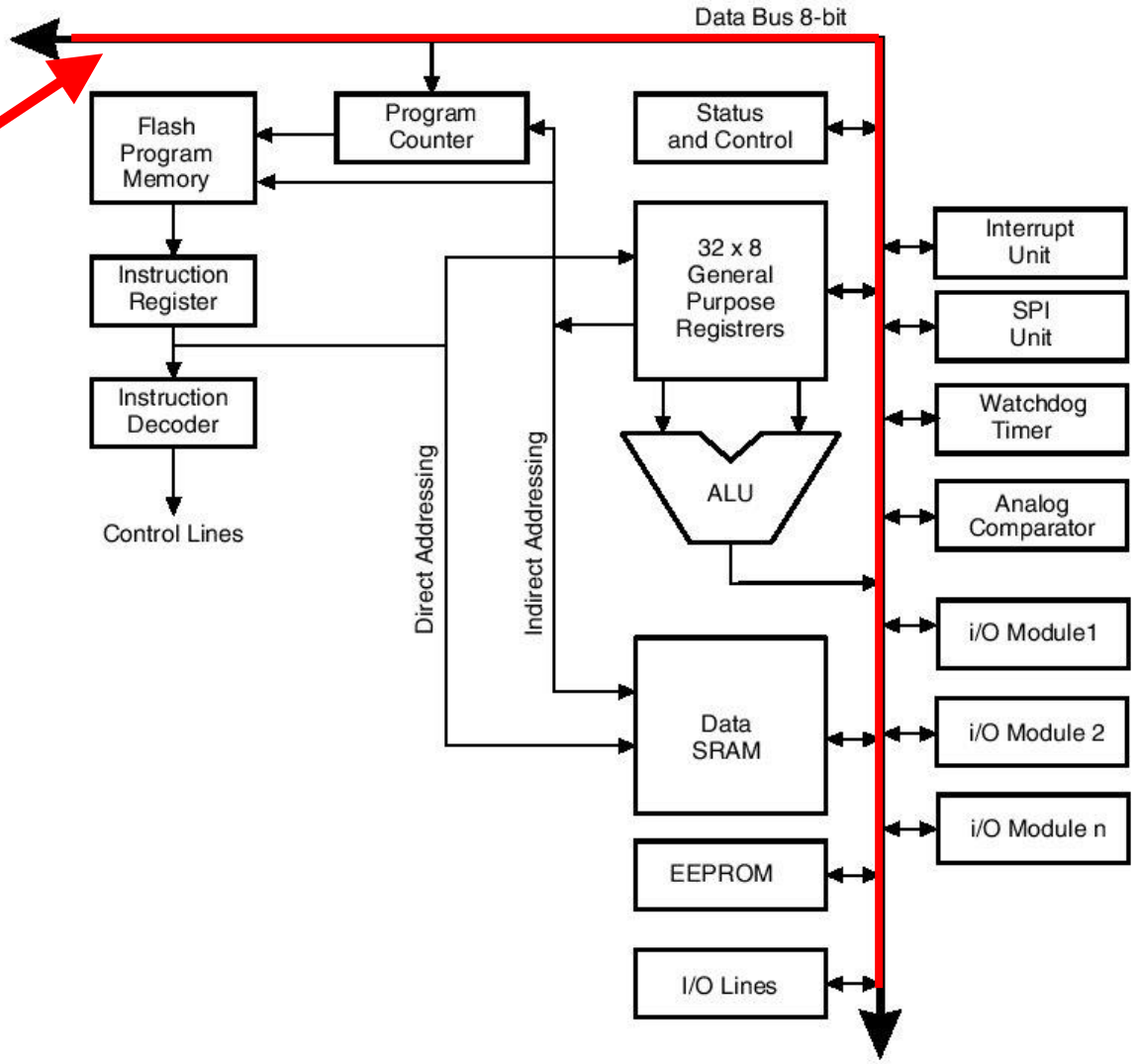
Atmel Mega2560 Architecture



Atmel Mega2560

8-bit data bus

- Primary mechanism for data exchange

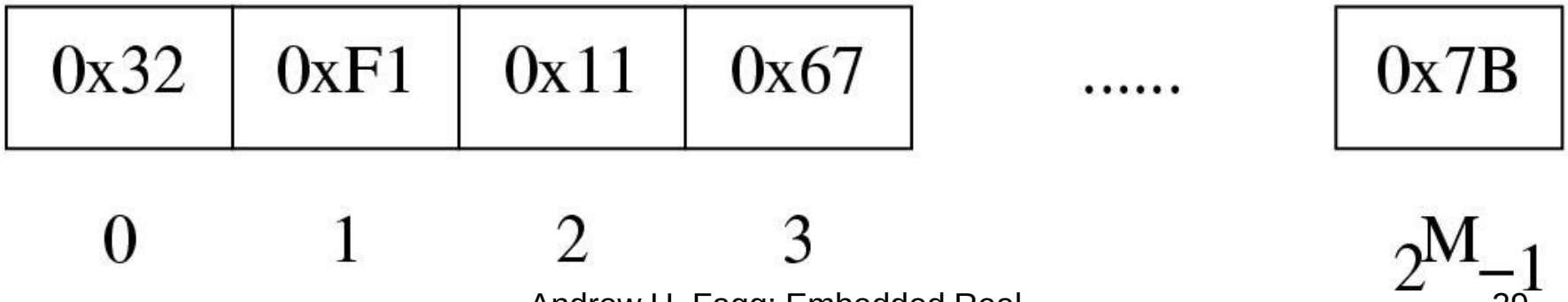


Memory

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 be 8-bits wide (so a byte)



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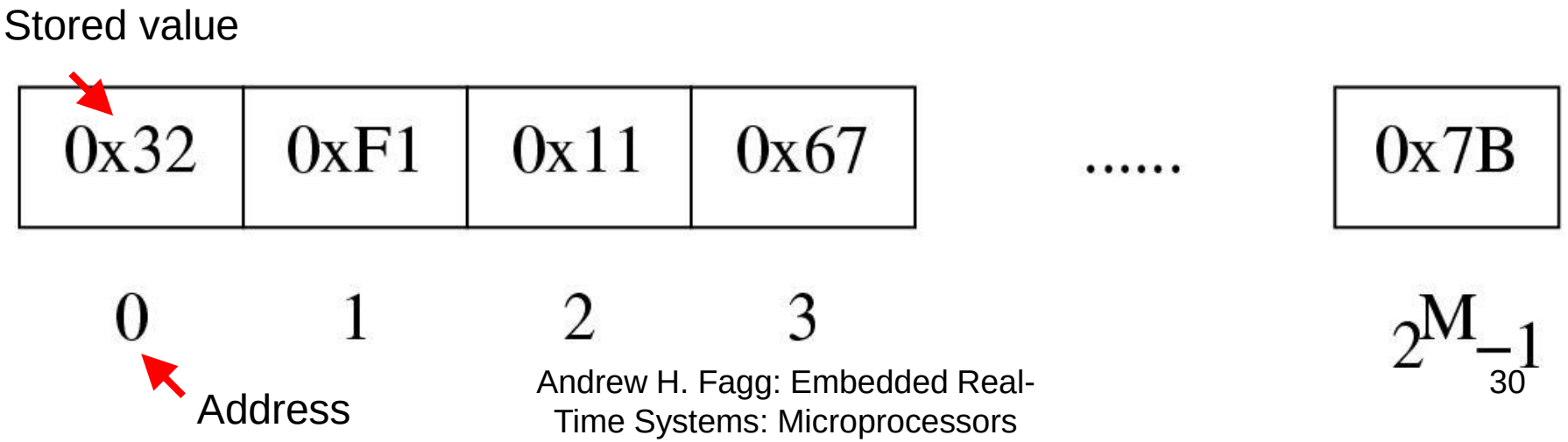


Memory Operations

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

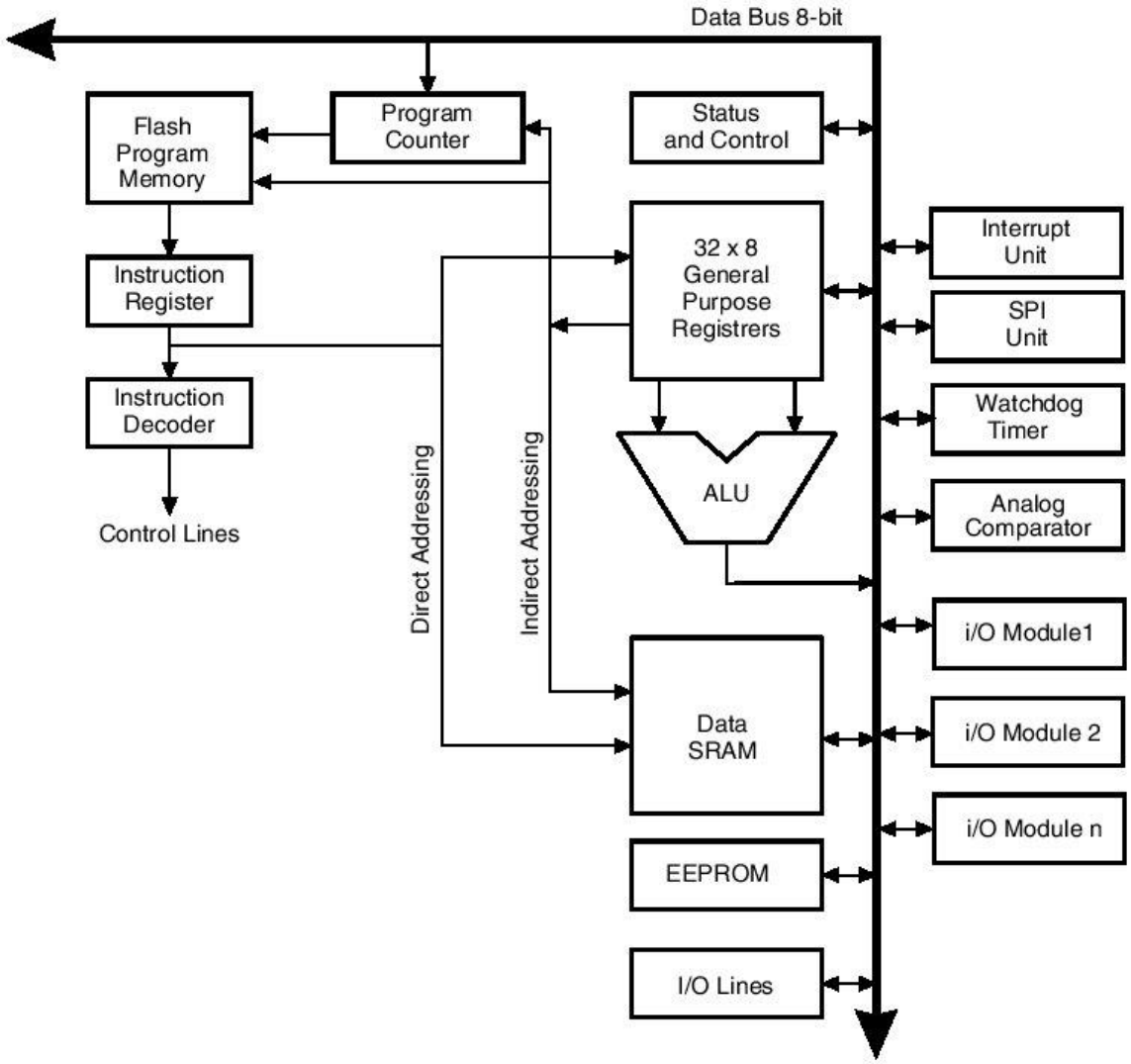
Types of Memory

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
  - Also called *Flash Memory*

