Administrivia

- Homework 1 is posted & is due in 1 week
- Additional sequential logic readings have been posted on the schedule

Last Time

- D-type Flip-flops
- Sequential logic circuits
  - Shift register
  - Frequency divider

Today

- One more sequential logic example
- Microprocessor components (just enough to be dangerous)

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
- Which component is allowed to write is usually determined by the code that is currently executing

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

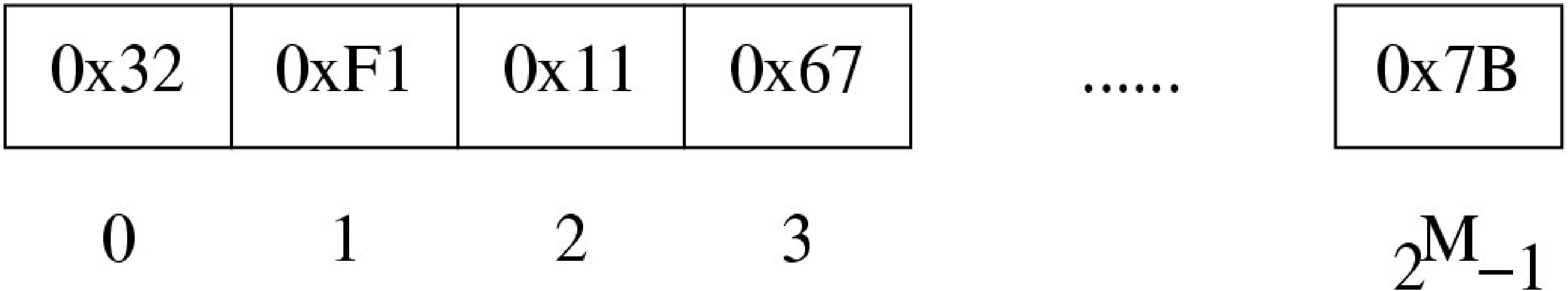
- A data bus typically captures a set of bits simultaneously
- Need one wire for each of these bits
- In the Atmel Mega8: the data bus is 8-bits “wide”
- In your home machines: 32 or 64 bits

Memory

What are the essential components of a memory?

A Memory Abstraction

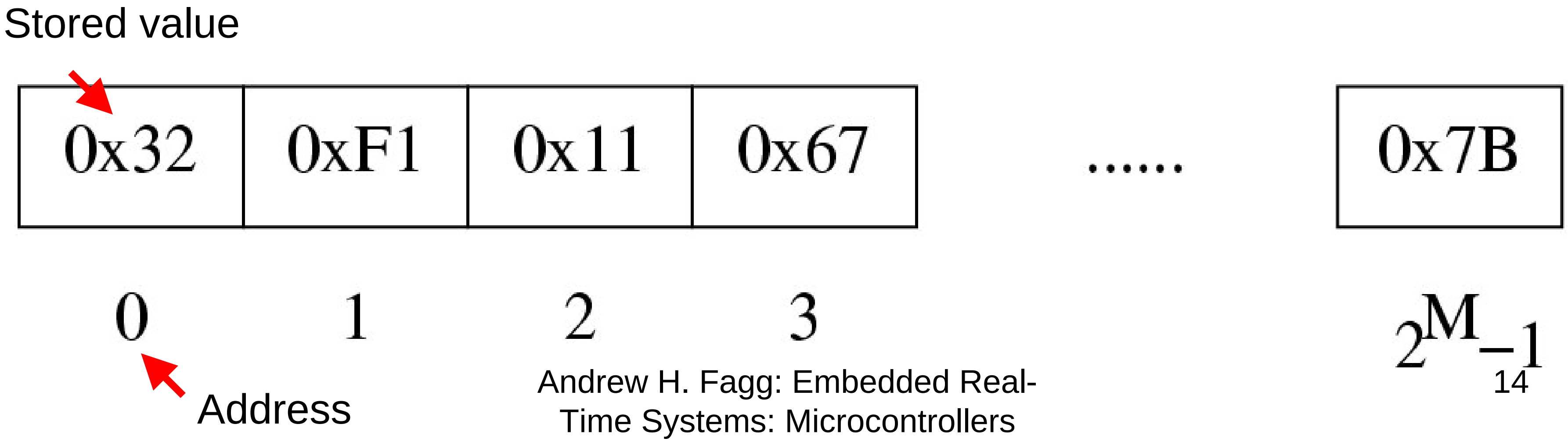
- We think of memory as an array of elements – each with its own address
- Each element contains a value
  - It is most common for the values to by 8-bits wide (so a byte)



0x32	0xF1	0x11	0x67	……	0x7B
0	1	2	3		2^M-1

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)



Stored value

0x32	0xF1	0x11	0x67	……	0x7B
0	1	2	3		$2^M - 1$

Address

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

Example: A Read/Write Memory Module

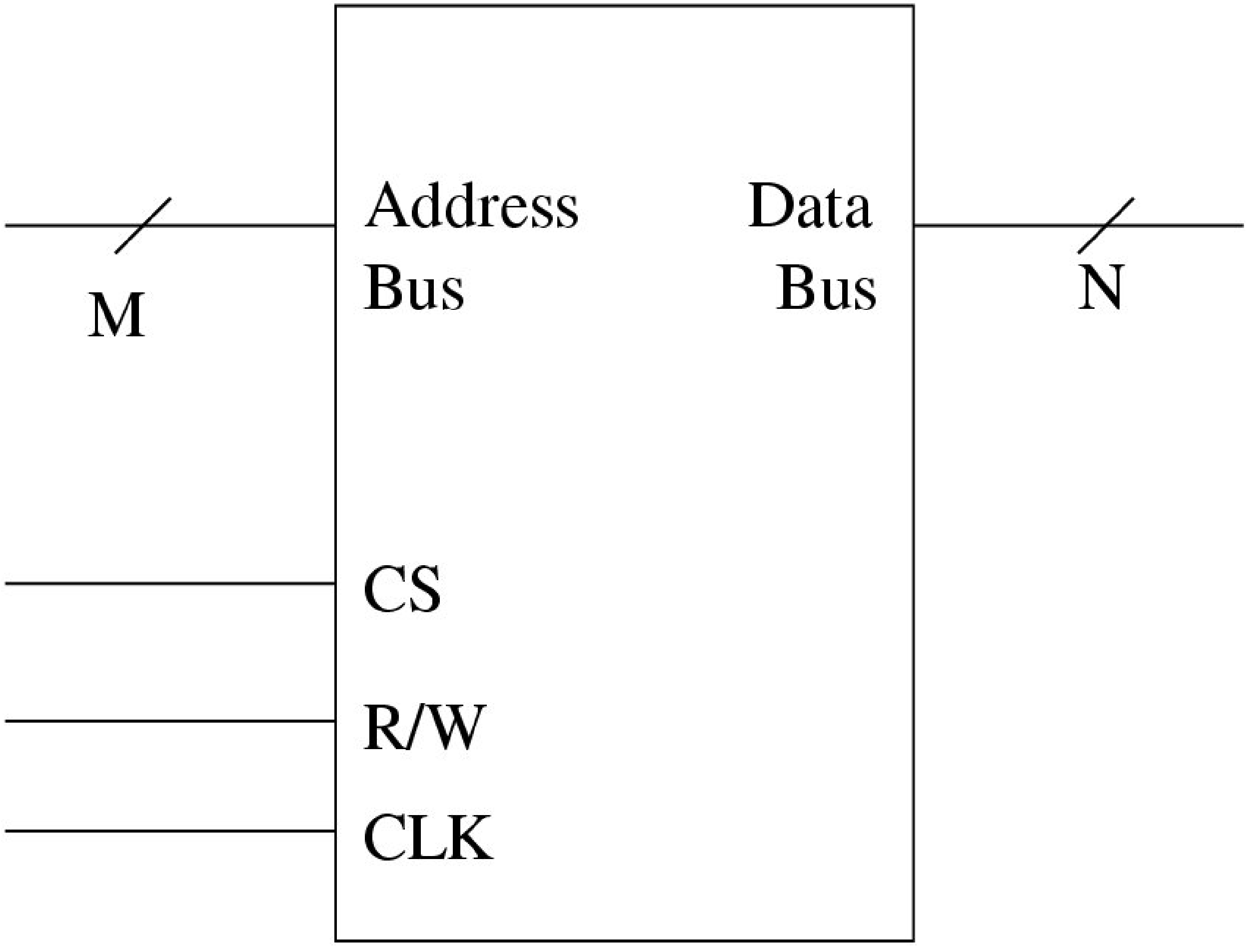
Inputs:

- 2 Address bits: A0 and A1
- 1 “chip select” (CS) bit
- 1 read/write bit (1 = read; 0 = write)
- 1 clock signal (CLK)

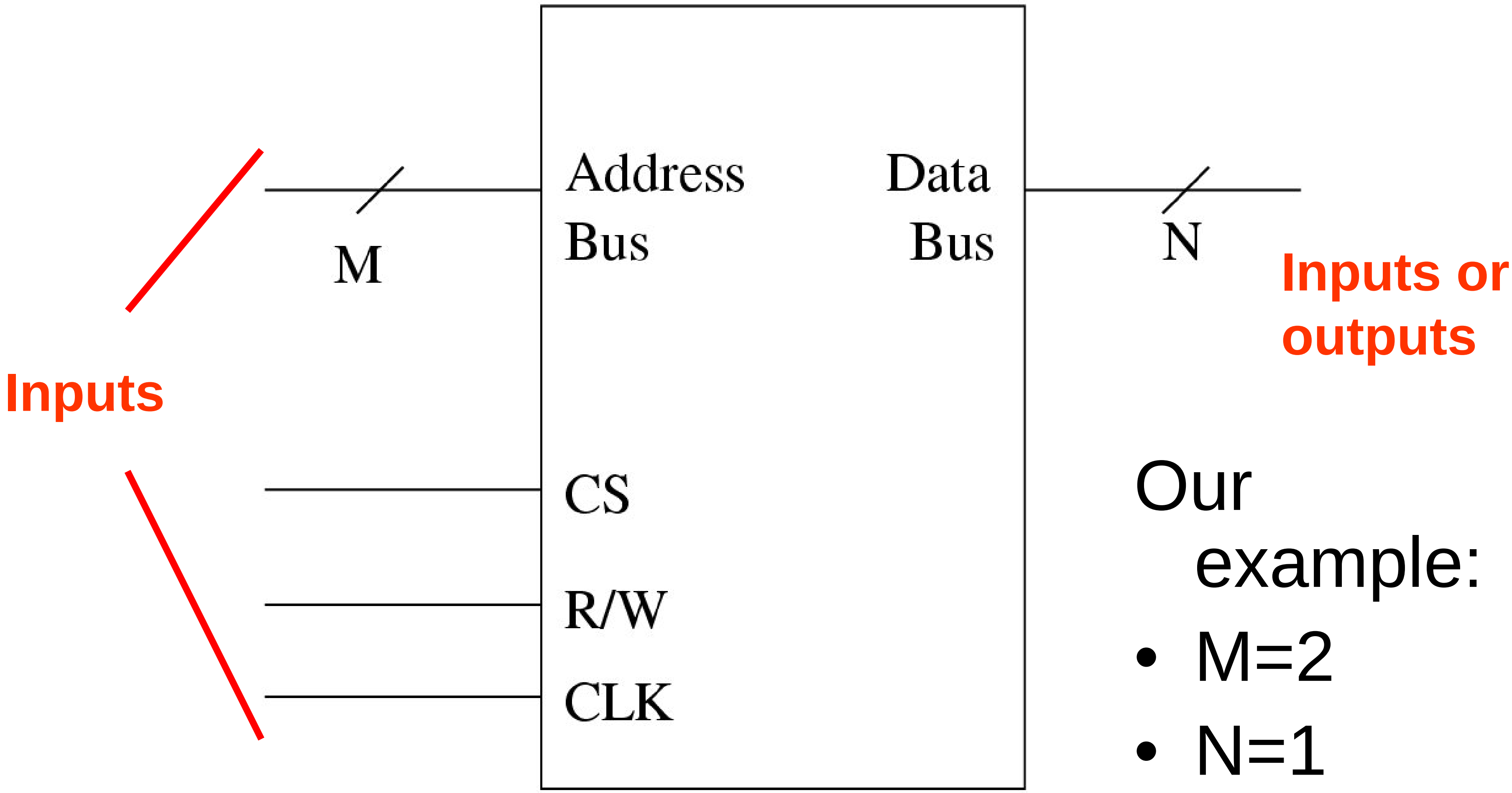
Input or Output:

- Data bit (connected to the “data bus”)

A Read/Write Memory Module



A Read/Write Memory Module



Our example:

- M=2
- N=1

Implementing A Read/Write Memory Module

With 2 address bits, how many memory elements can we address?

How could we implement each memory element?

Implementing A Read/Write Memory Module

With 2 address bits, how many memory elements can we address?

- 4 1-bit elements

How could we implement each memory element?