Atmel Mega2560 Architecture



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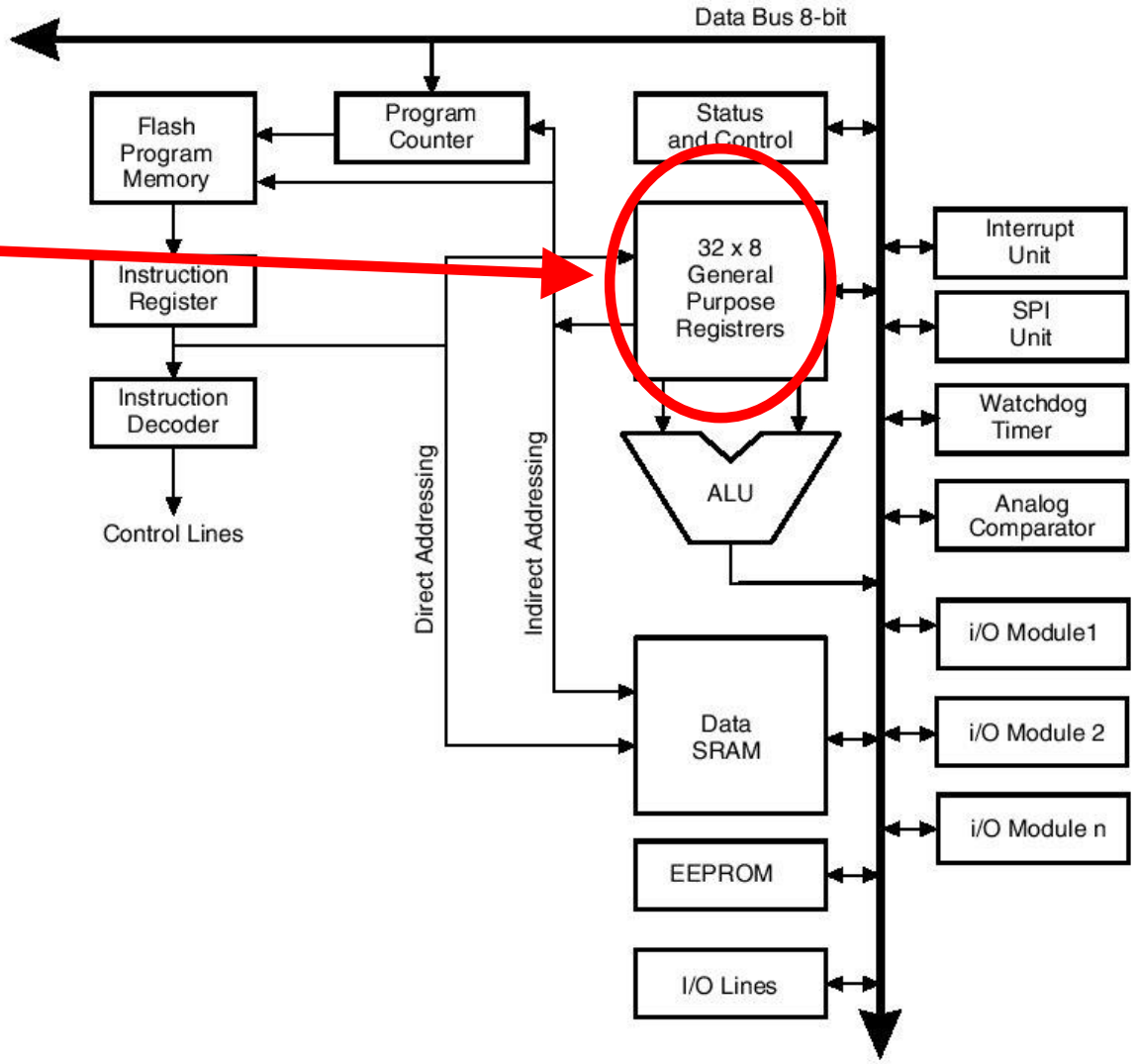
32 general purpose registers

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



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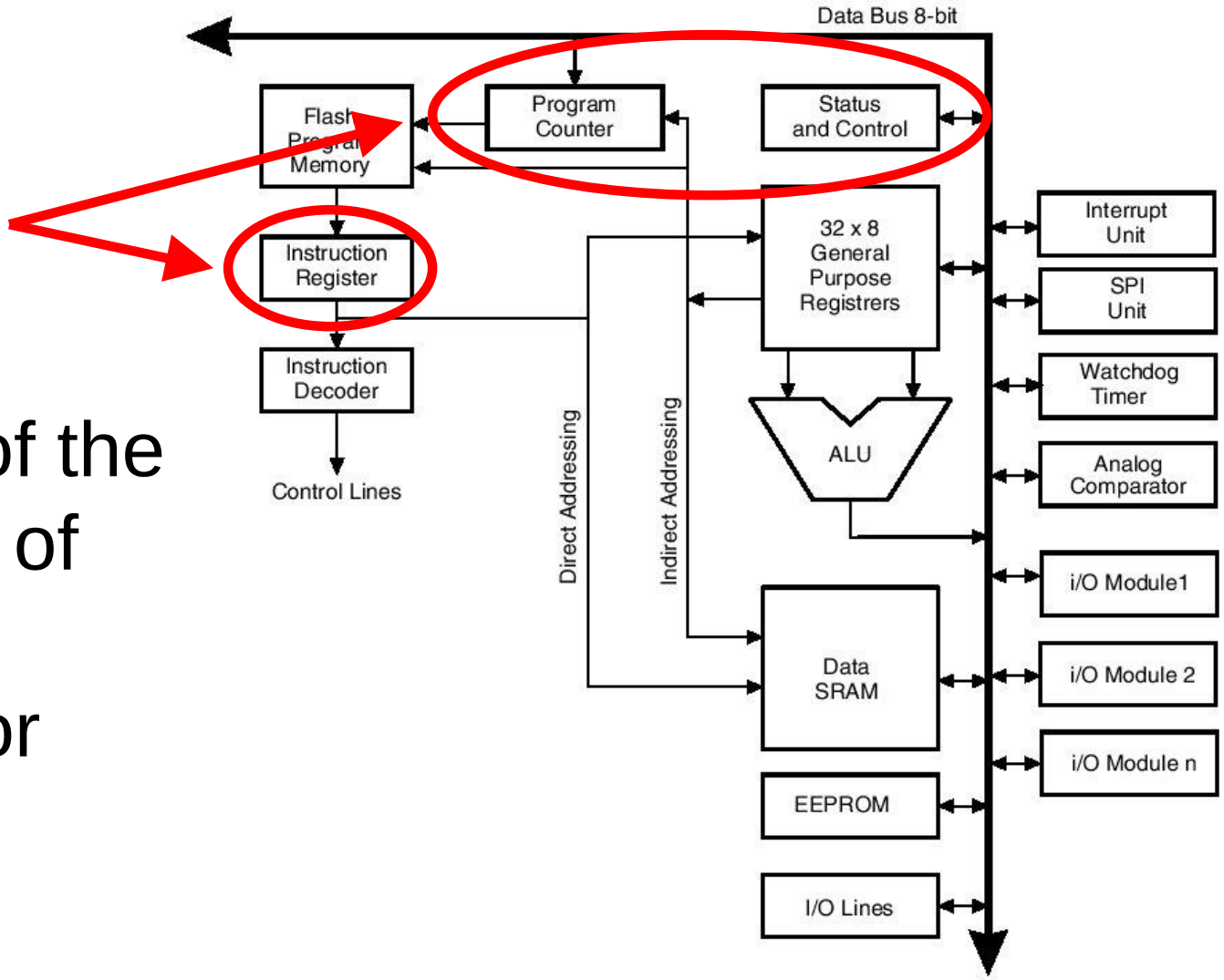
Special purpose registers

- Control of the internals of the processor



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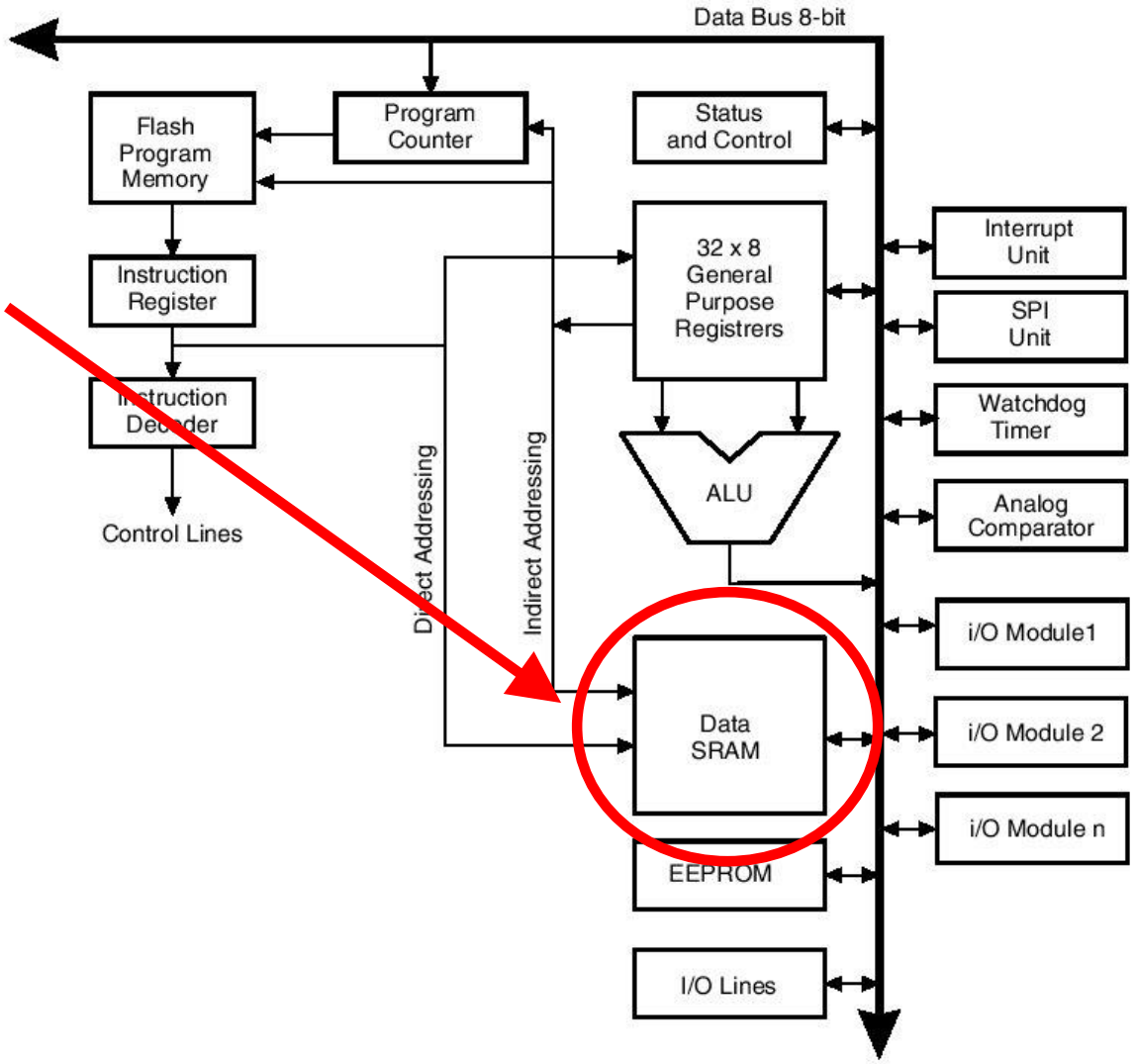
Random Access Memory (RAM)