- With a D flip-flop

Memory Module Specification

“chip select” signal:

- Allows us to have multiple devices (e.g., memory modules) that can write to the bus
- But: only one device will ever be selected at one time

Memory Module Specification

When chip select is low:

- No memory elements change state
- The memory does not drive the data bus

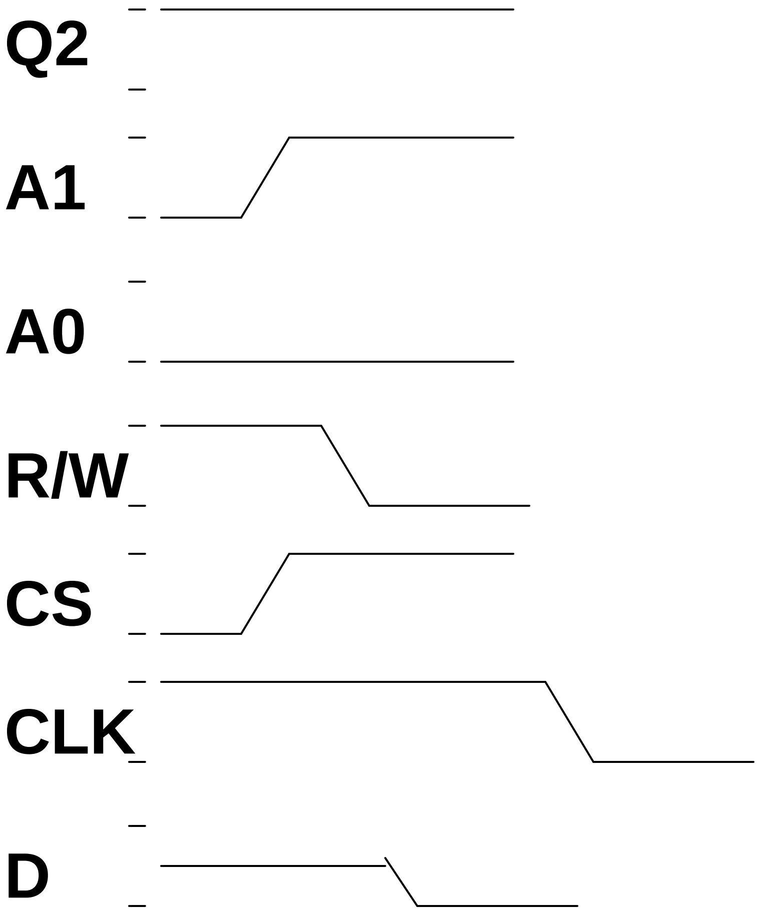
Memory Module Specification

When chip select is high:

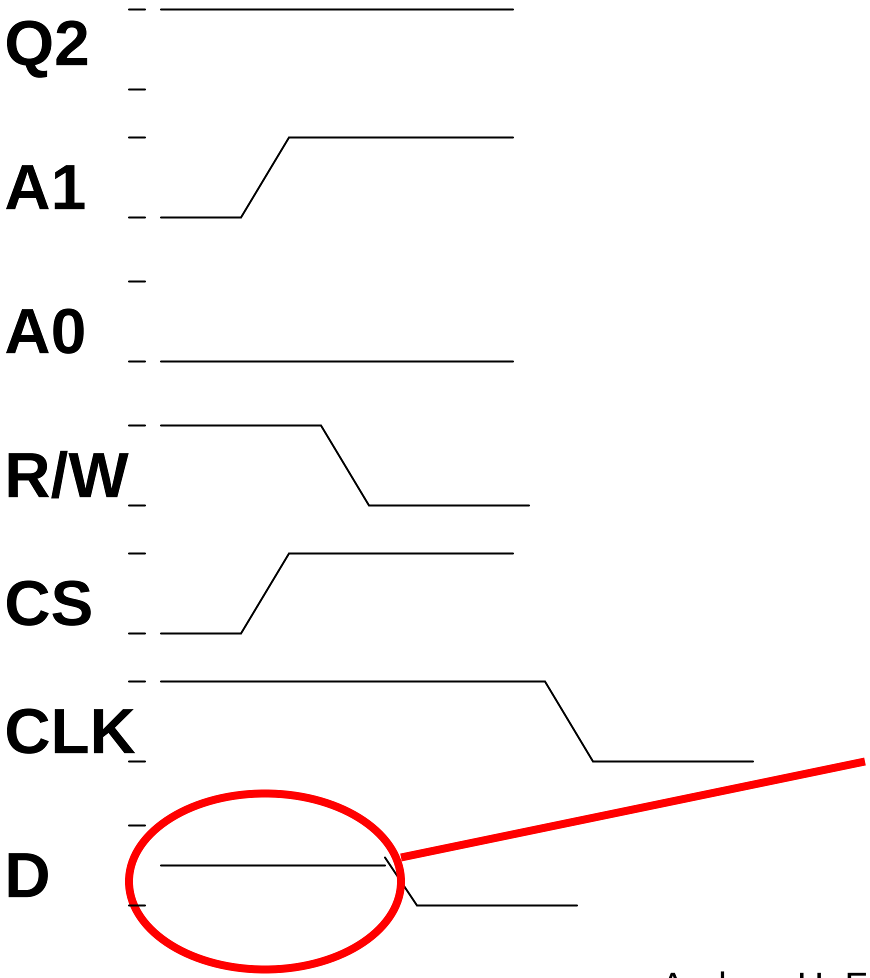
- If R/W is high:
  - The memory drives the data bus with the value that is stored in the element specified by A1, A0

- If R/W is low:
  - Store the value that is on the data bus in the memory element specified by A1, A0

Memory Timing Diagram

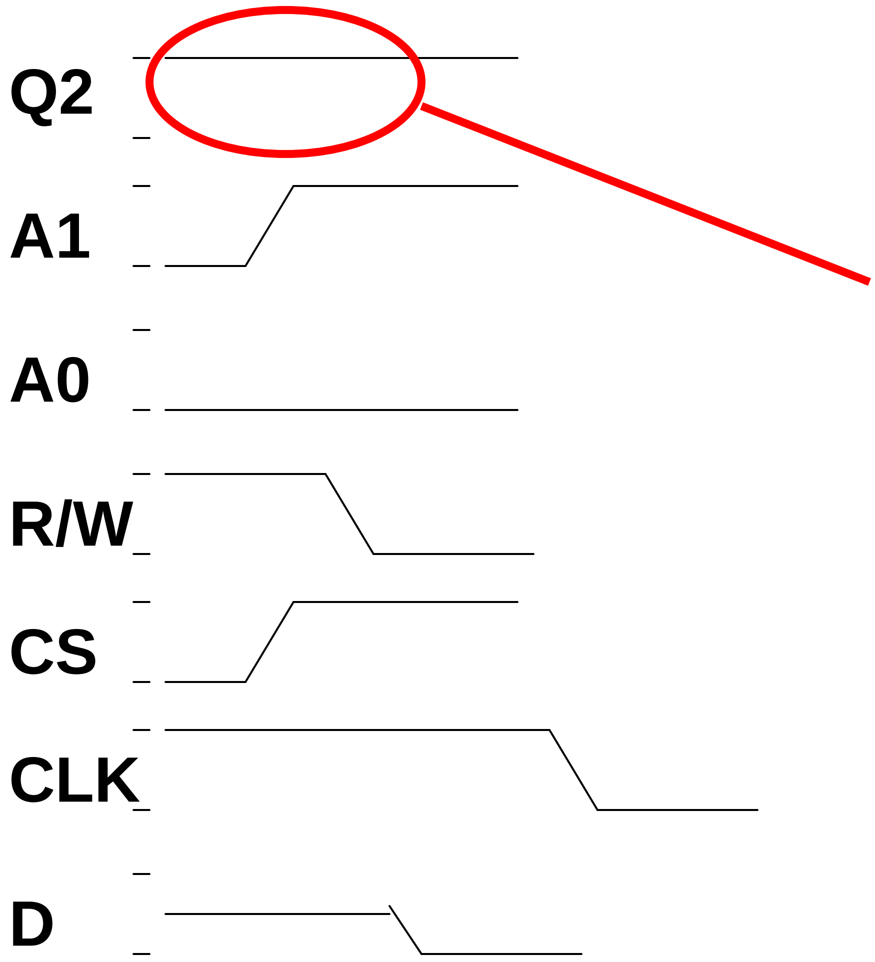


Memory Timing Diagram



Data bus not driven

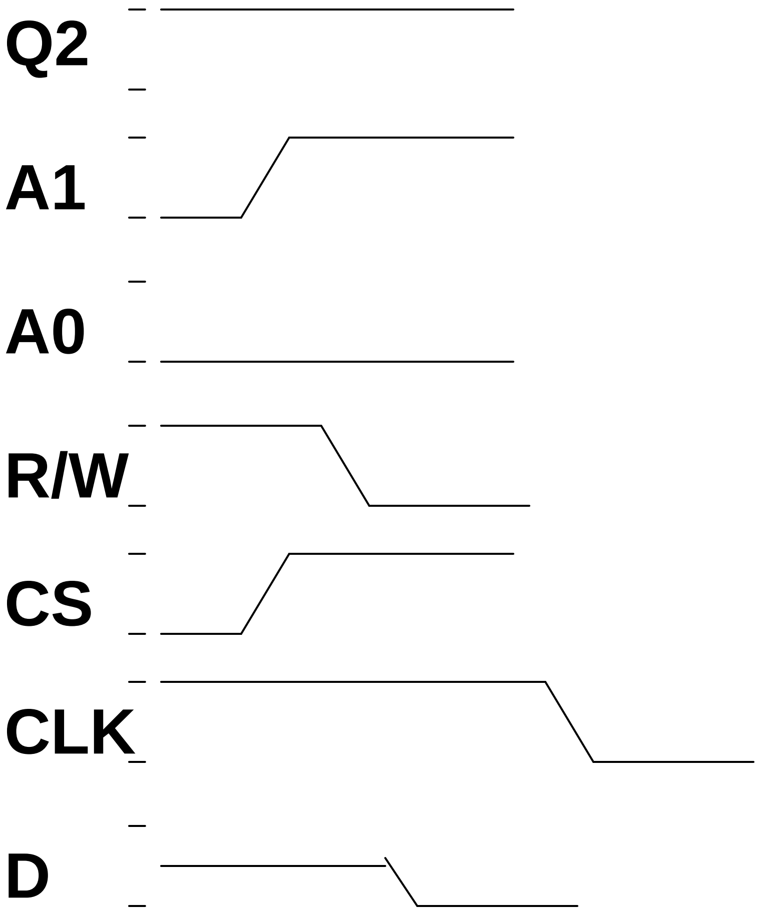
Memory Timing Diagram



Memory element 2 is initially in a high state

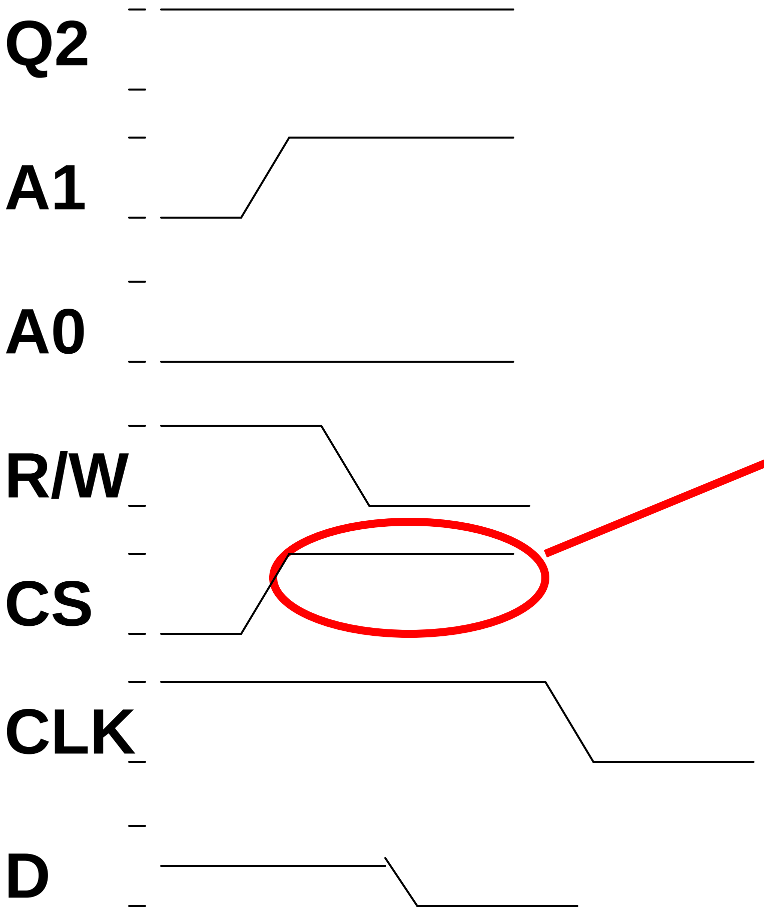
Note: memory elements 0, 1, & 3 not shown

Memory Timing Diagram



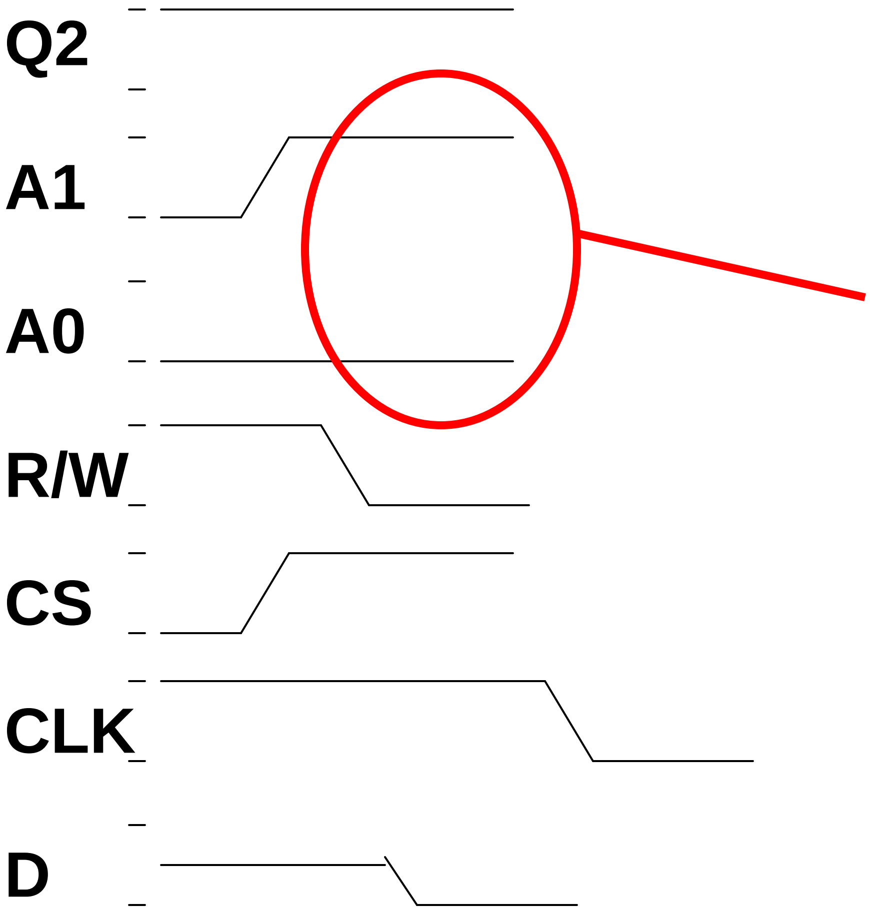
What happens next?