- 8 KByte in size

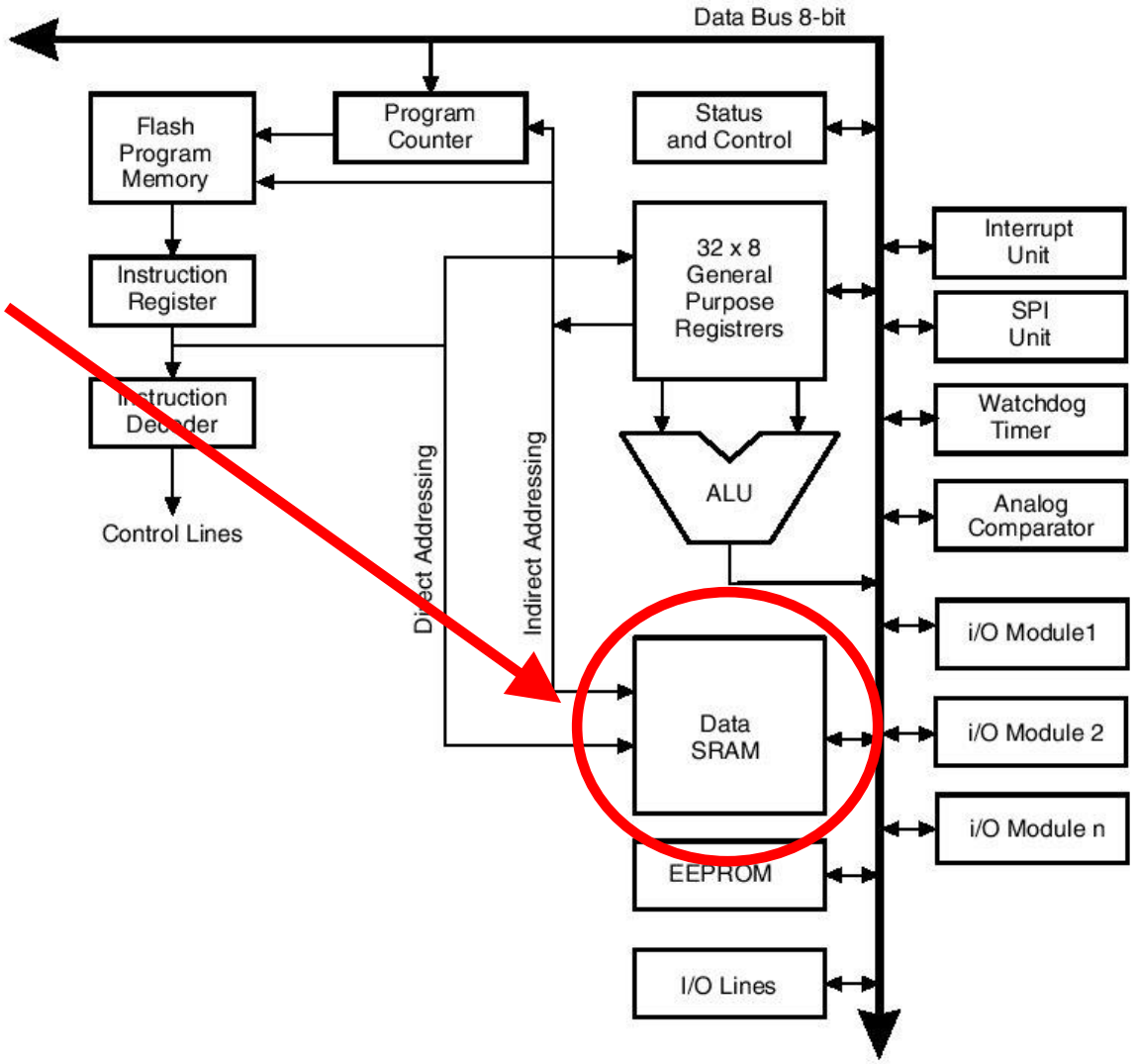


Atmel Mega2560

Random Access Memory (RAM)

- 8 KByte in size

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



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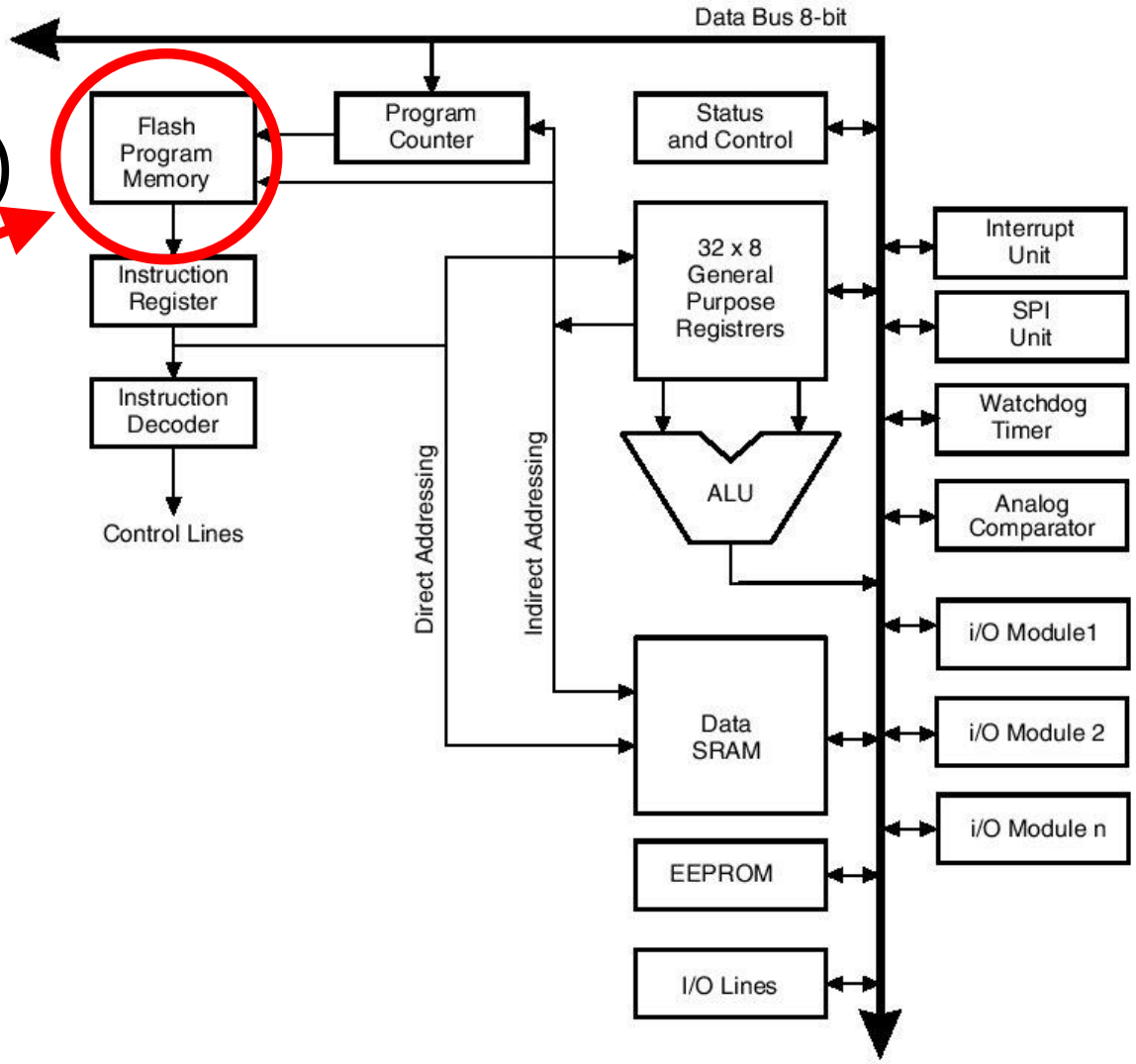
Flash (EEPROM)

- Program storage
- 256 KByte in size



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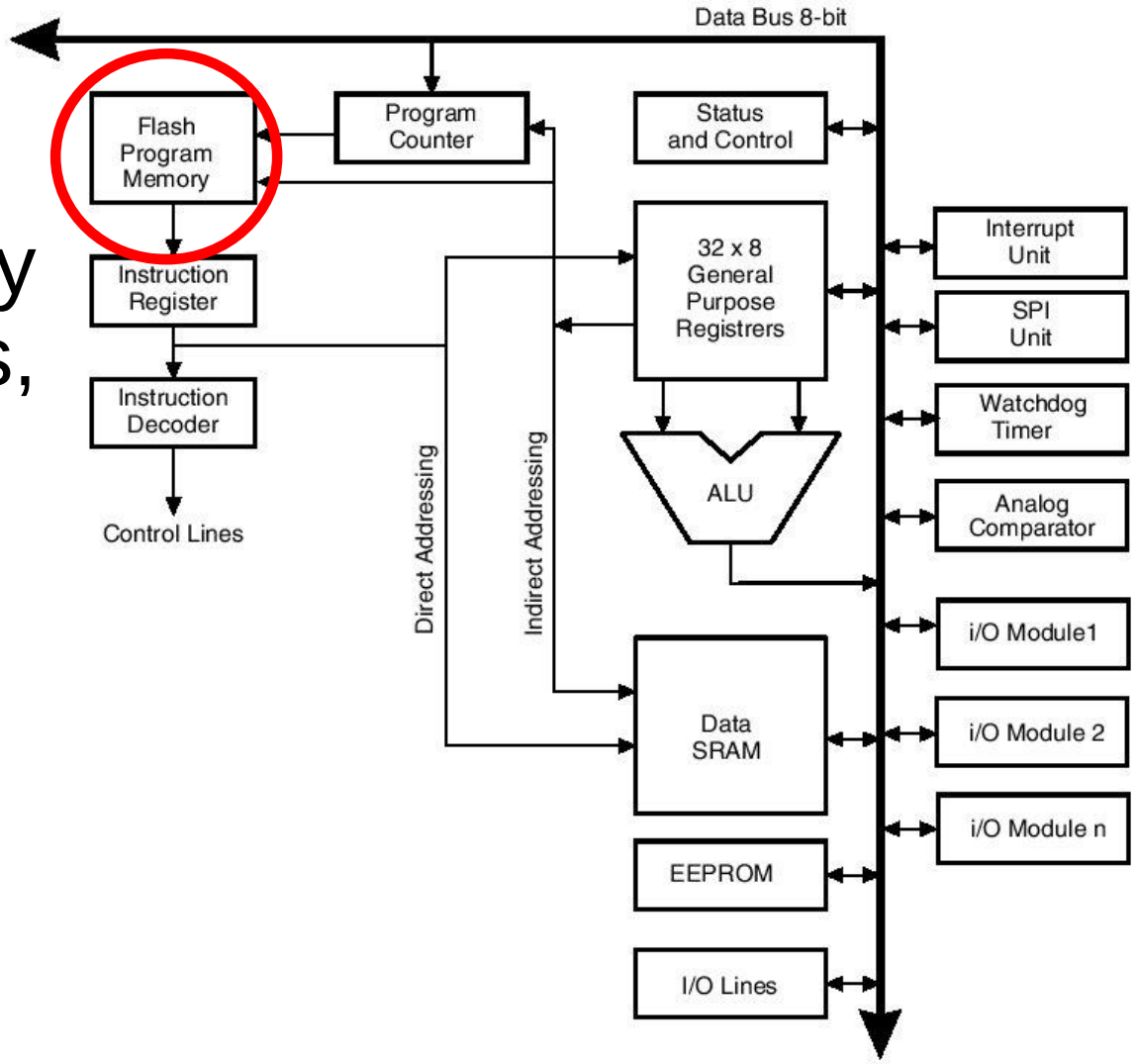
Flash (EEPROM)

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



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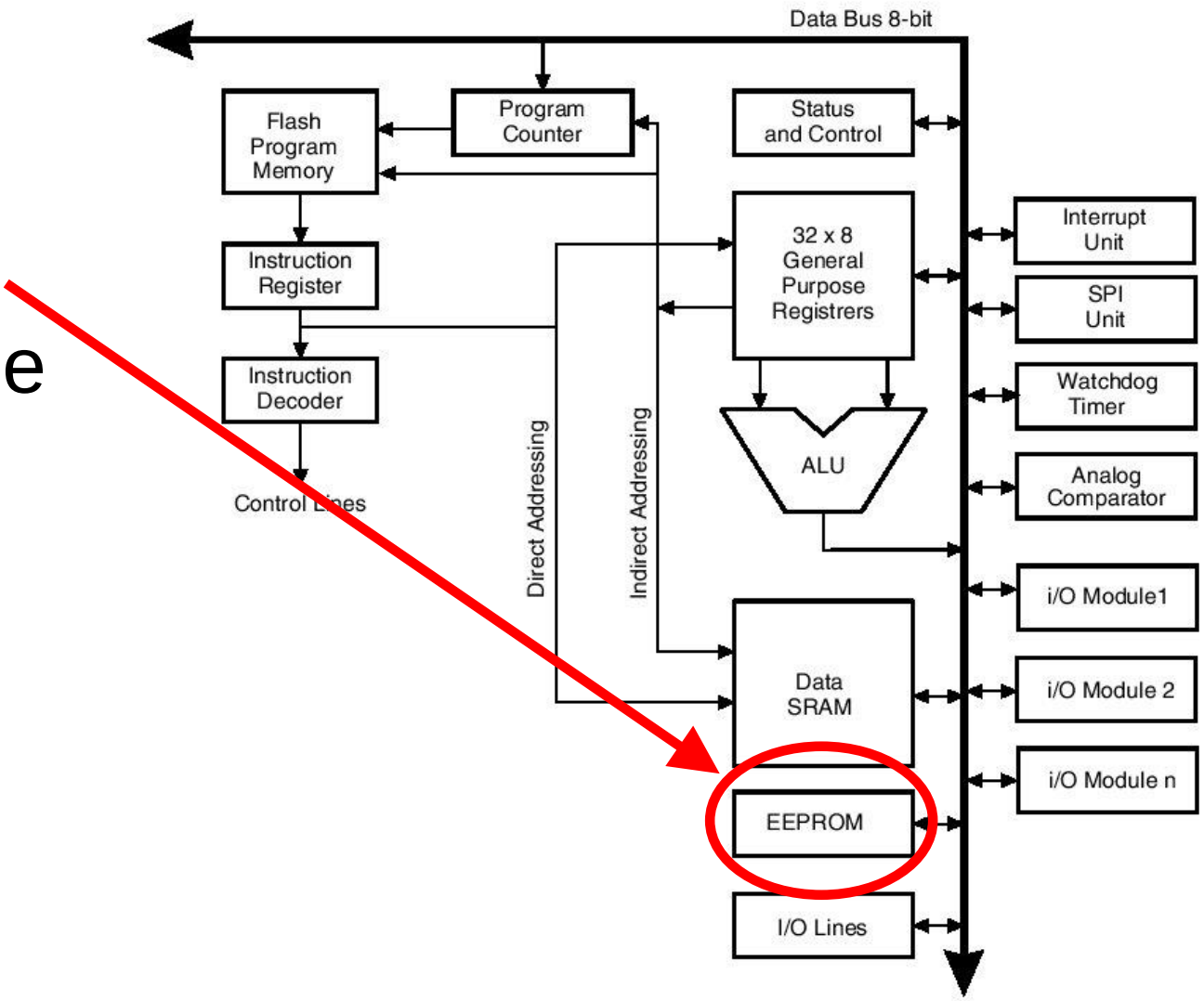
EEPROM

- Permanent data storage



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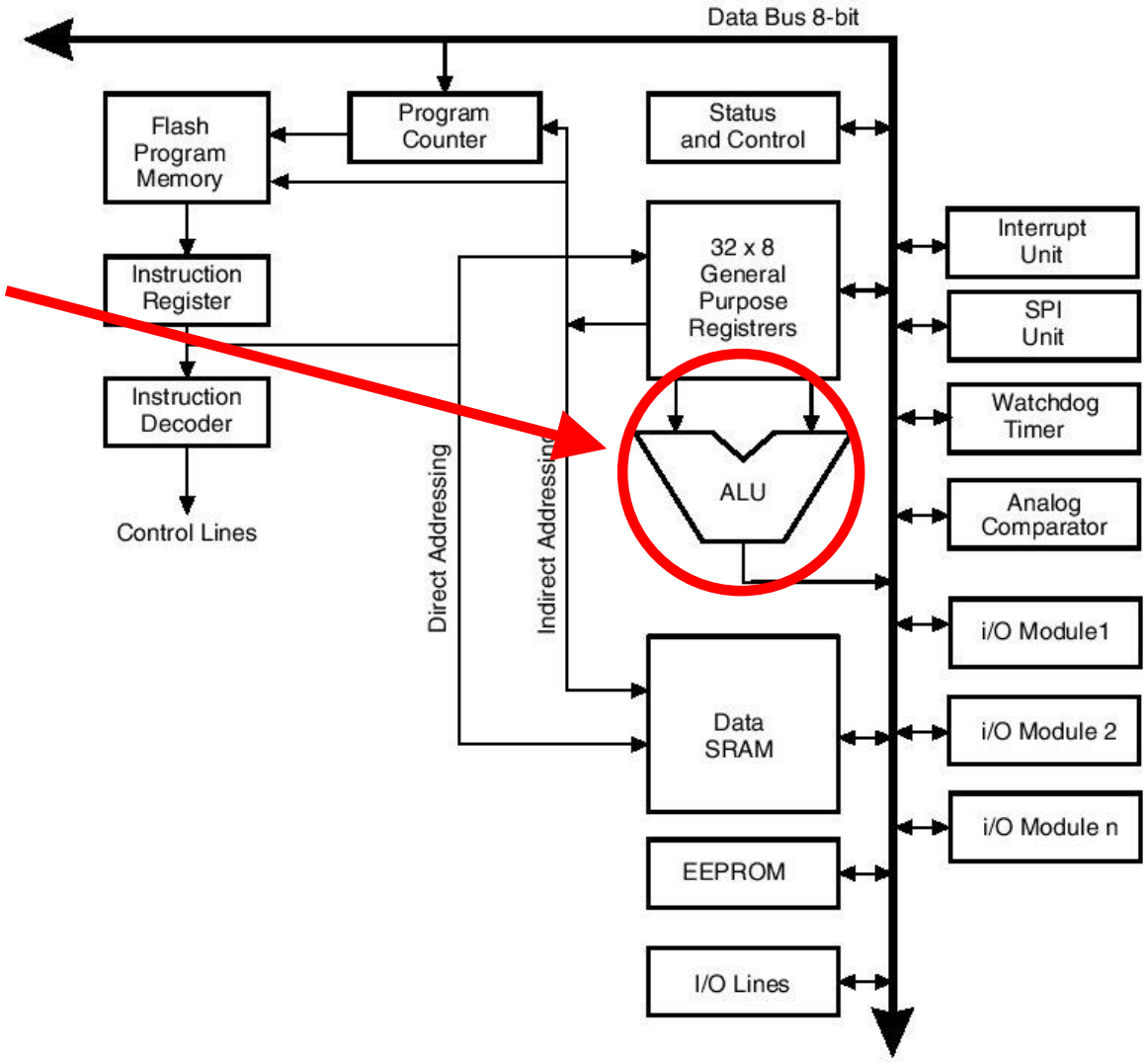
Arithmetic Logical Unit