Memory Timing Diagram



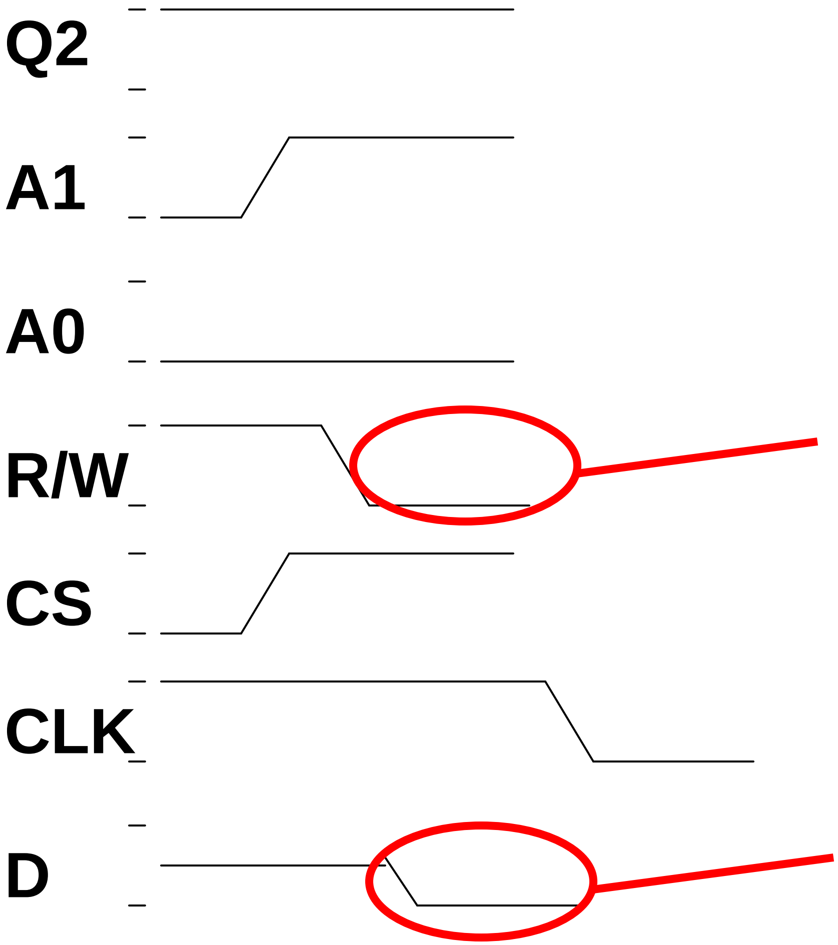
Chip is selected

Memory Timing Diagram



Address memory element 2

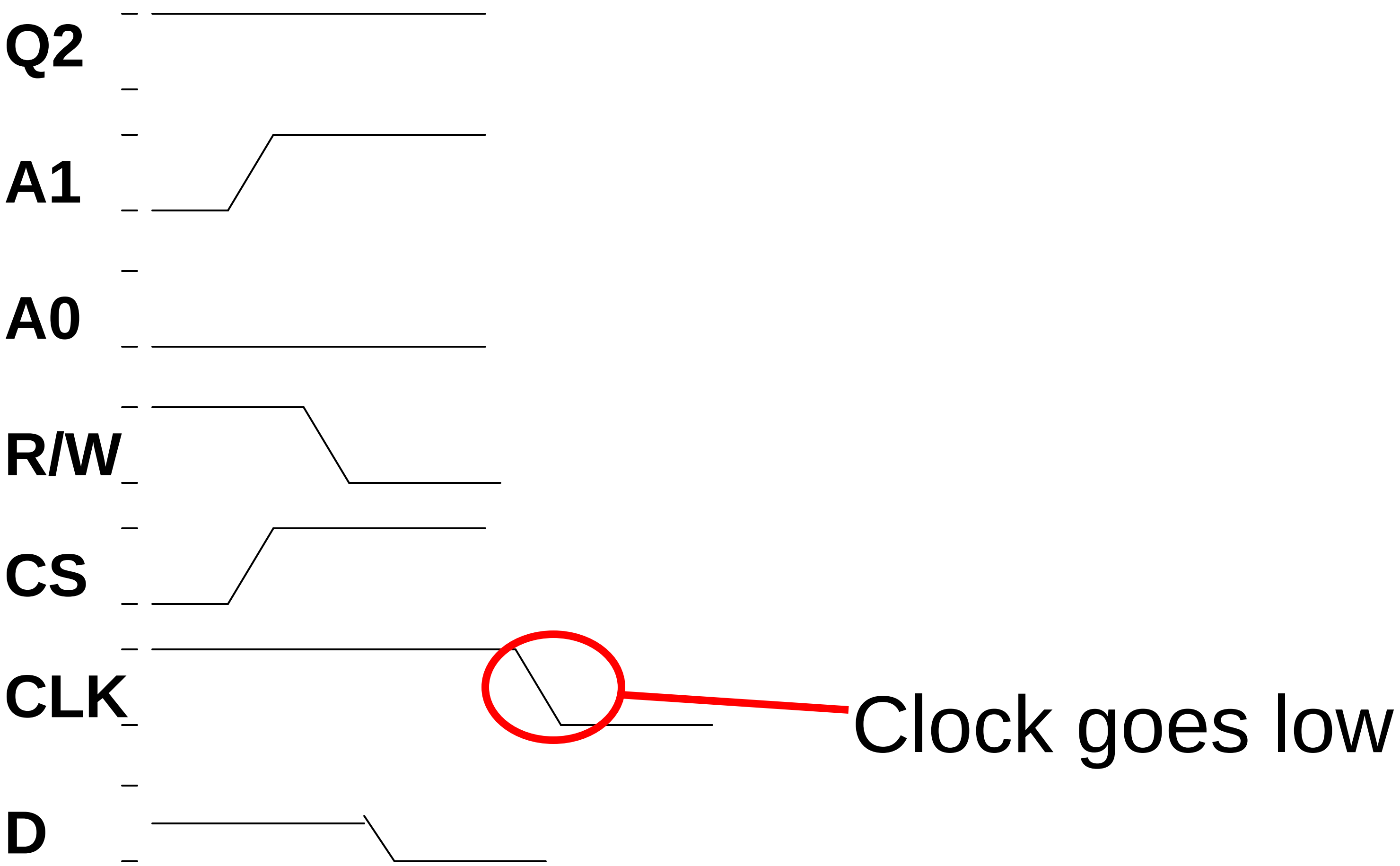
Memory Timing Diagram



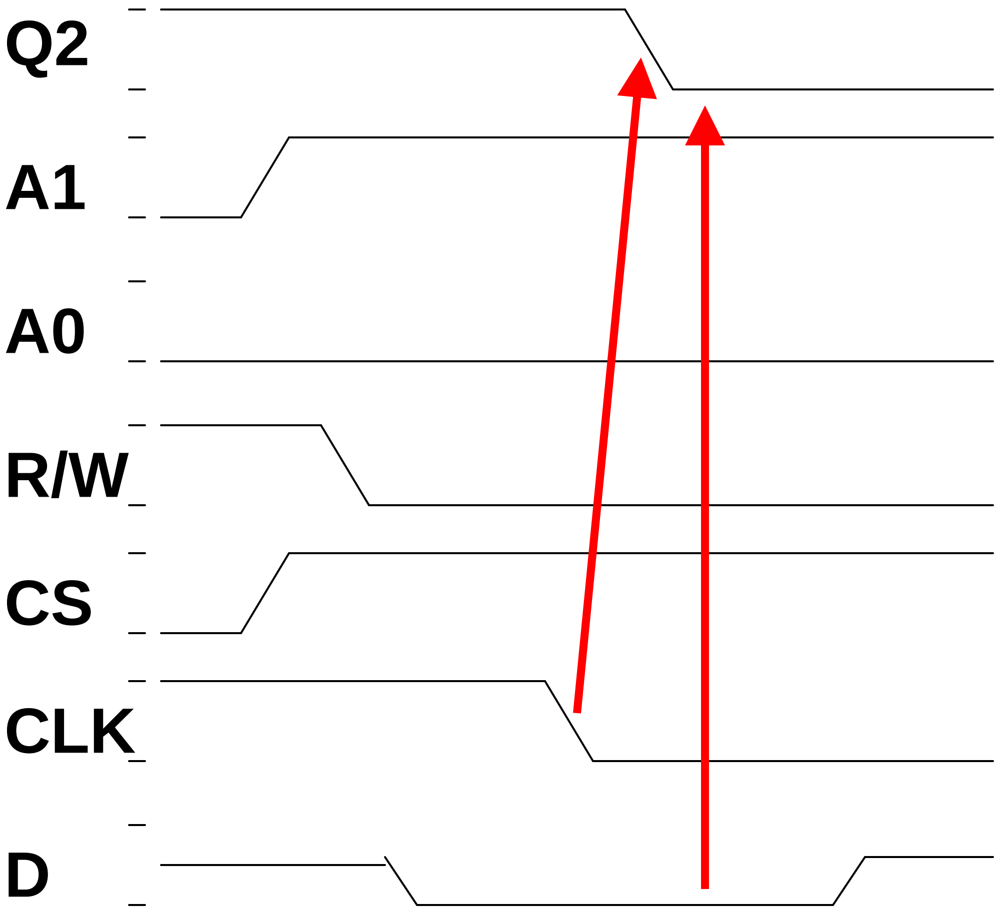
Specify a write operation

Data bus is driven low
(by another device)