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



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

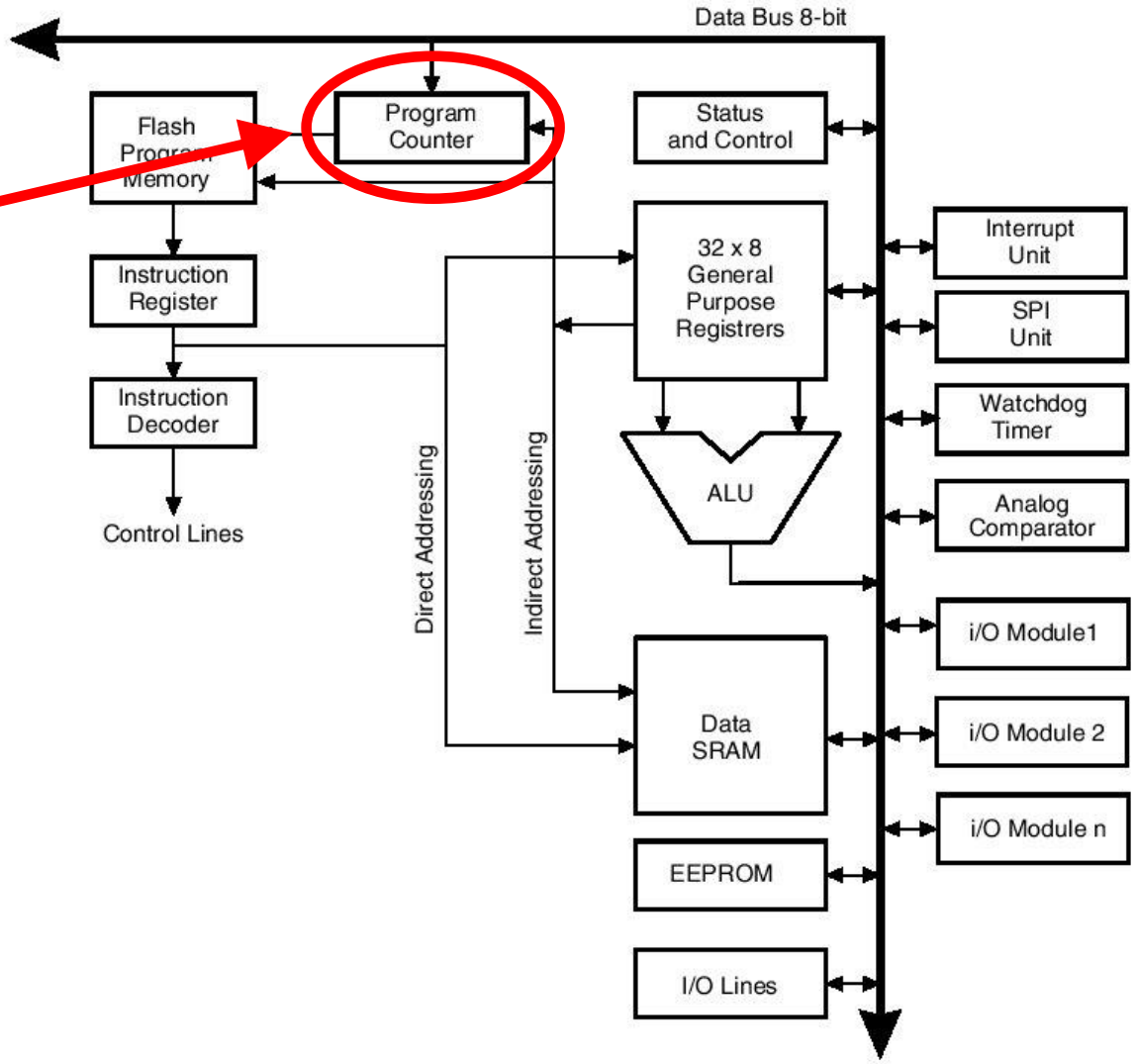
Types of Instructions

- 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

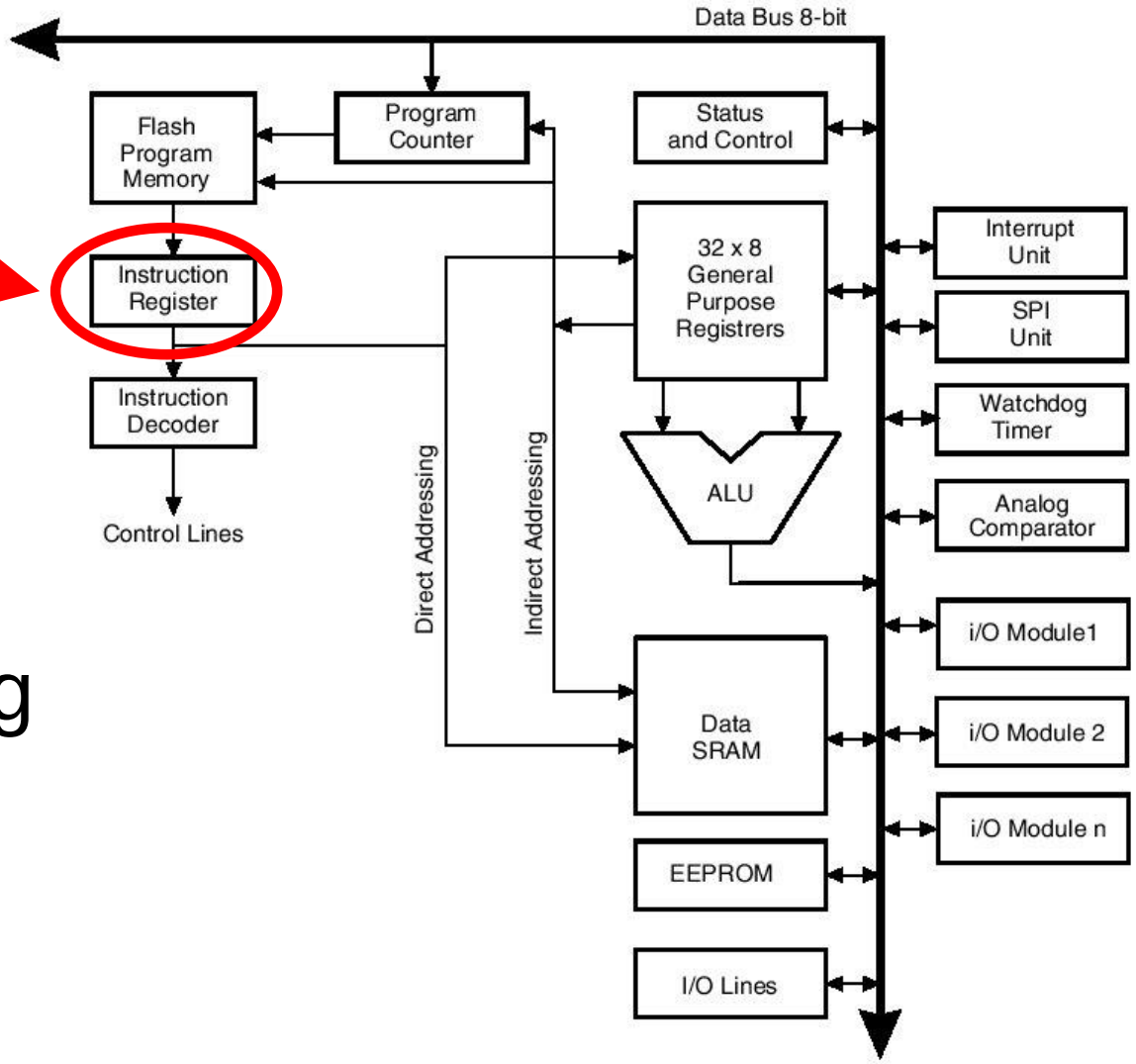
- Address of currently executing instruction



Mega2560: Decoding Instructions

Instruction register

- Stores the machine-level instruction currently being executed



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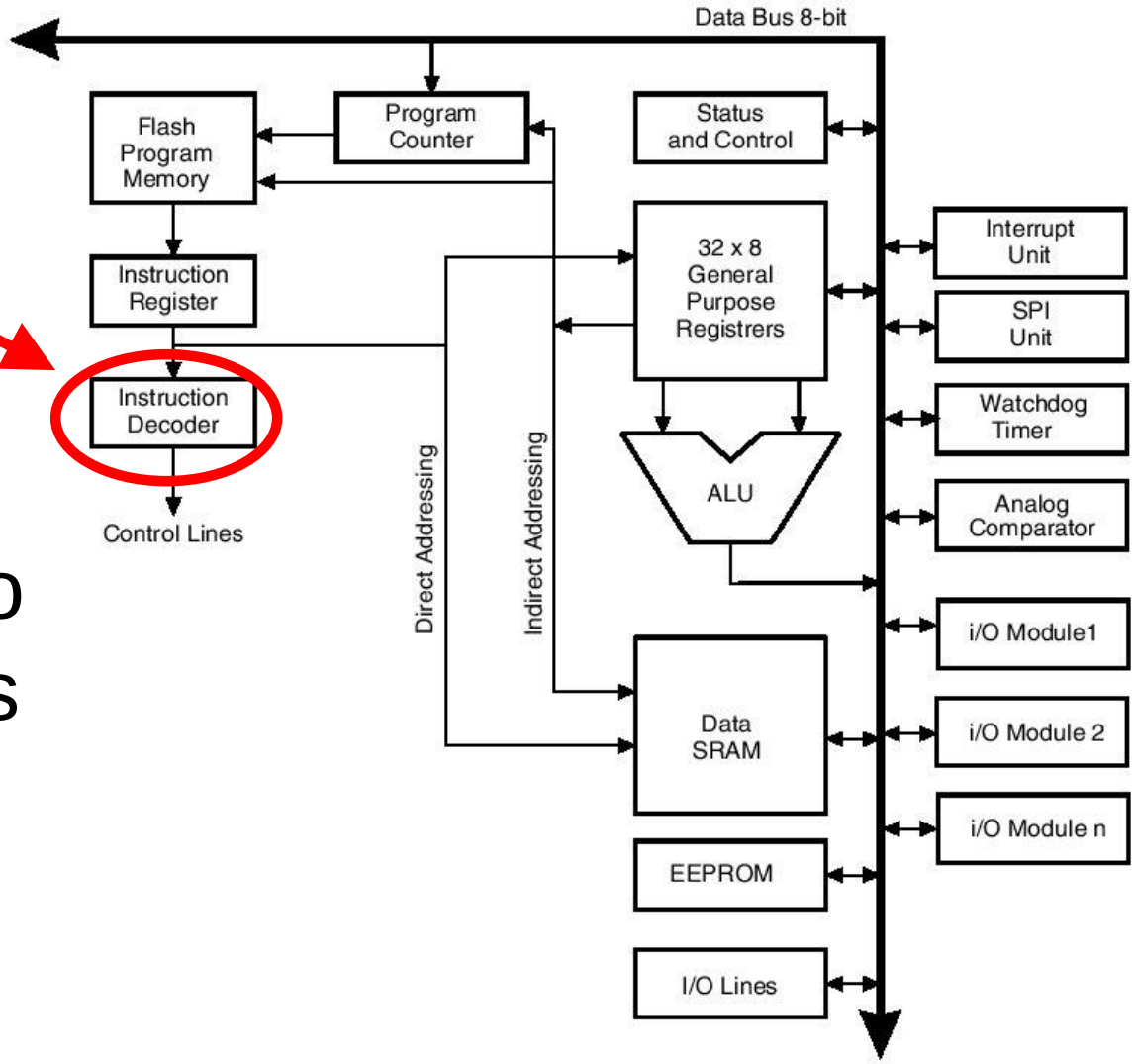
Instruction decoder

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



Atmel Instructions

Some Mega2560 Memory Operations

We refer to this as "Assembly Language"

LDS Rd, k

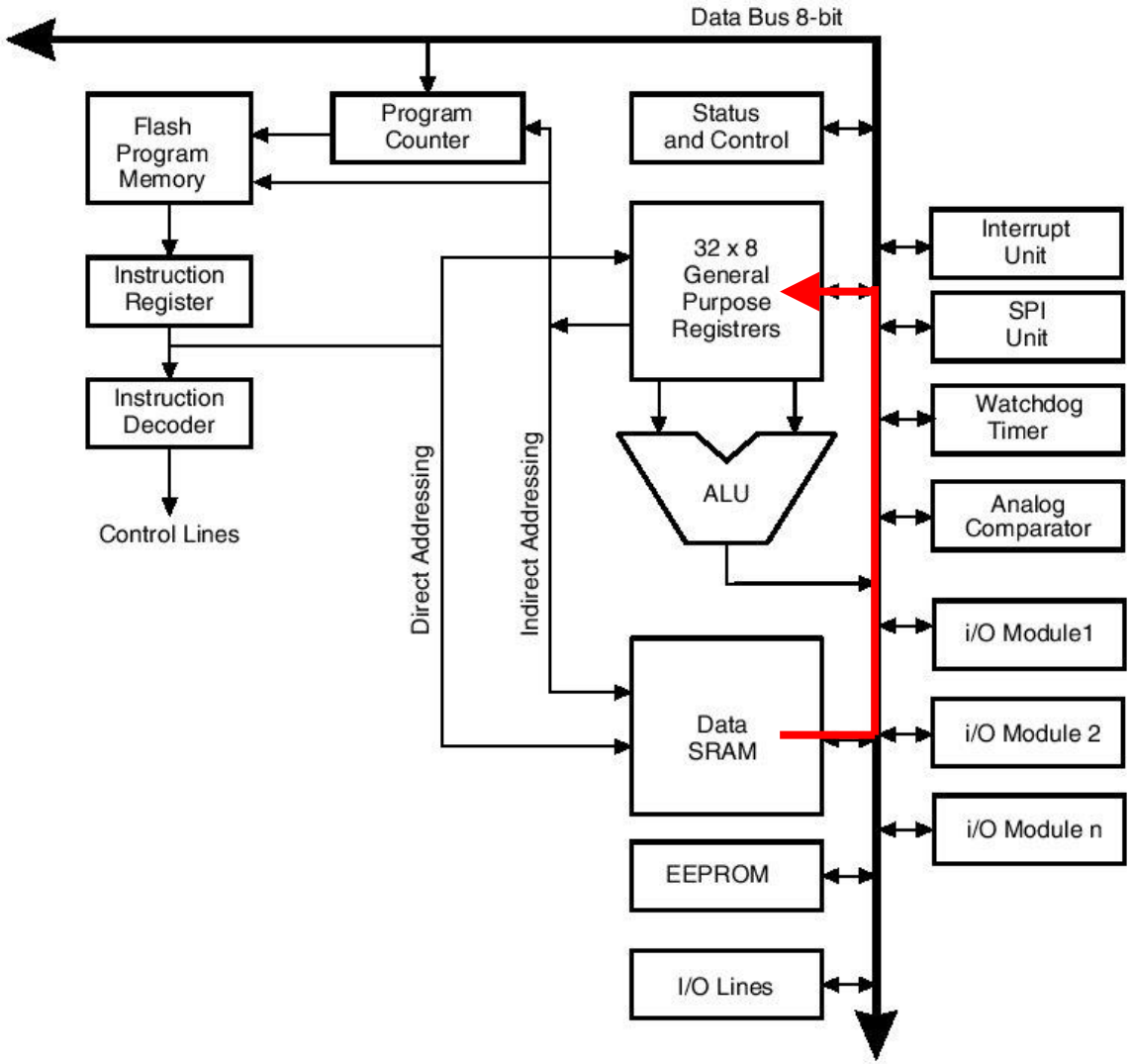
- Load SRAM memory location k into register Rd
- Rd <- (k)