Memory Timing Diagram

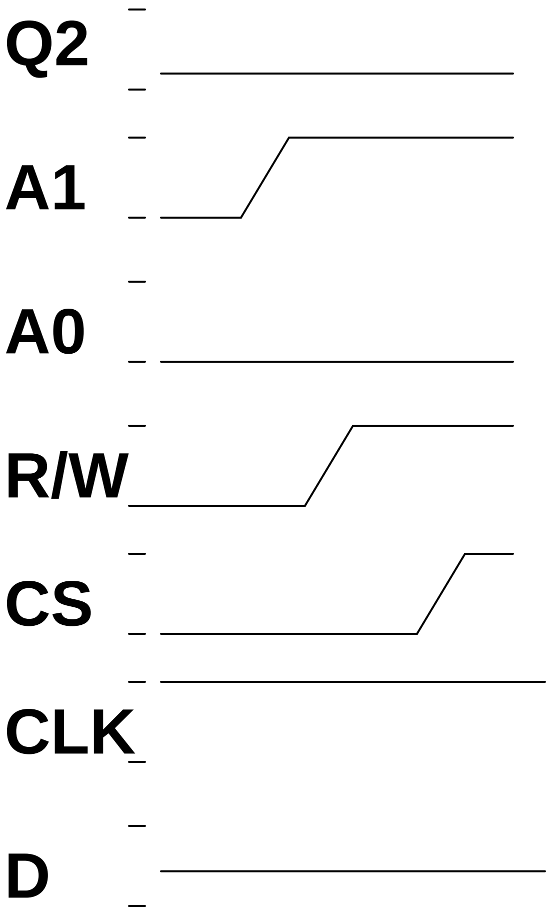


Memory Timing Diagram

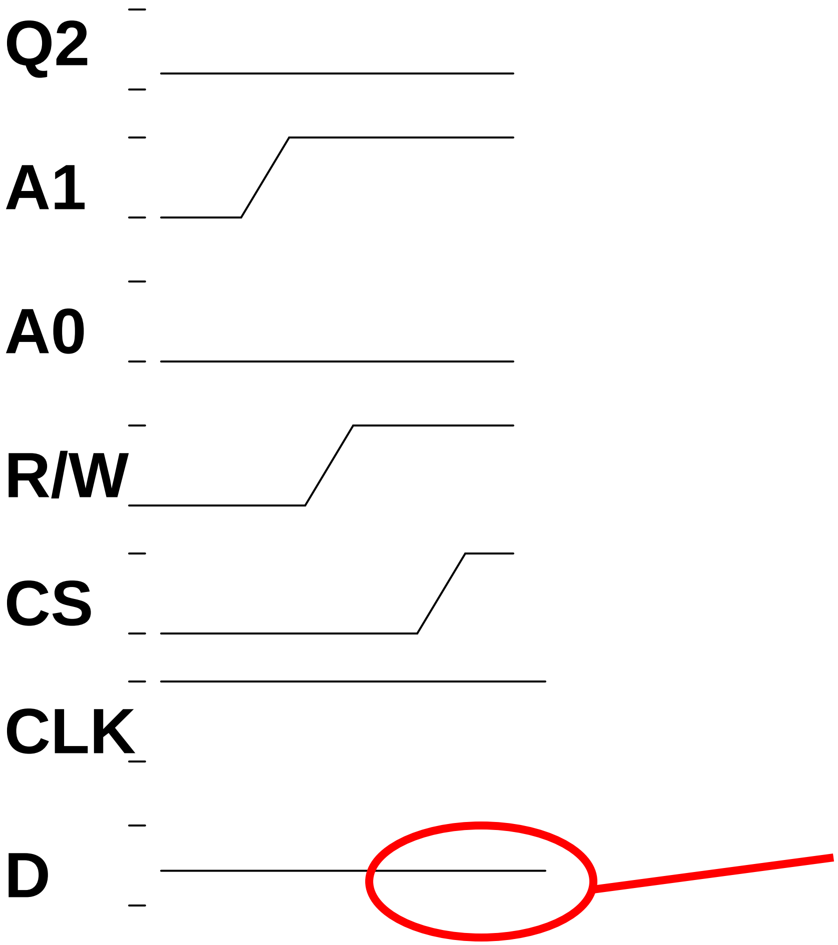


Memory element 2 changes state to low

Memory Timing Diagram II

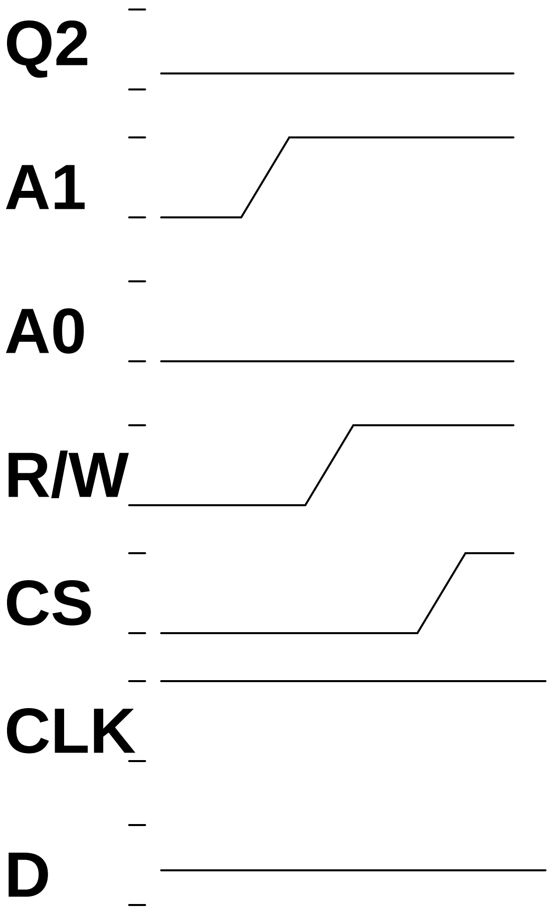


Memory Timing Diagram II



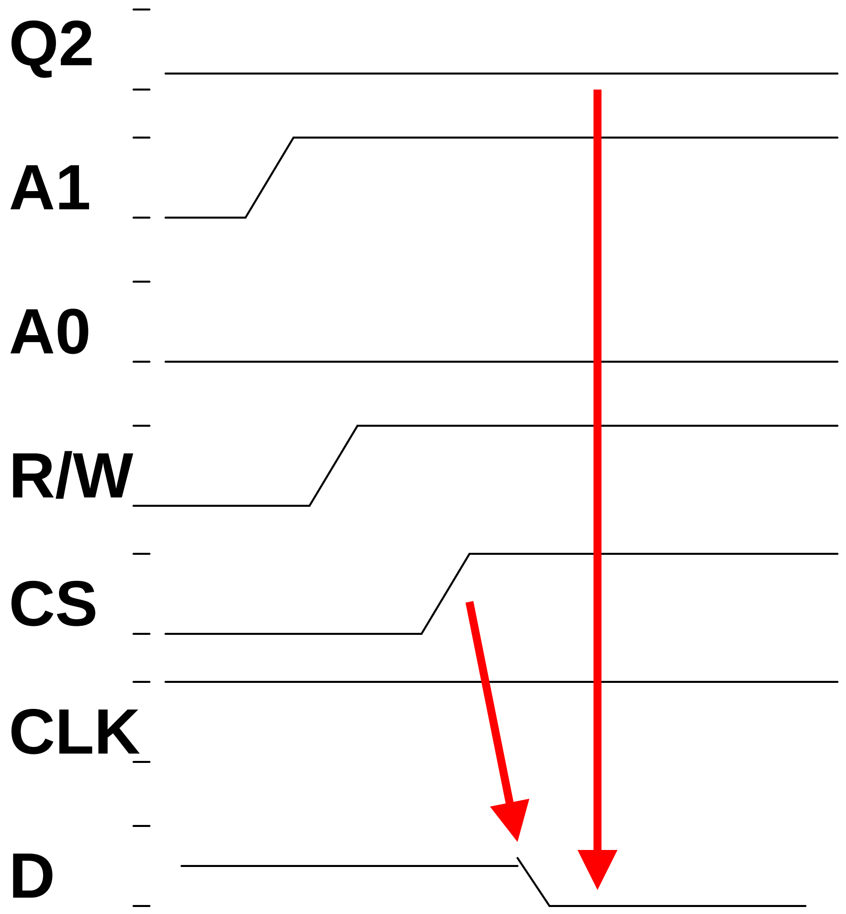
Data bus is not driven

Memory Timing Diagram II



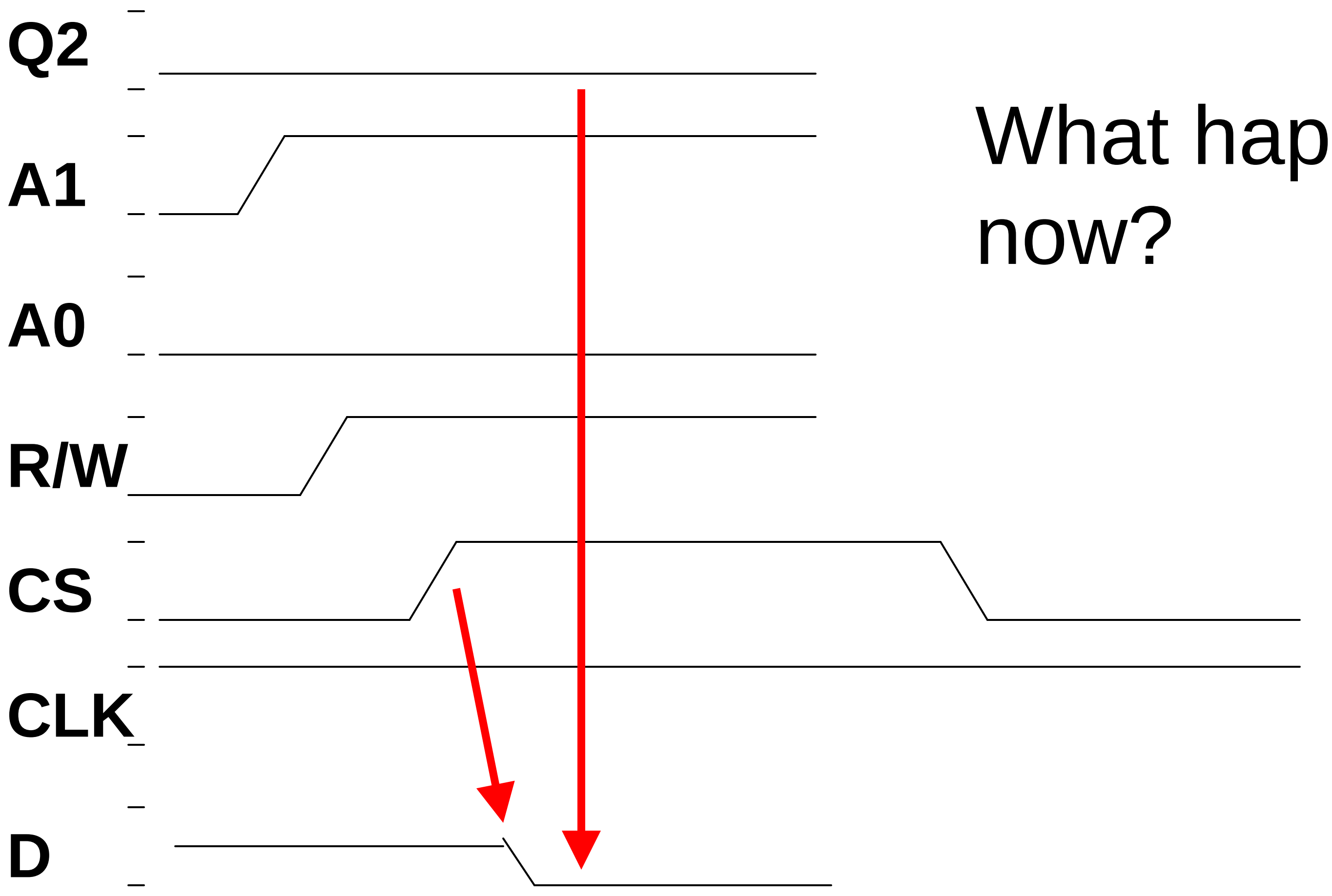
What happens next?

Memory Timing Diagram II



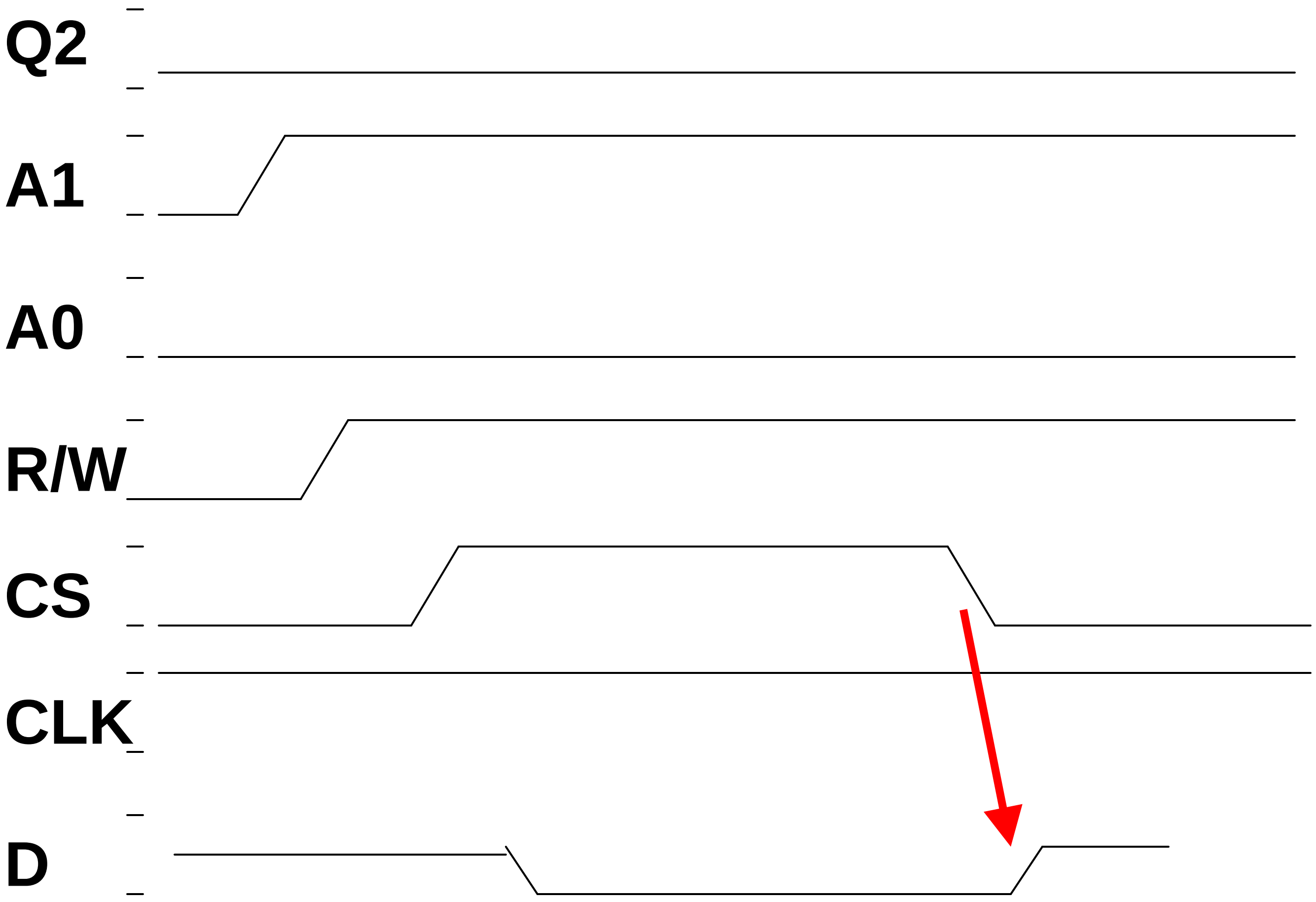
On chip select – drive data bus from Q2

Memory Timing Diagram II



What happens now?

Memory Timing Diagram II



Data bus returns to a non-driven state

Memory Summary

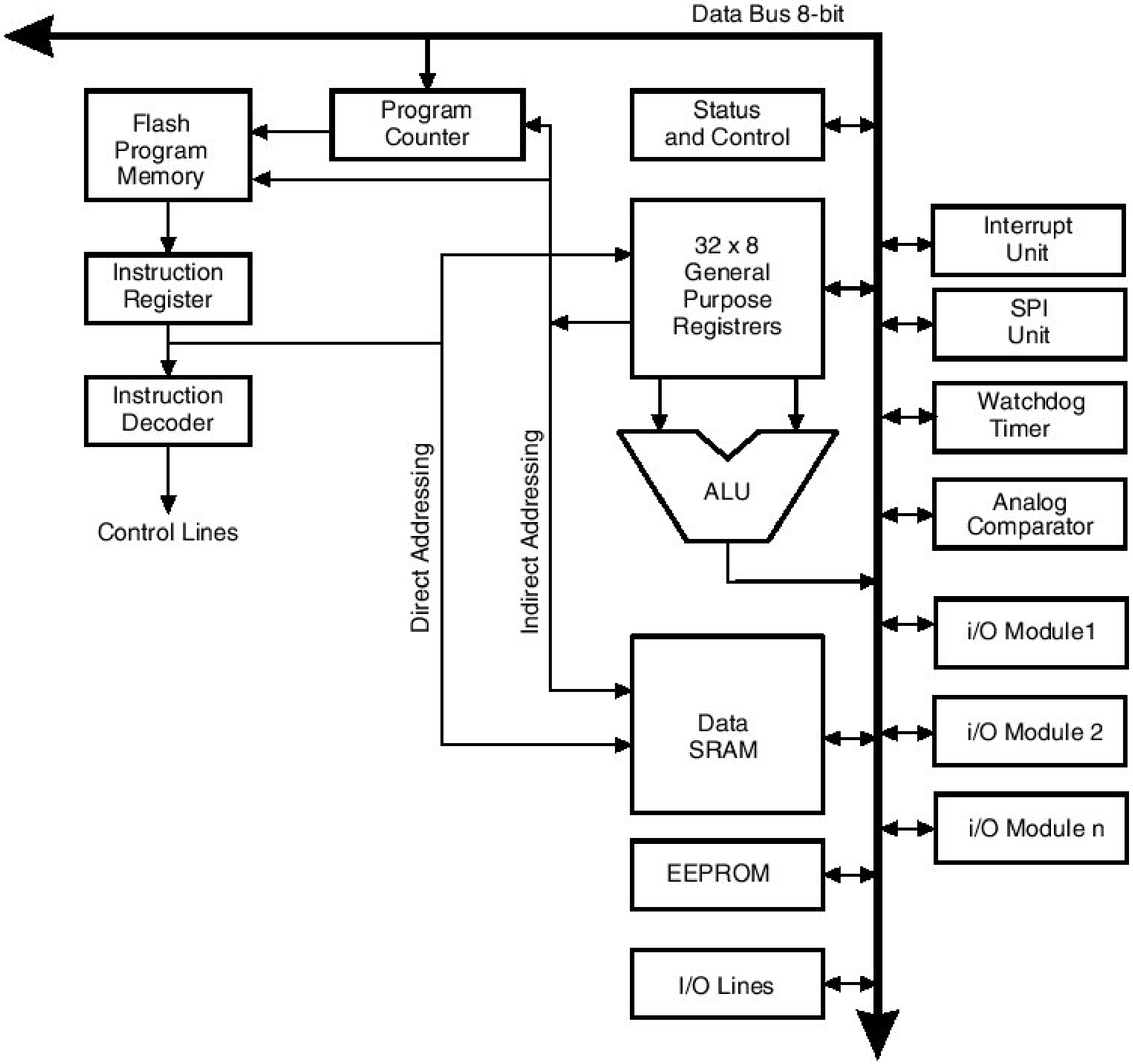
- Many independent storage elements
- Elements are typically organized into 8-bit bytes
- Each byte has its own address
- The value of each byte can be read
- In RAM: the value can also be changed

One More Bus Note

Many devices on the bus. However, at a given time:

- There is exactly one device that is the “writer”
- There is exactly one that is the “reader”