STS Rd, k

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

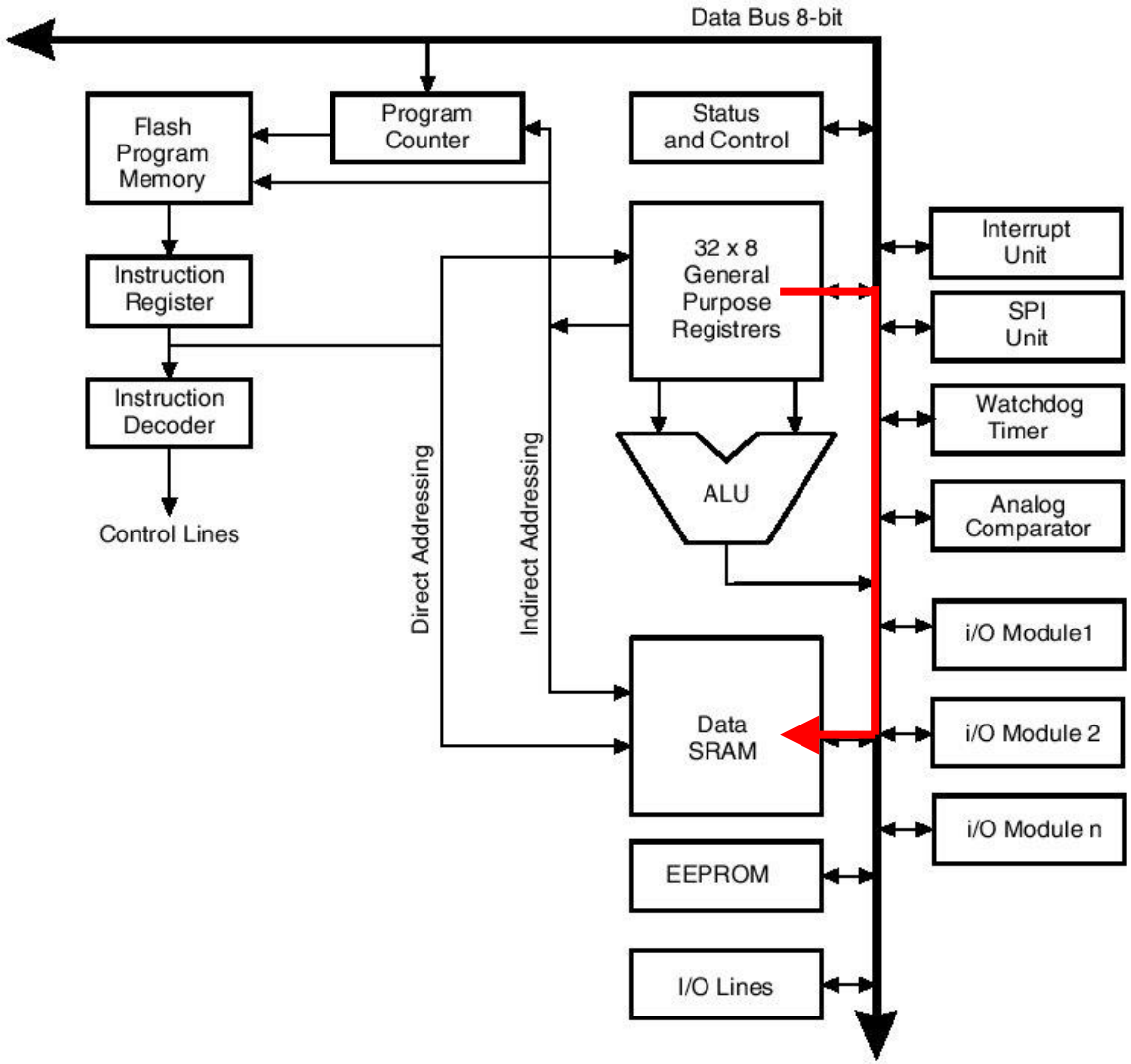
Load SRAM Value to Register

LDS Rd, k



Store Register Value to SRAM

STS Rd, k



Some Mega2560 Arithmetic and Logical Instructions

ADD Rd, Rr

- Add Rd and Rr (these are registers)
- Operation: Rd <- Rd + Rr

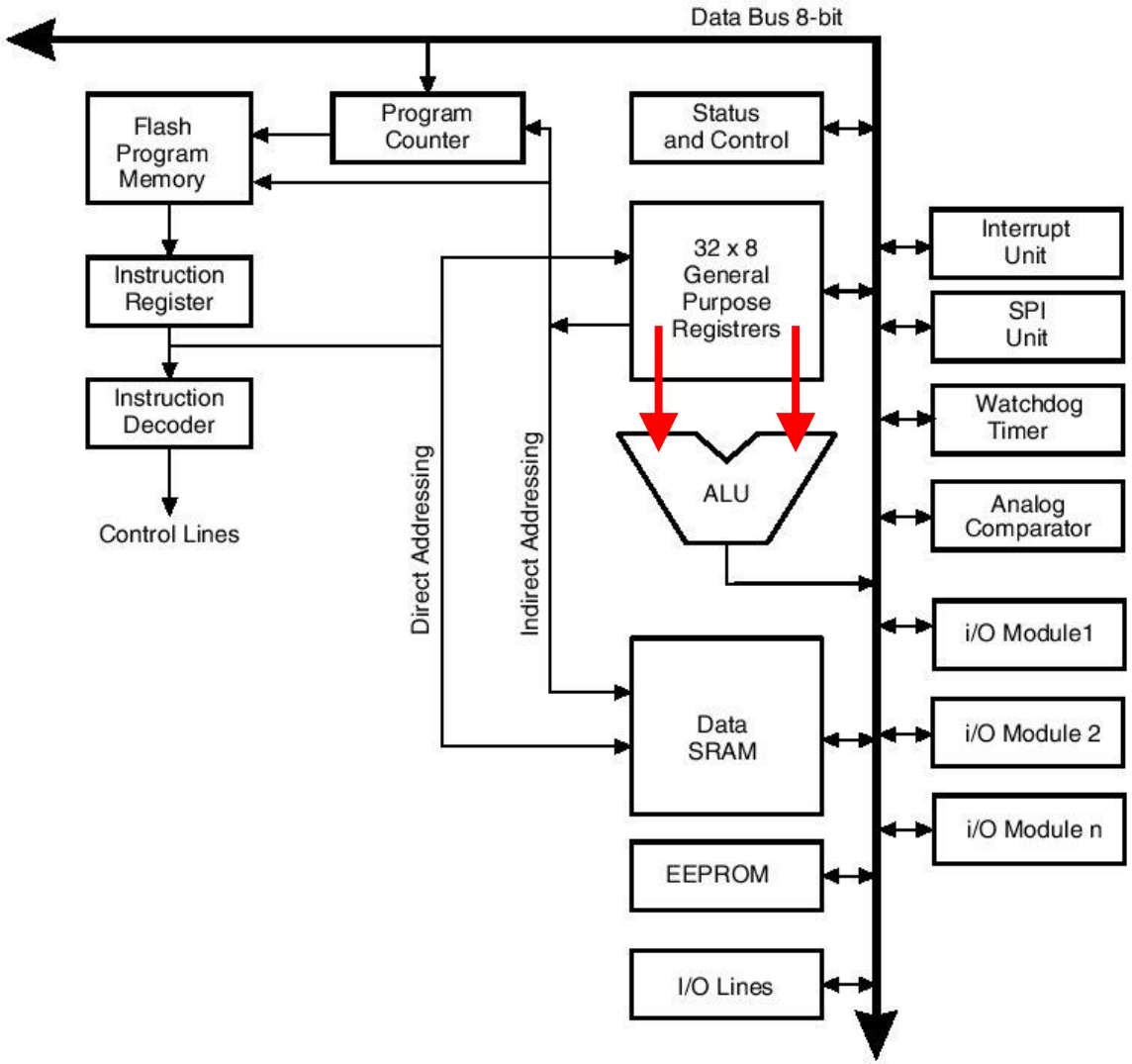
ADC Rd, Rr

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

Add Two Register Values

ADD Rd, Rr

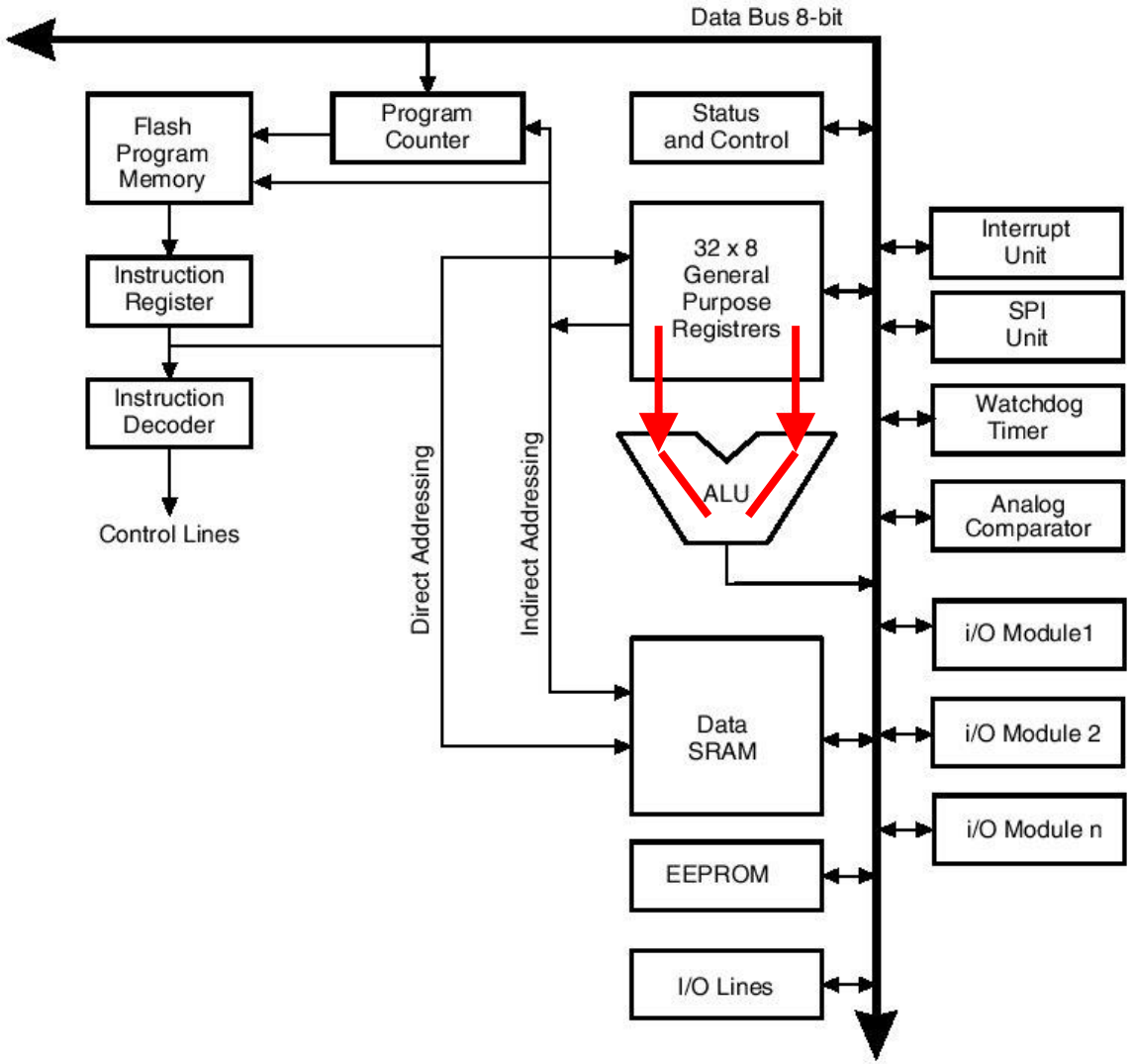
- Fetch register values



Add Two Register Values

ADD Rd, Rr

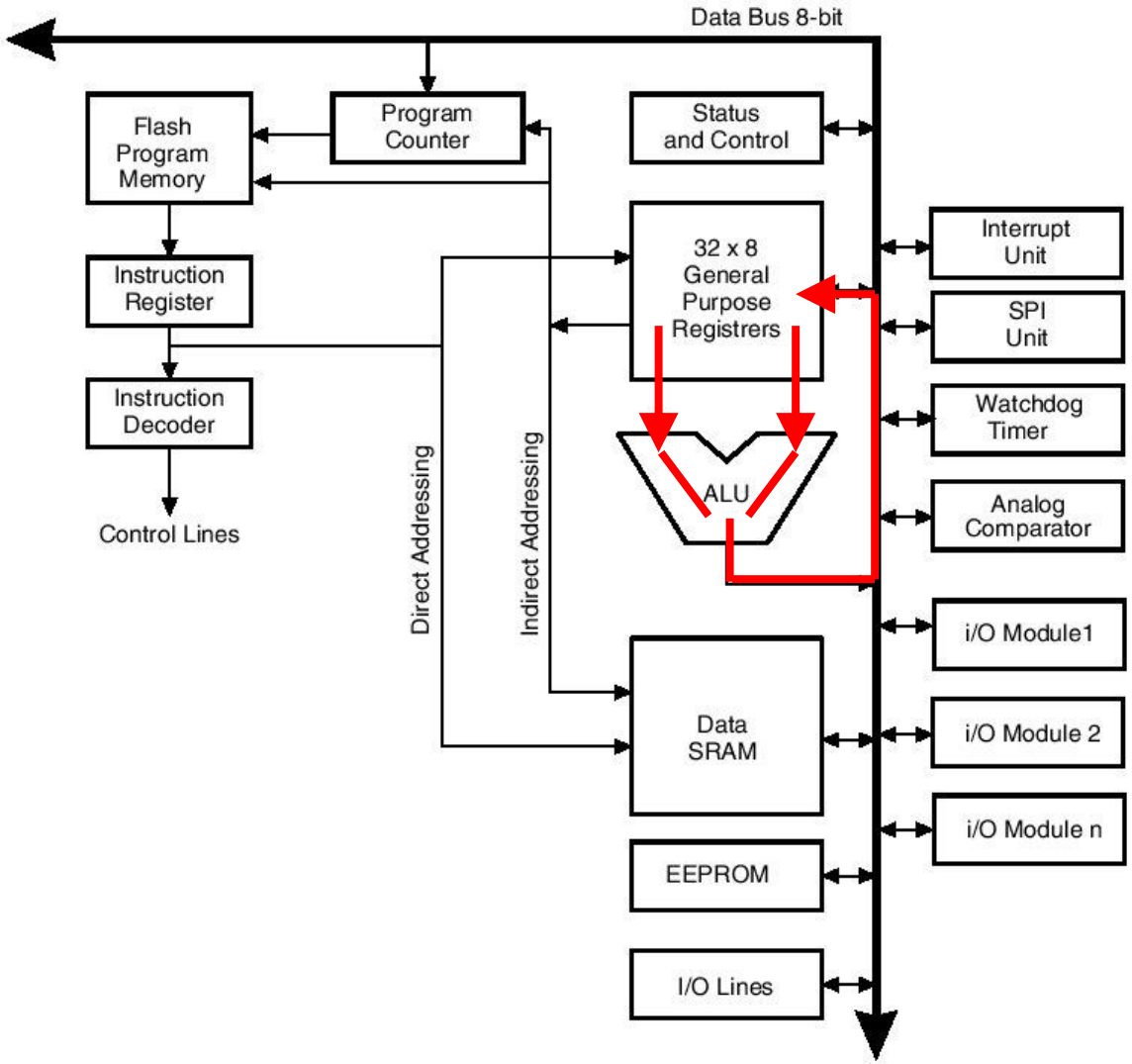
- Fetch register values
- ALU performs ADD



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, Rr: multiply (signed)

An Example

```
#include "oulib.h"

volatile uint8_t a = 10;

int main (void)
{
  a = a+5;

  while(1) {
    delay_ms(++a);
  };
}
```

Compiled Result

```
0000013c <main>:

volatile uint8_t a = 10;

int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    8b 5f            subi    r24, 0xFB        ; 251
 142:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 146:    80 91 00 02      lds     r24, 0x0200
 14a:    8f 5f            subi    r24, 0xFF        ; 255
 14c:    80 93 00 02      sts     0x0200, r24
 150:    80 91 00 02      lds     r24, 0x0200
 154:    90 e0            ldi     r25, 0x00        ; 0
 156:    0e 94 ae 00      call    0x15c    ; 0x15c <delay_ms>
 15a:    f5 cf            rjmp    .-22             ; 0x146 <main+0xa>
```