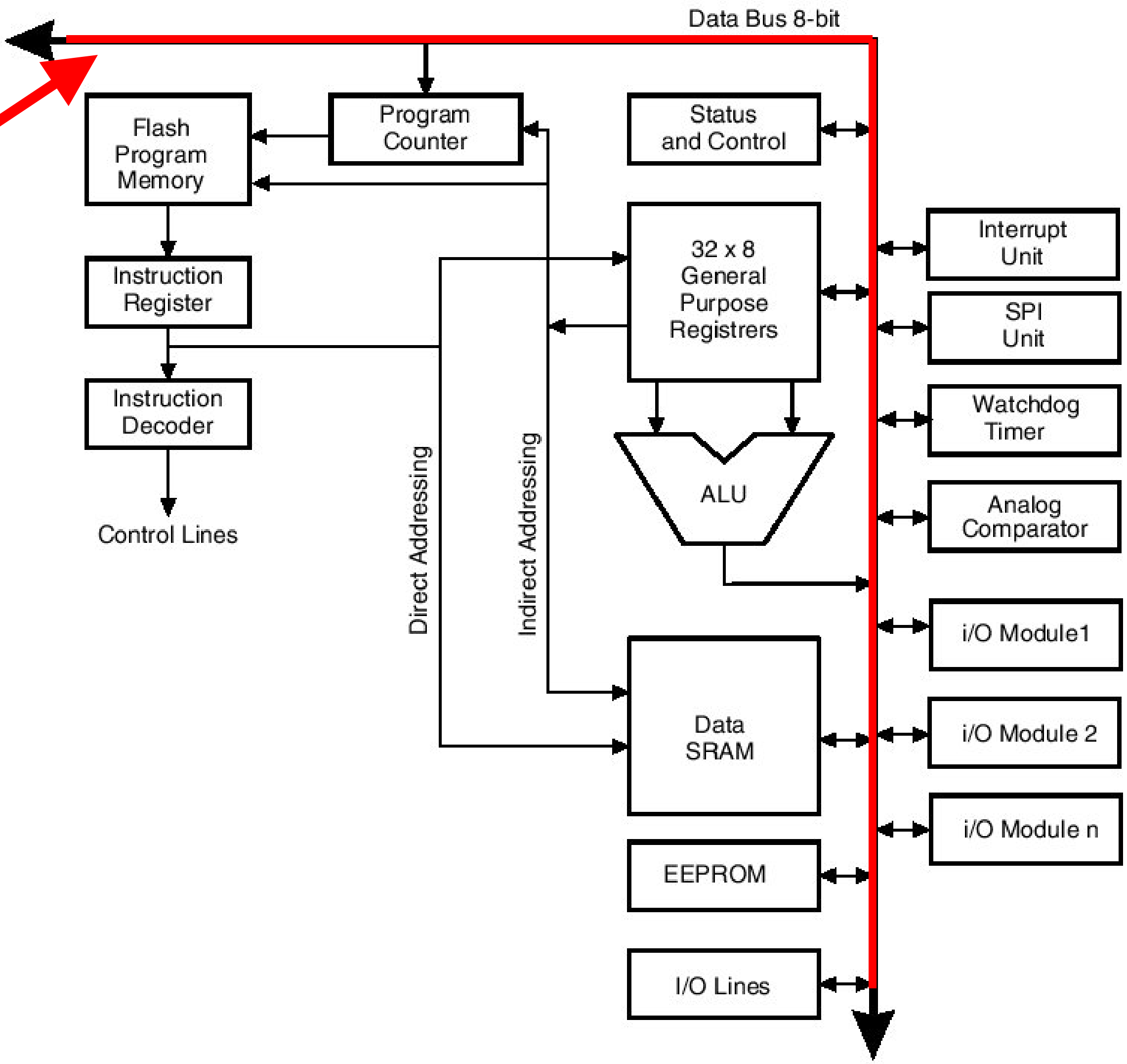
Atmel Mega8 Architecture



Atmel Mega8

8-bit data bus

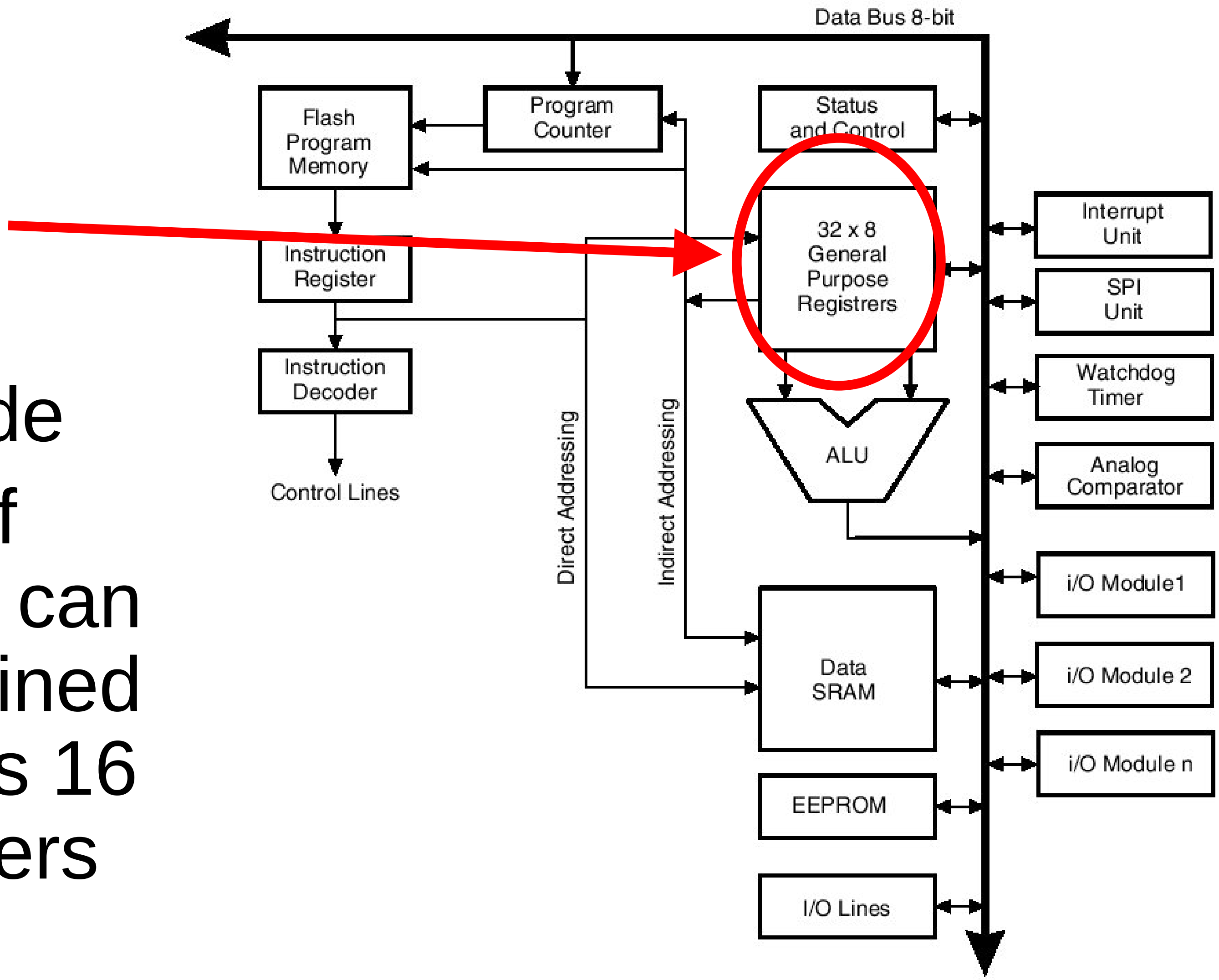
- Primary mechanism for data exchange



Atmel Mega8

32 general purpose registers

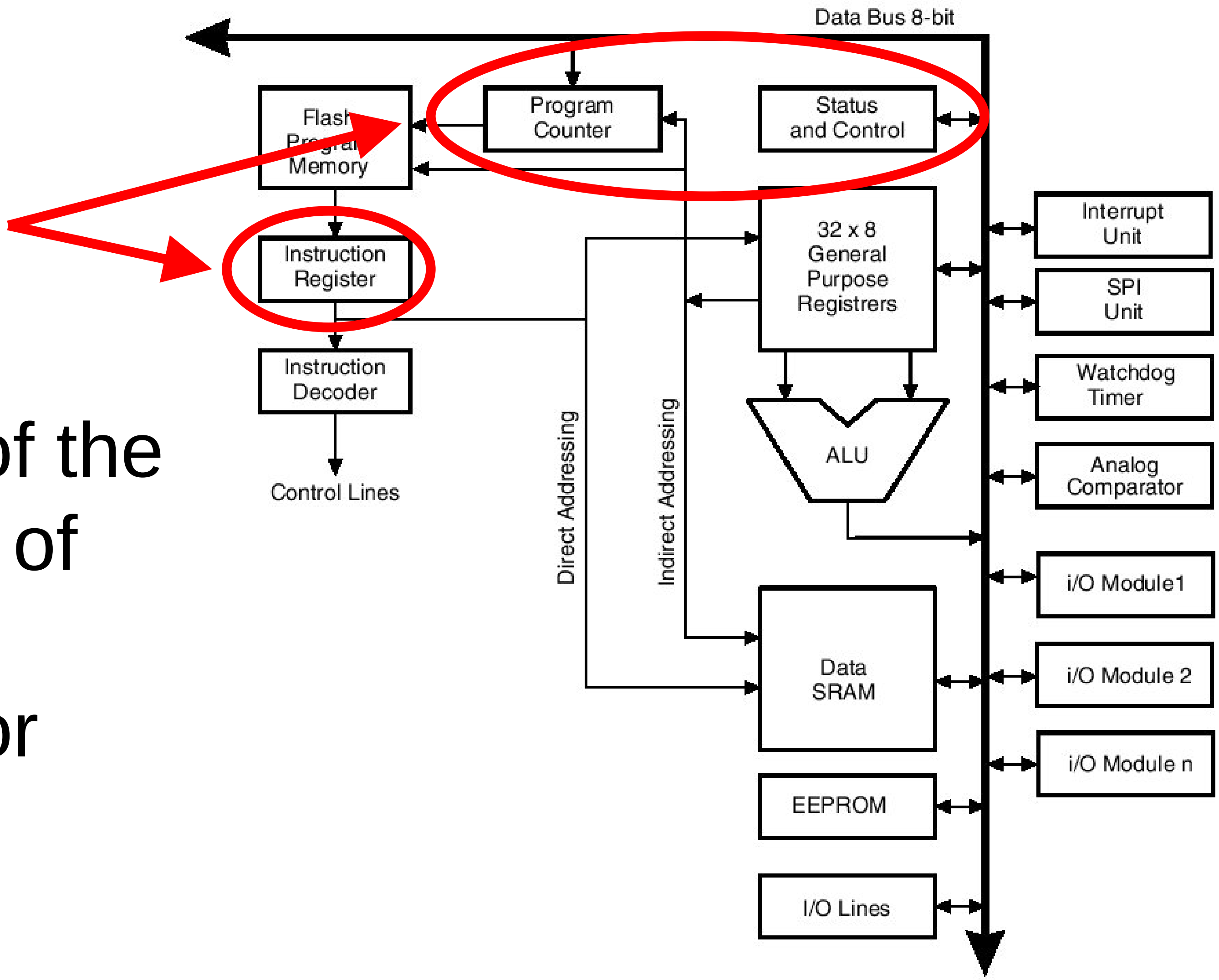
- 8 bits wide
- 3 pairs of registers can be combined to give us 16 bit registers



Atmel Mega8

Special purpose registers

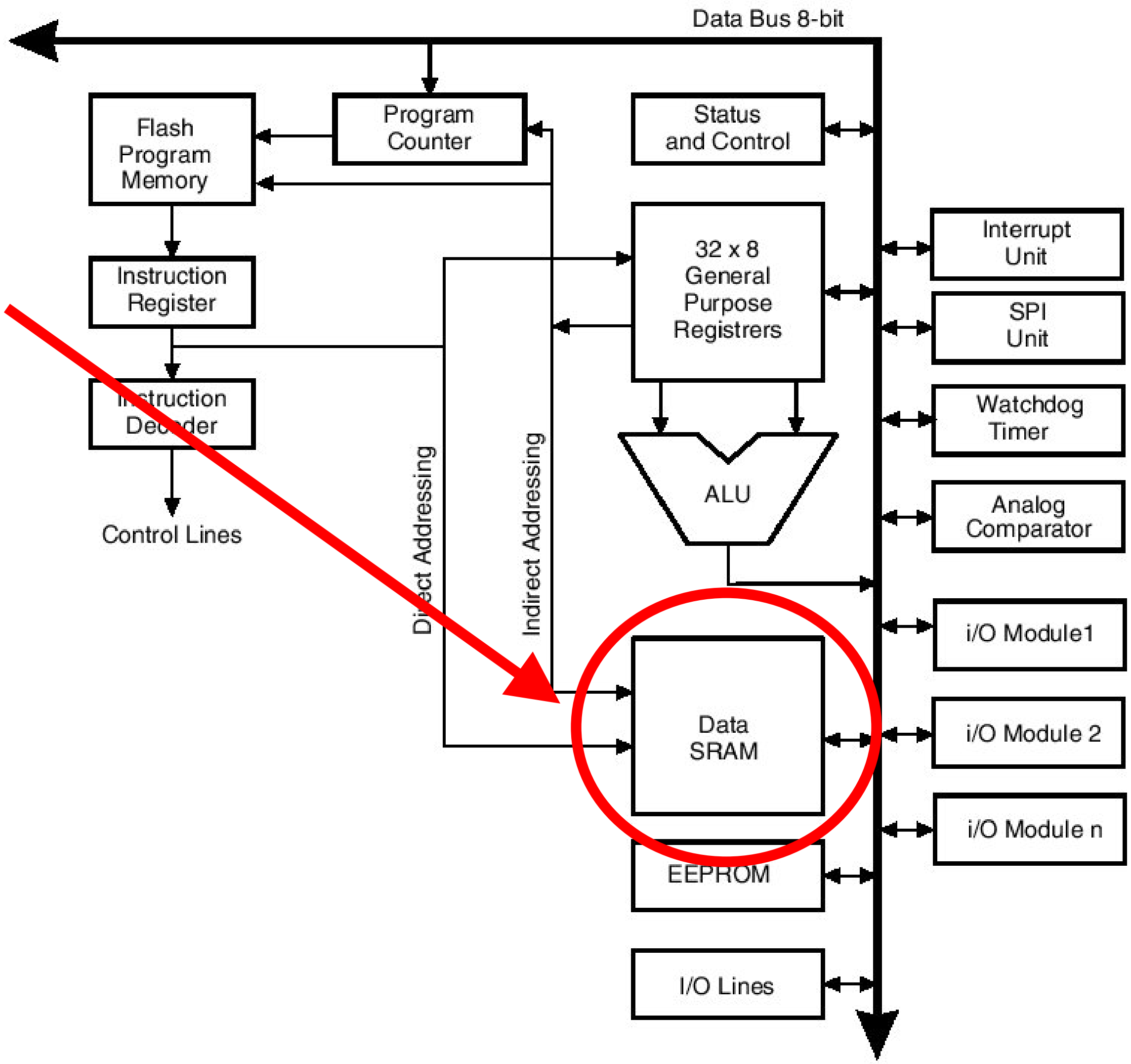
- Control of the internals of the processor