Compiled Result

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```

Location in program memory

Compiled Result

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 15a:    f5 cf            rjmp    .-22             ; 0x146 <main+0xa>
```

Load memory location 0x200 to r24

Compiled Result

```
0000013c <main>:

volatile uint8_t a = 10;

int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    8b 5f            subi    r24, 0xFB       ; 251
 142:    80 93 00 02      sts     0x0200, r24

  while(1) {
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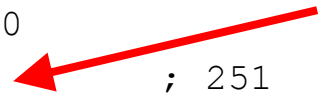
 154:    90 e0            ldi     r25, 0x00       ; 0
 156:    0e 94 ae 00      call    0x15c   ; 0x15c <delay_ms>
 15a:    f5 cf            rjmp    .-22            ; 0x146 <main+0xa>
```

Add 5 to r24



Compiled Result

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0000013c <main>:

volatile uint8_t a = 10;

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{
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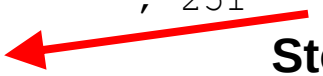

Store r24 to memory location 0x200

Compiled Result

```
0000013c <main>:

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int main (void)
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Load memory location 0x200 to r24

Compiled Result

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int main (void)
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 154:    90 e0            ldi     r25, 0x00        ; 0
 156:    0e 94 ae 00      call    0x15c    ; 0x15c <delay_ms>
 15a:    f5 cf            rjmp    .-22             ; 0x146 <main+0xa>
```

Add 1 to r24

Compiled Result

```
0000013c <main>:

volatile uint8_t a = 10;

int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    8b 5f            subi    r24, 0xFB        ; 251
 142:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 146:    80 91 00 02      lds     r24, 0x0200
 14a:    8f 5f            subi    r24, 0xFF        ; 255
 14c:    80 93 00 02      sts     0x0200, r24
 150:    80 91 00 02      lds     r24, 0x0200
 154:    90 e0            ldi     r25, 0x00        ; 0
 156:    0e 94 ae 00      call    0x15c    ; 0x15c <delay_ms>
 15a:    f5 cf            rjmp    .-22             ; 0x146 <main+0xa>
```

Store r24 to memory location 0x200

Compiled Result

```
0000013c <main>:

volatile uint8_t a = 10;

int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    8b 5f            subi    r24, 0xFB        ; 251
 142:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 146:    80 91 00 02      lds     r24, 0x0200
 14a:    8f 5f            subi    r24, 0xFF        ; 255
 14c:    80 93 00 02      sts     0x0200, r24
 150:    80 91 00 02      lds     r24, 0x0200
 154:    90 e0            ldi     r25, 0x00        ; 0
 156:    0e 94 ae 00      call    0x15c    ; 0x15c <delay_ms>
 15a:    f5 cf            rjmp    .-22             ; 0x146 <main+0xa>
```

Load memory location 0x200 to r25, r24

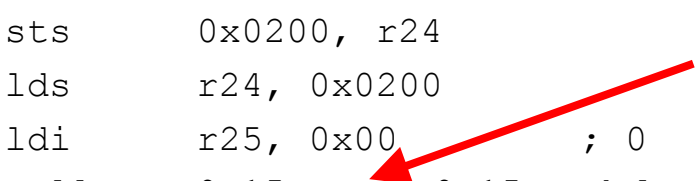
Compiled Result

```
0000013c <main>:

volatile uint8_t a = 10;

int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    8b 5f            subi    r24, 0xFB        ; 251
 142:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 146:    80 91 00 02      lds     r24, 0x0200
 14a:    8f 5f            subi    r24, 0xFF        ; 255
 14c:    80 93 00 02      sts     0x0200, r24
 150:    80 91 00 02      lds     r24, 0x0200
 154:    90 e0            ldi     r25, 0x00        ; 0
 156:    0e 94 ae 00      call    0x15c    ; 0x15c <delay_ms>
 15a:    f5 cf            rjmp    .-22             ; 0x146 <main+0xa>
```



Compiled Result

```
0000013c <main>:

volatile uint8_t a = 10;

int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    8b 5f            subi    r24, 0xFB        ; 251
 142:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 146:    80 91 00 02      lds     r24, 0x0200
 14a:    8f 5f            subi    r24, 0xFF        ; 255
 14c:    80 93 00 02      sts     0x0200, r24
 150:    80 91 00 02      lds     r24, 0x0200
 154:    90 e0            ldi     r25, 0x00        ; 0
 156:    0e 94 ae 00      call    0x15c    ; 0x15c <delay_ms>
 15a:    f5 cf            rjmp    .-22             ; 0x146 <main+0xa>
```

Go back to top of while() loop

Example II

```
#include "oulib.h"

volatile uint16_t a = 10;

int main (void)
{
  a = a+5;

  while(1) {
    delay_ms(++a);
  };
}
```

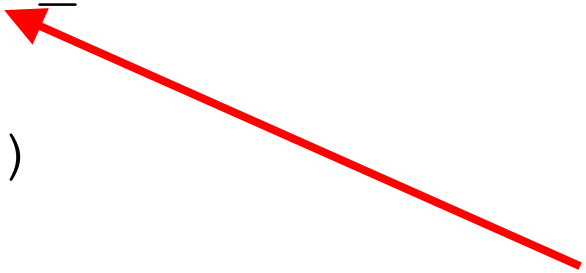
Example II

```
#include "oulib.h"

volatile uint16_t a = 10;

int main (void)
{
  a = a+5;

  while(1) {
    delay_ms(++a);
  };
}
```



Size of integer has changed!

We need two bytes

Compiled Result

```
0000013c <main>:
volatile uint16_t a = 10;
int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    90 91 01 02      lds     r25, 0x0201
 144:    05 96            adiw    r24, 0x05        ; 5
 146:    90 93 01 02      sts     0x0201, r25
 14a:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 14e:    80 91 00 02      lds     r24, 0x0200
 152:    90 91 01 02      lds     r25, 0x0201
 156:    01 96            adiw    r24, 0x01        ; 1
 158:    90 93 01 02      sts     0x0201, r25
 15c:    80 93 00 02      sts     0x0200, r24
 160:    80 91 00 02      lds     r24, 0x0200
 164:    90 91 01 02      lds     r25, 0x0201
 168:    0e 94 b7 00      call    0x16e    ; 0x16e <delay_ms>
 16c:    f0 cf            rjmp    .-32             ; 0x14e <main+0x12>
```

Compiled Result

```
0000013c <main>:
volatile uint16_t a = 10;
int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    90 91 01 02      lds     r25, 0x0201
 144:    05 96            adiw    r24, 0x05       ; 5
 146:    90 93 01 02      sts     0x0201, r25
 14a:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 14e:    80 91 00 02      lds     r24, 0x0200
 152:    90 91 01 02      lds     r25, 0x0201
 156:    01 96            adiw    r24, 0x01       ; 1
 158:    90 93 01 02      sts     0x0201, r25
 15c:    80 93 00 02      sts     0x0200, r24
 160:    80 91 00 02      lds     r24, 0x0200
 164:    90 91 01 02      lds     r25, 0x0201
 168:    0e 94 b7 00      call    0x16e   ; 0x16e <delay_ms>
 16c:    f0 cf            rjmp    .-32            ; 0x14e <main+0x12>
```

Load memory locations 0x201, 0x200 to r25, r24

Compiled Result

```
0000013c <main>:
volatile uint16_t a = 10;
int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    90 91 01 02      lds     r25, 0x0201
 144:    05 96            adiw    r24, 0x05       ; 5
 146:    90 93 01 02      sts     0x0201, r25
 14a:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 14e:    80 91 00 02      lds     r24, 0x0200
 152:    90 91 01 02      lds     r25, 0x0201
 156:    01 96            adiw    r24, 0x01       ; 1
 158:    90 93 01 02      sts     0x0201, r25
 15c:    80 93 00 02      sts     0x0200, r24
 160:    80 91 00 02      lds     r24, 0x0200
 164:    90 91 01 02      lds     r25, 0x0201
 168:    0e 94 b7 00      call    0x16e   ; 0x16e <delay_ms>
 16c:    f0 cf            rjmp    .-32            ; 0x14e <main+0x12>
```

Add 5 to r25, r24

Compiled Result

```
0000013c <main>:
volatile uint16_t a = 10;
int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    90 91 01 02      lds     r25, 0x0201
 144:    05 96            adiw    r24, 0x05        ; 5
 146:    90 93 01 02      sts     0x0201, r25
 14a:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 14e:    80 91 00 02      lds     r24, 0x0200
 152:    90 91 01 02      lds     r25, 0x0201
 156:    01 96            adiw    r24, 0x01        ; 1
 158:    90 93 01 02      sts     0x0201, r25
 15c:    80 93 00 02      sts     0x0200, r24
 160:    80 91 00 02      lds     r24, 0x0200
 164:    90 91 01 02      lds     r25, 0x0201
 168:    0e 94 b7 00      call    0x16e    ; 0x16e <delay_ms>
 16c:    f0 cf            rjmp    .-32             ; 0x14e <main+0x12>
```

Store r25, r24 to memory locations 0x201, 0x200

Compiled Result

```
0000013c <main>:
volatile uint16_t a = 10;
int main (void)
{
  a = a+5;
 13c:    80 91 00 02      lds     r24, 0x0200
 140:    90 91 01 02      lds     r25, 0x0201
 144:    05 96            adiw    r24, 0x05       ; 5
 146:    90 93 01 02      sts     0x0201, r25
 14a:    80 93 00 02      sts     0x0200, r24

  while(1) {
    delay_ms(++a);
 14e:    80 91 00 02      lds     r24, 0x0200
 152:    90 91 01 02      lds     r25, 0x0201
 156:    01 96            adiw    r24, 0x01       ; 1
 158:    90 93 01 02      sts     0x0201, r25
 15c:    80 93 00 02      sts     0x0200, r24
 160:    80 91 00 02      lds     r24, 0x0200
 164:    90 91 01 02      lds     r25, 0x0201
 168:    0e 94 b7 00      call    0x16e   ; 0x16e <delay_ms>
 16c:    f0 cf            rjmp    .-32            ; 0x14e <main+0x12>
```

Store r25, r24 to memory locations 0x201, 0x200

We have doubled the number of memory operations!

Take-Home Message I

We want to carefully choose our data types

- Smaller variables are handled more efficiently
- But: we need to make sure that the results of the math that we do with these variables fits in the size that we have chosen
  - Intermediate values must fit, too!

Take-Home Message II

- A line a C code usually translates into a sequence of atomic instructions
- Most instructions are executed in one cycle of the system clock
- For a given instruction, many different components work together to make that instruction happen
  - Program counter, instruction register and decoder, general and special purpose registers, memory, ALU, etc.

Take-Home Message III

- You should know what these different components are and what they do at an abstract level
- You don’t need to know the details of the assembly language or how these details relate to specific lines of C code

Next Time

- Project 8