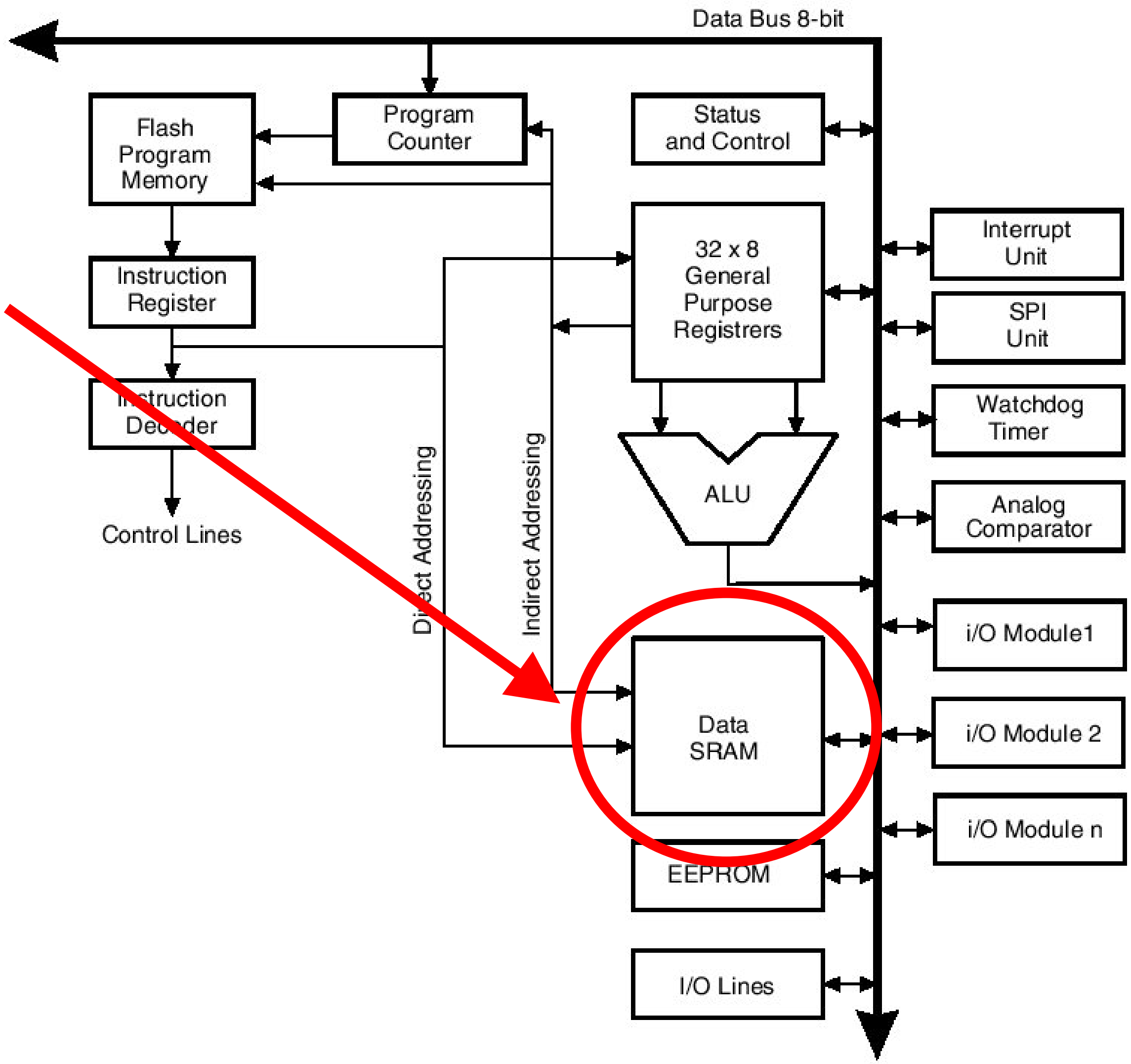
Atmel Mega8

Random Access Memory (RAM)

- 1 KByte in size



Atmel Mega8



Random Access Memory (RAM)

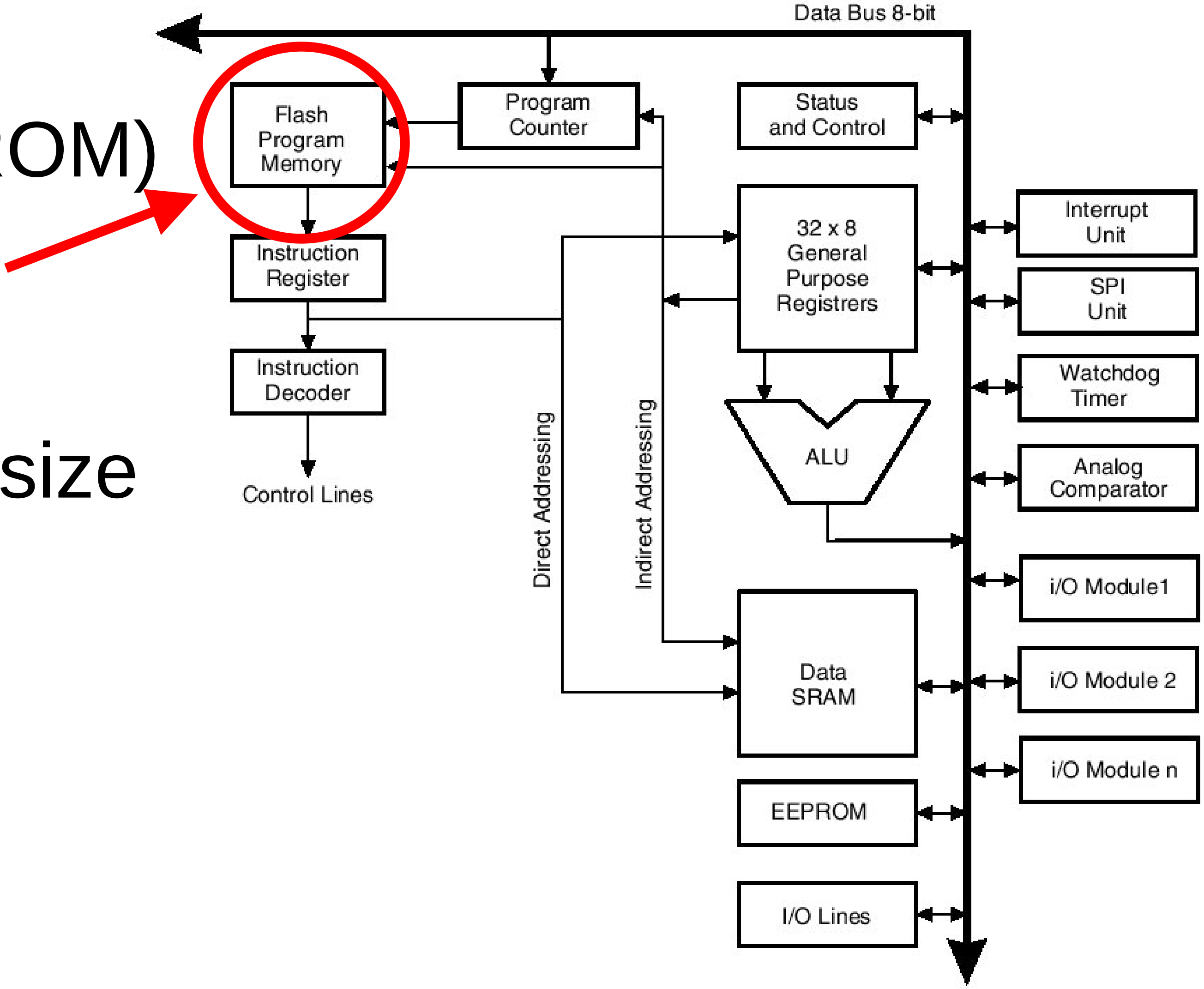
- 1 KByte in size

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

Atmel Mega8

Flash (EEPROM)

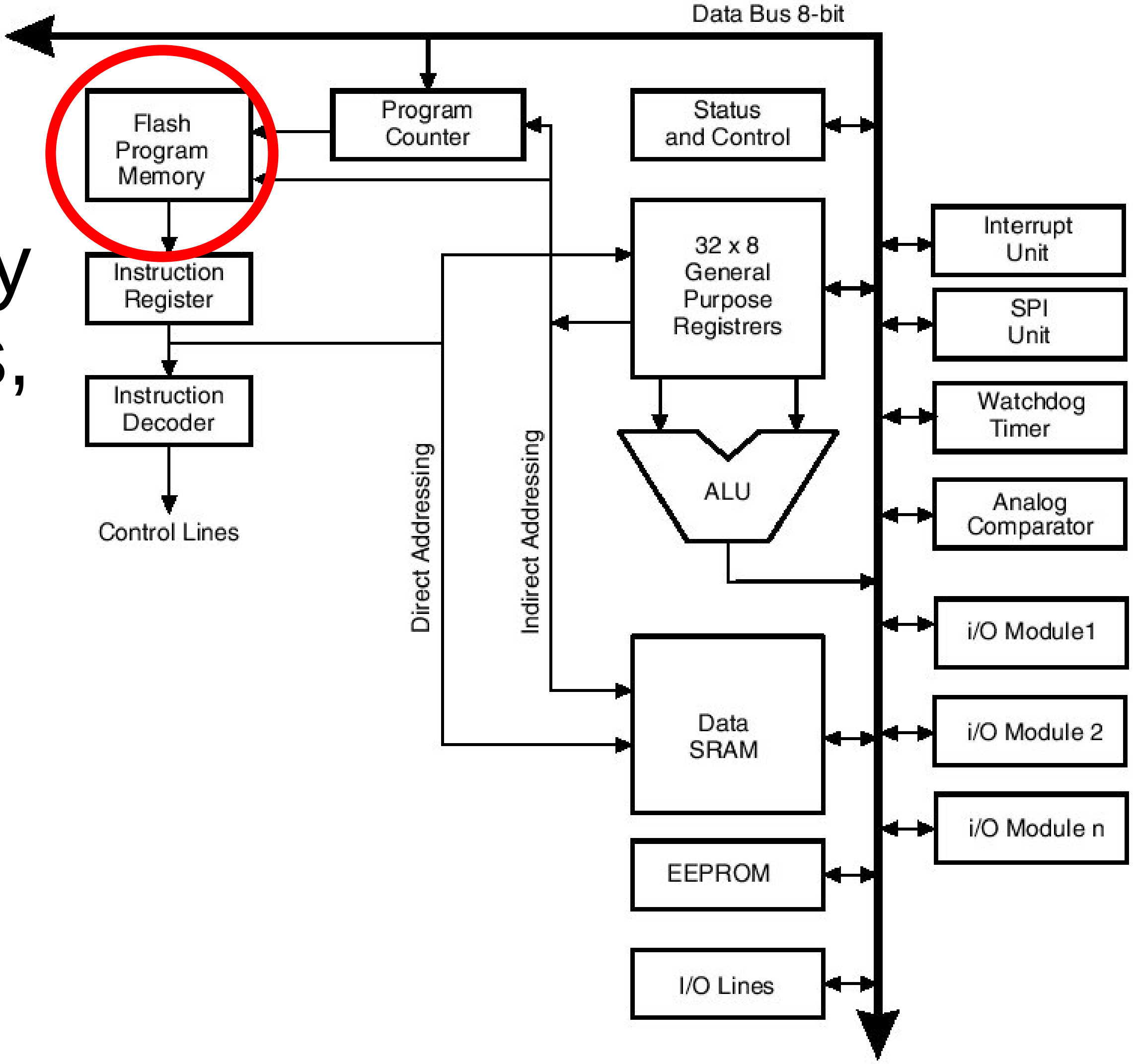
- Program storage
- 8 KByte in size



Atmel Mega8

Flash (EEPROM)

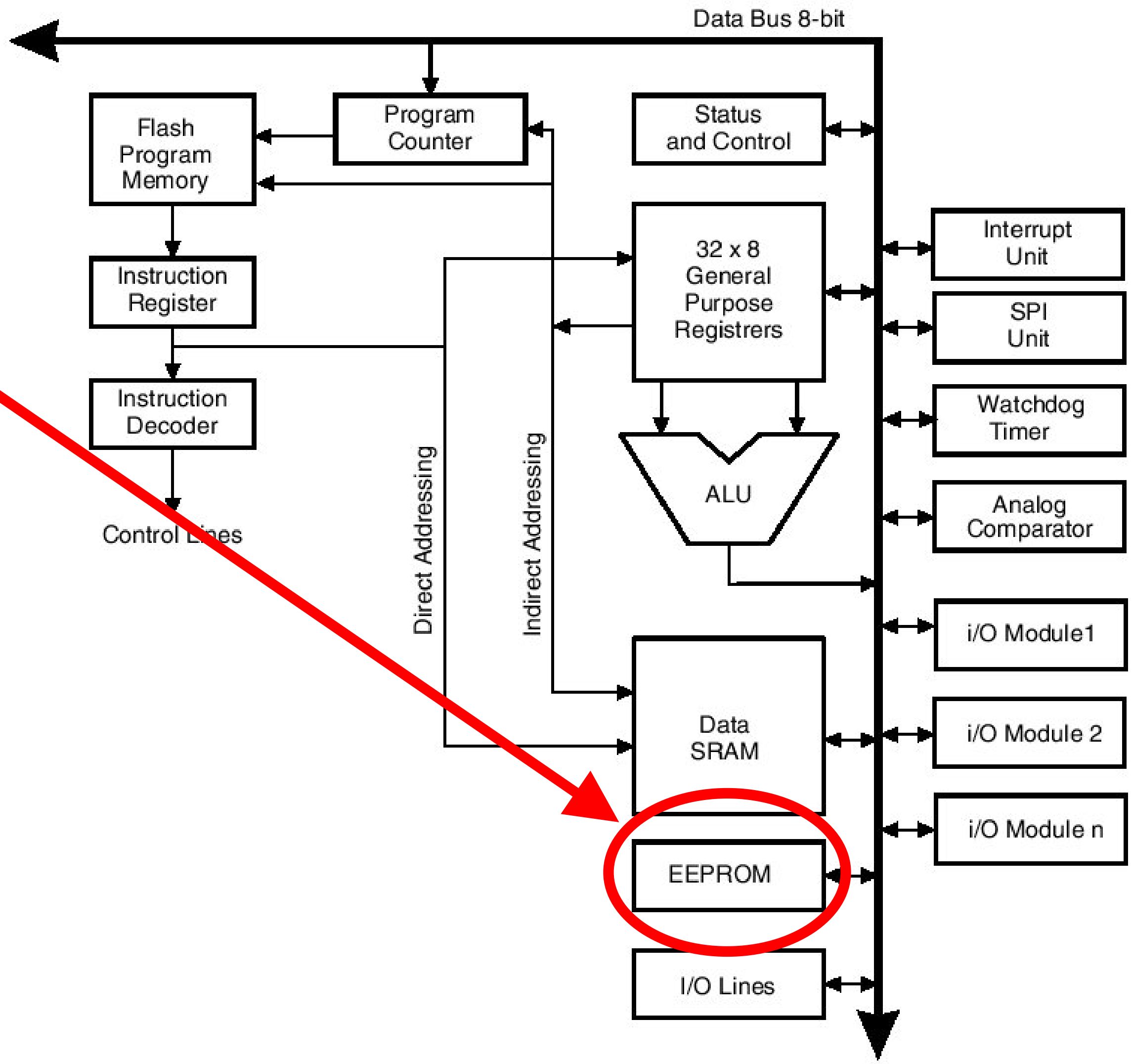
- In this and many microcontrollers, program and data storage is separate
- Not the case in our general purpose computers



Atmel Mega8

EEPROM

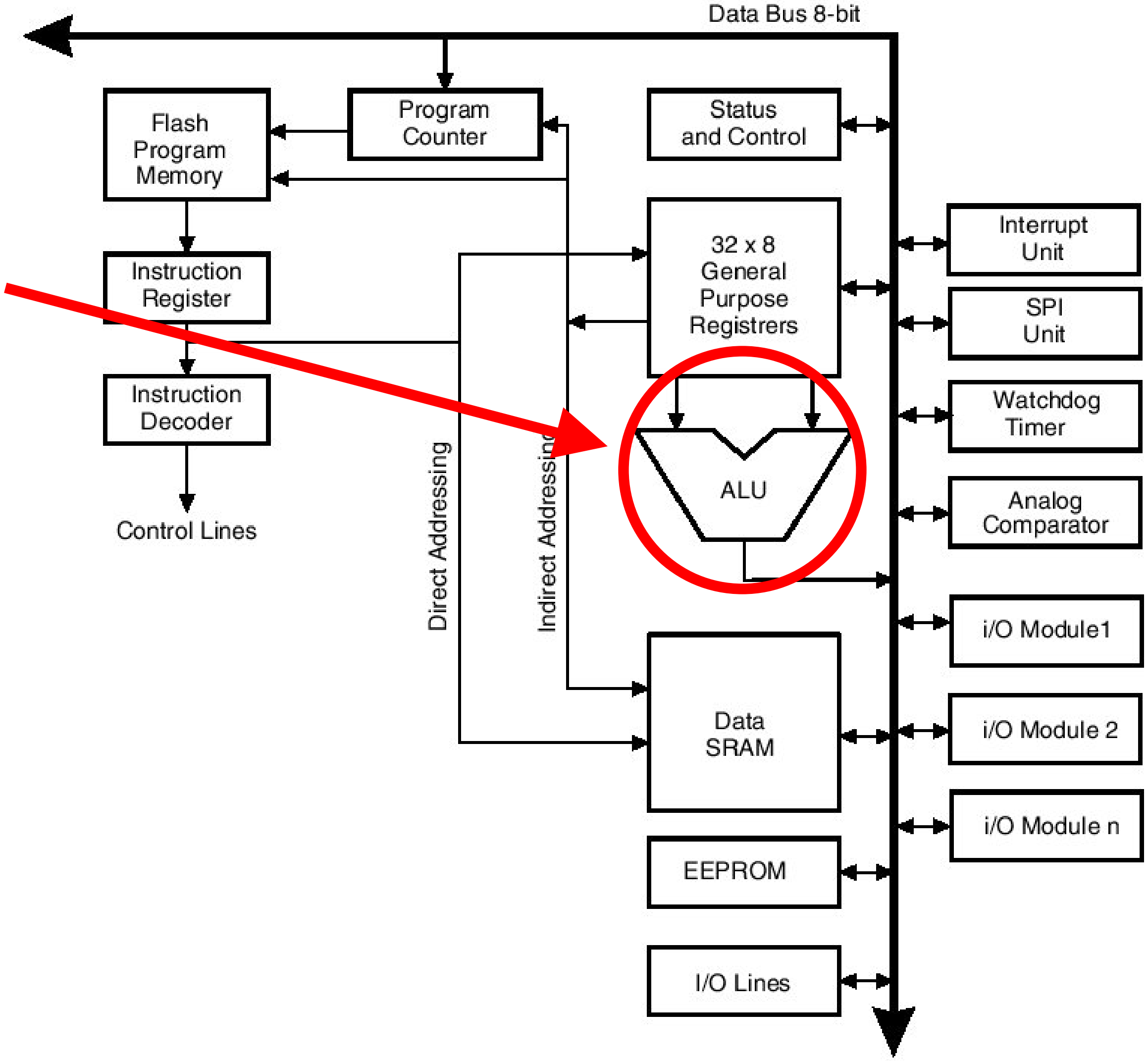
- Permanent data storage



Atmel Mega8

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

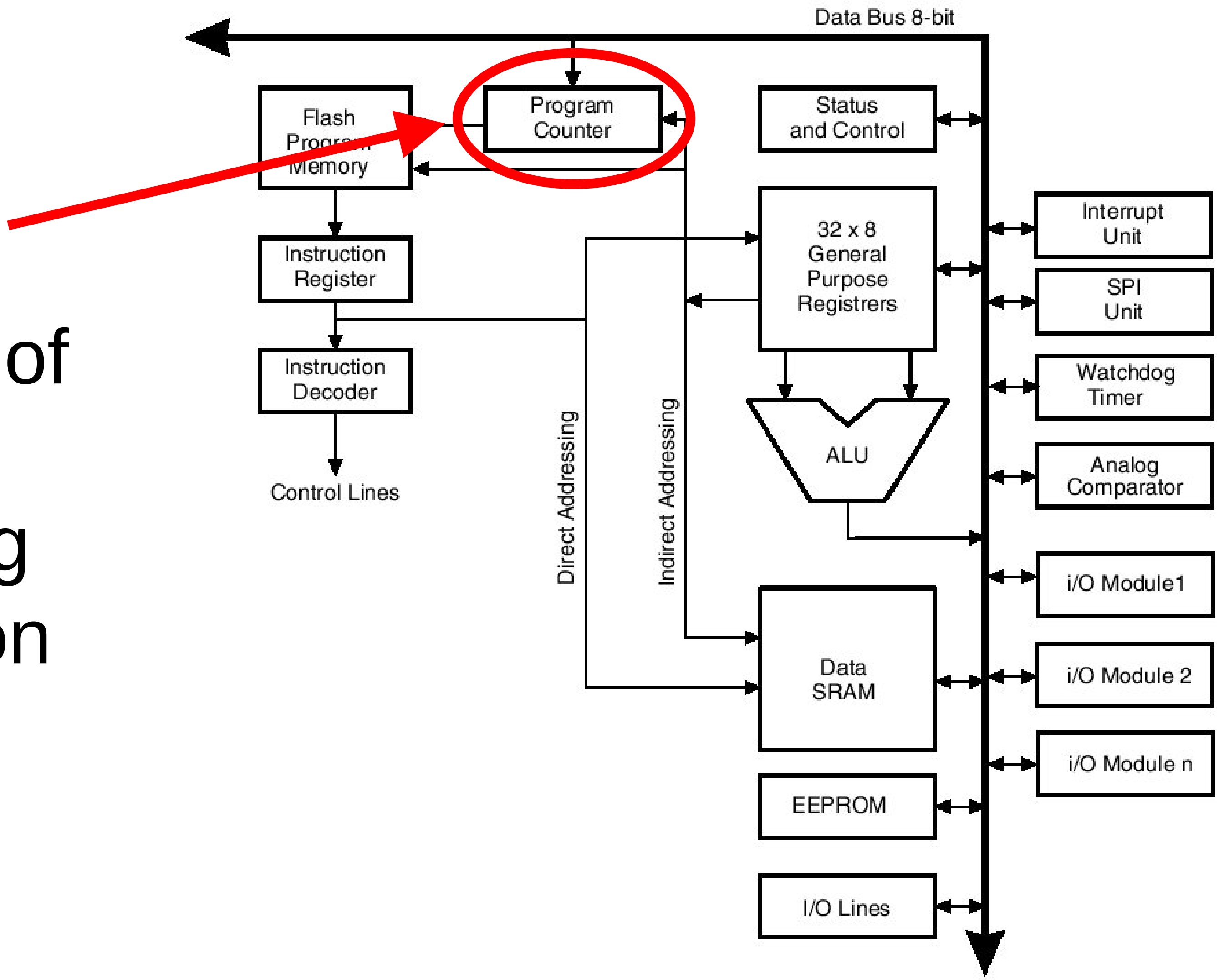
Types of Instructions

- 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)

Atmel Mega8: Decoding Instructions

Program counter

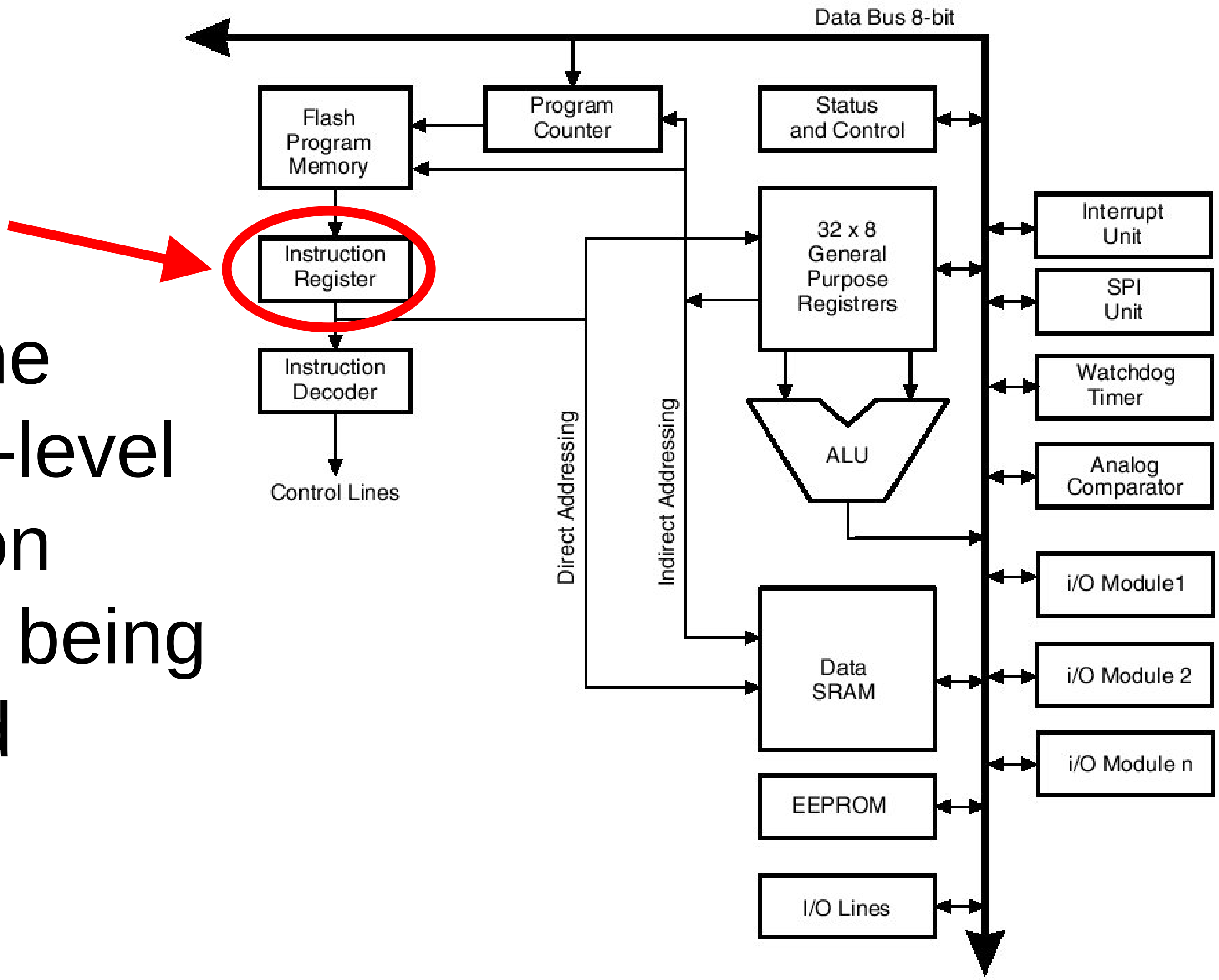
- Address of currently executing instruction



Atmel Mega8: Decoding Instructions

Instruction register

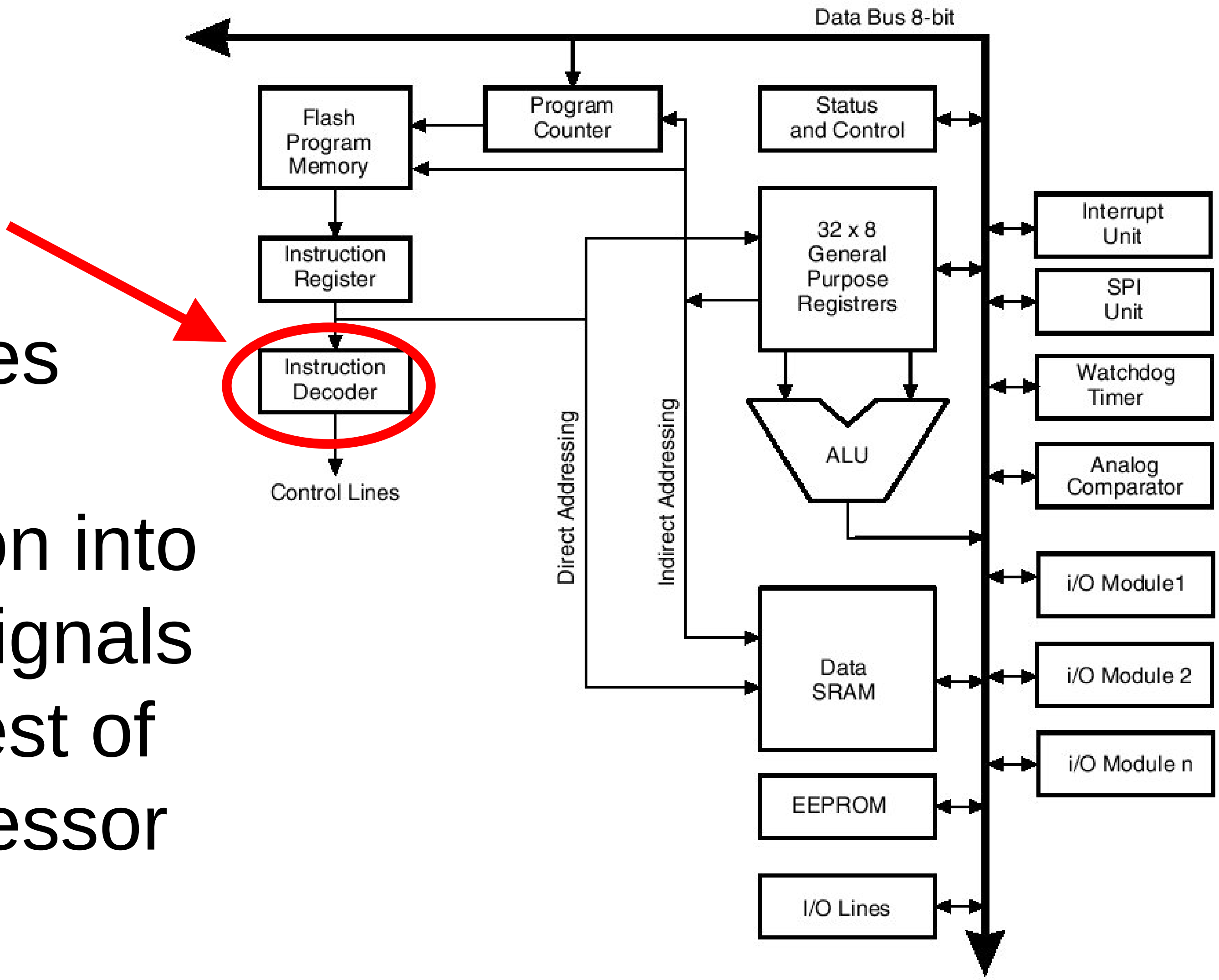
- Stores the machine-level instruction currently being executed



Atmel Mega8

Instruction decoder

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



Some Mega8 Memory Operations

LDS Rd, k

We refer to this as “Assembly Language”

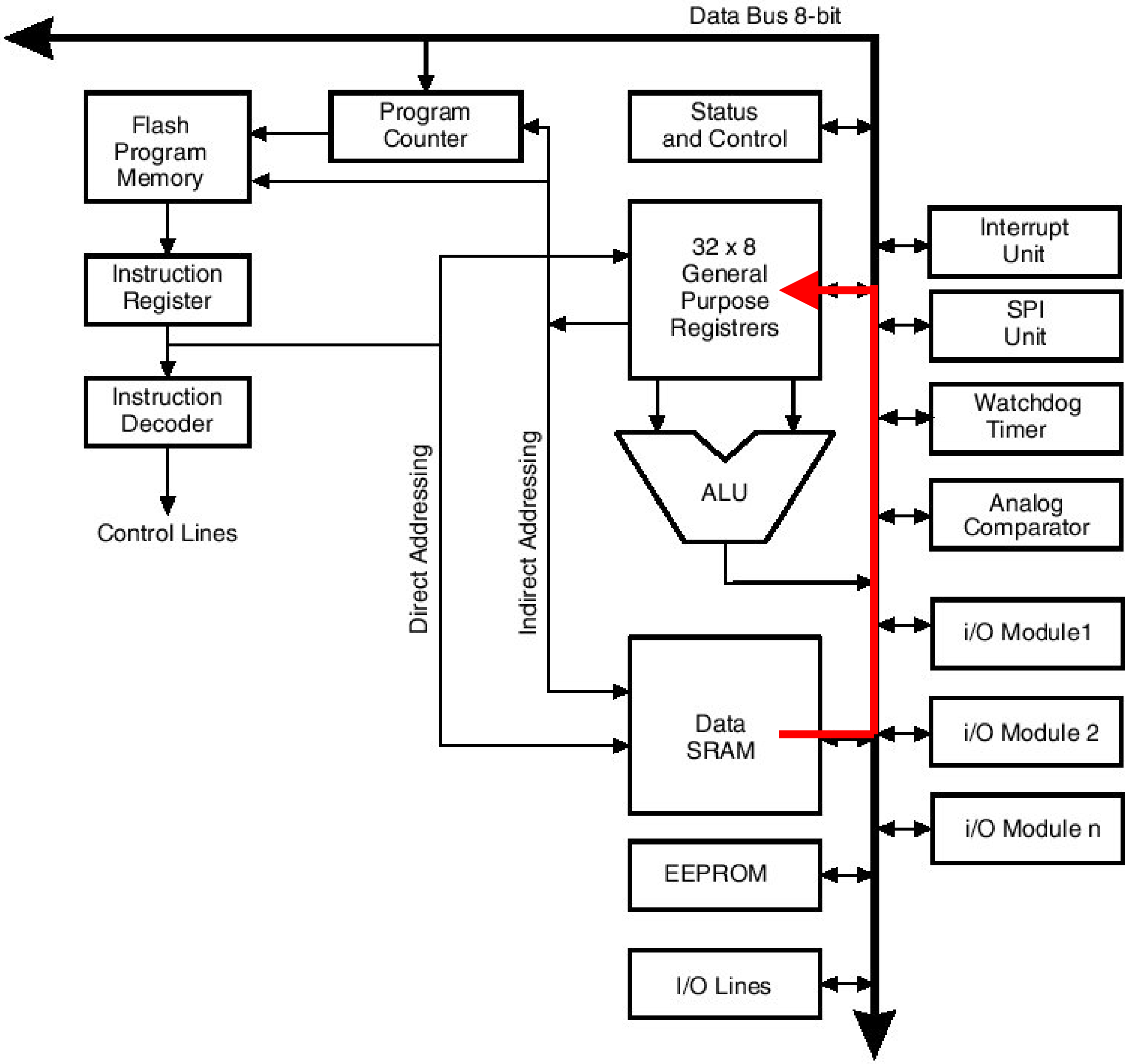
- Load SRAM memory location k into register Rd
- Rd <- (k)

STS Rd, k

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

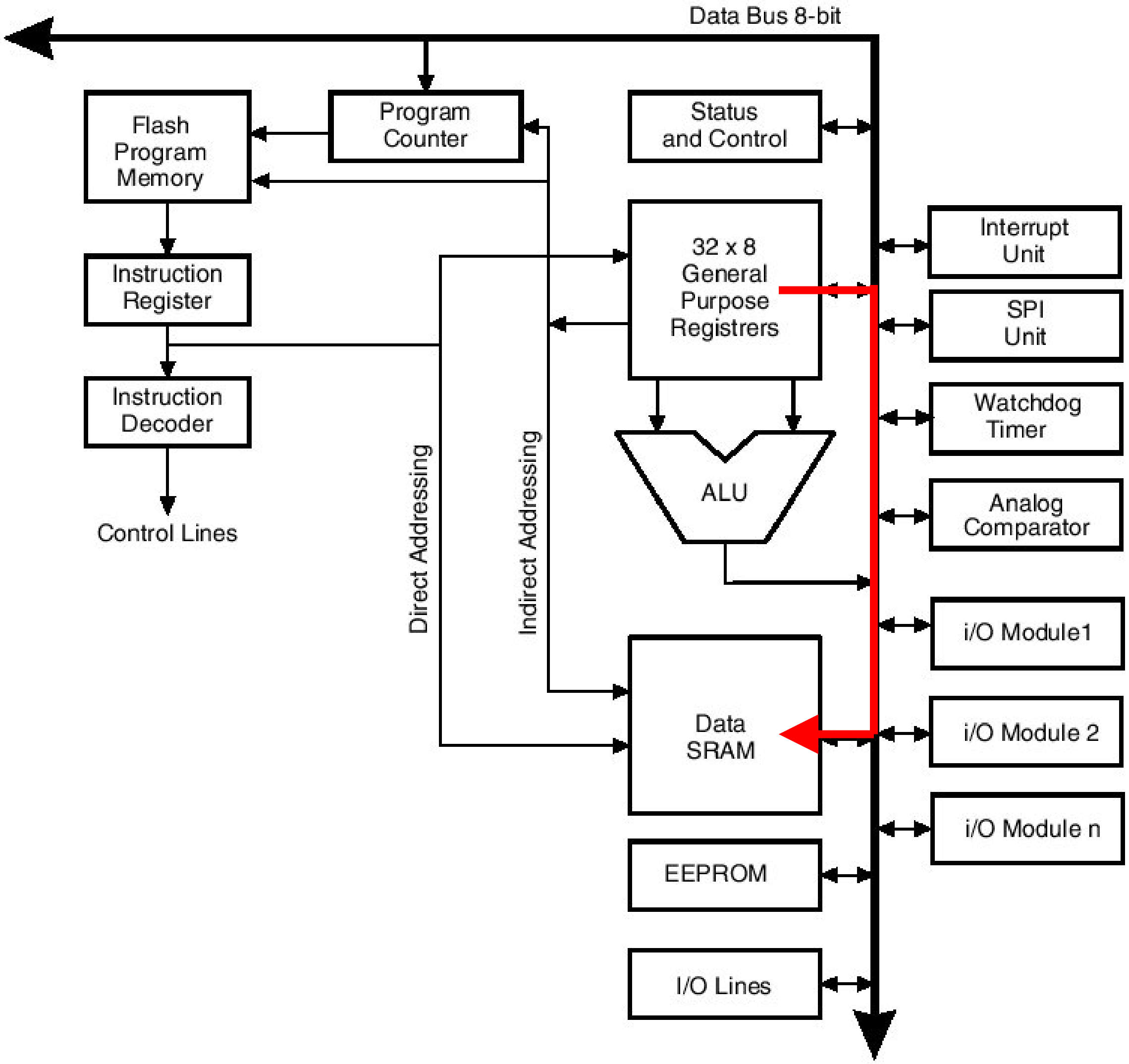
Load SRAM Value to Register

LDS Rd, k



Store Register Value to SRAM

STS Rd, k



Some Mega8 Arithmetic and Logical Instructions

ADD Rd, Rr

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

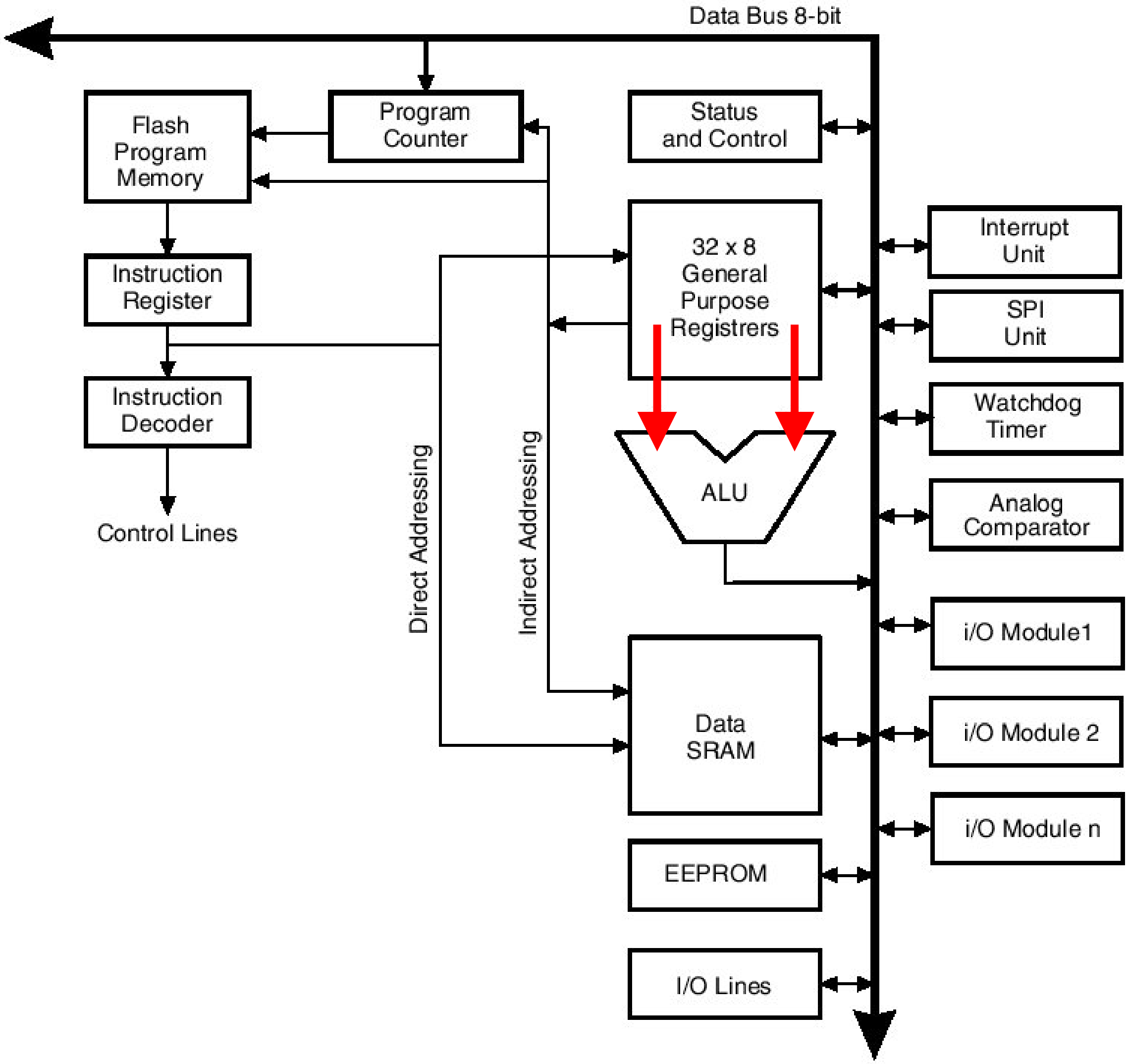
ADC Rd, Rr

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

Add Two Register Values

ADD Rd, Rr

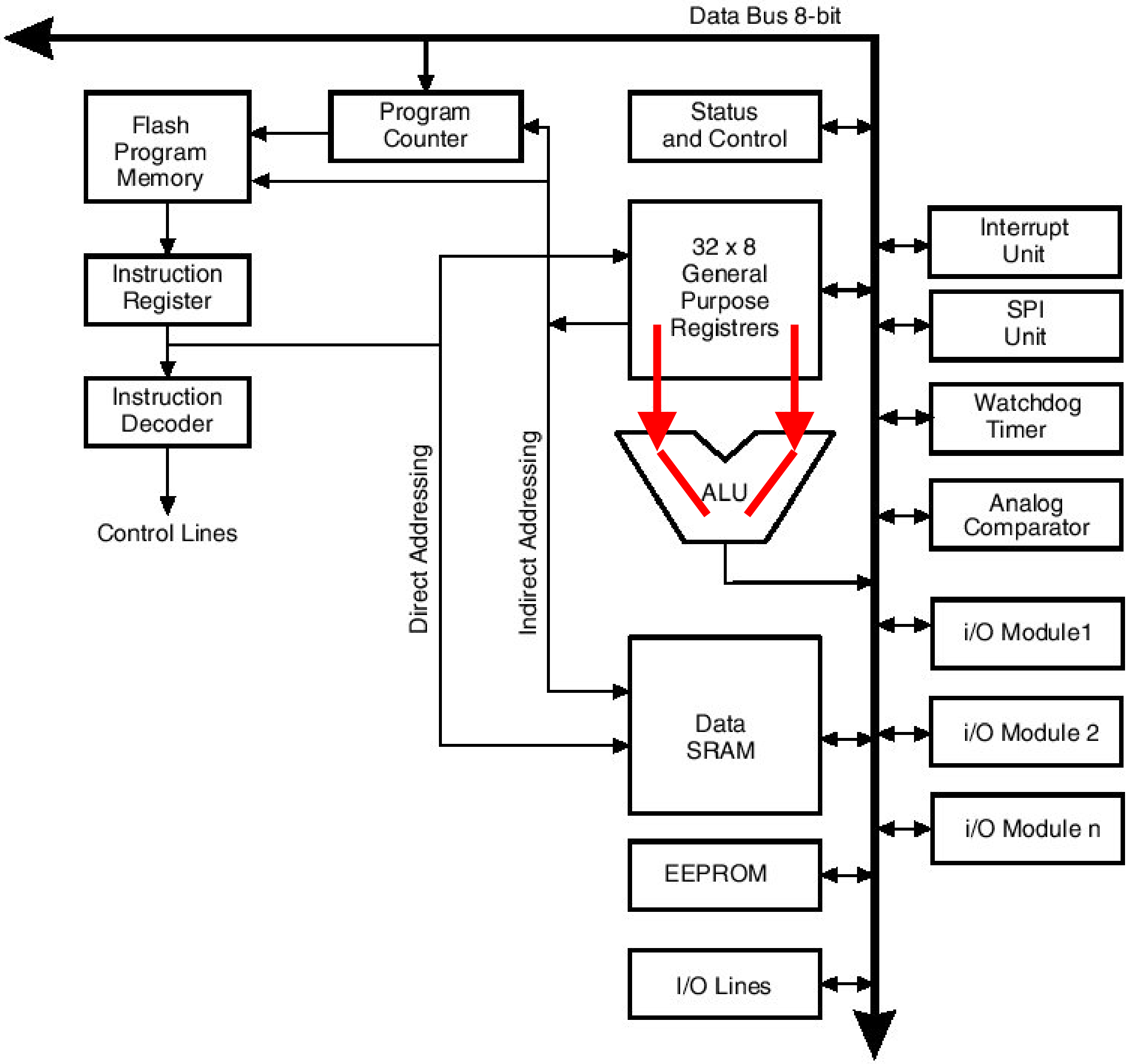
- Fetch register values



Add Two Register Values

ADD Rd, Rr

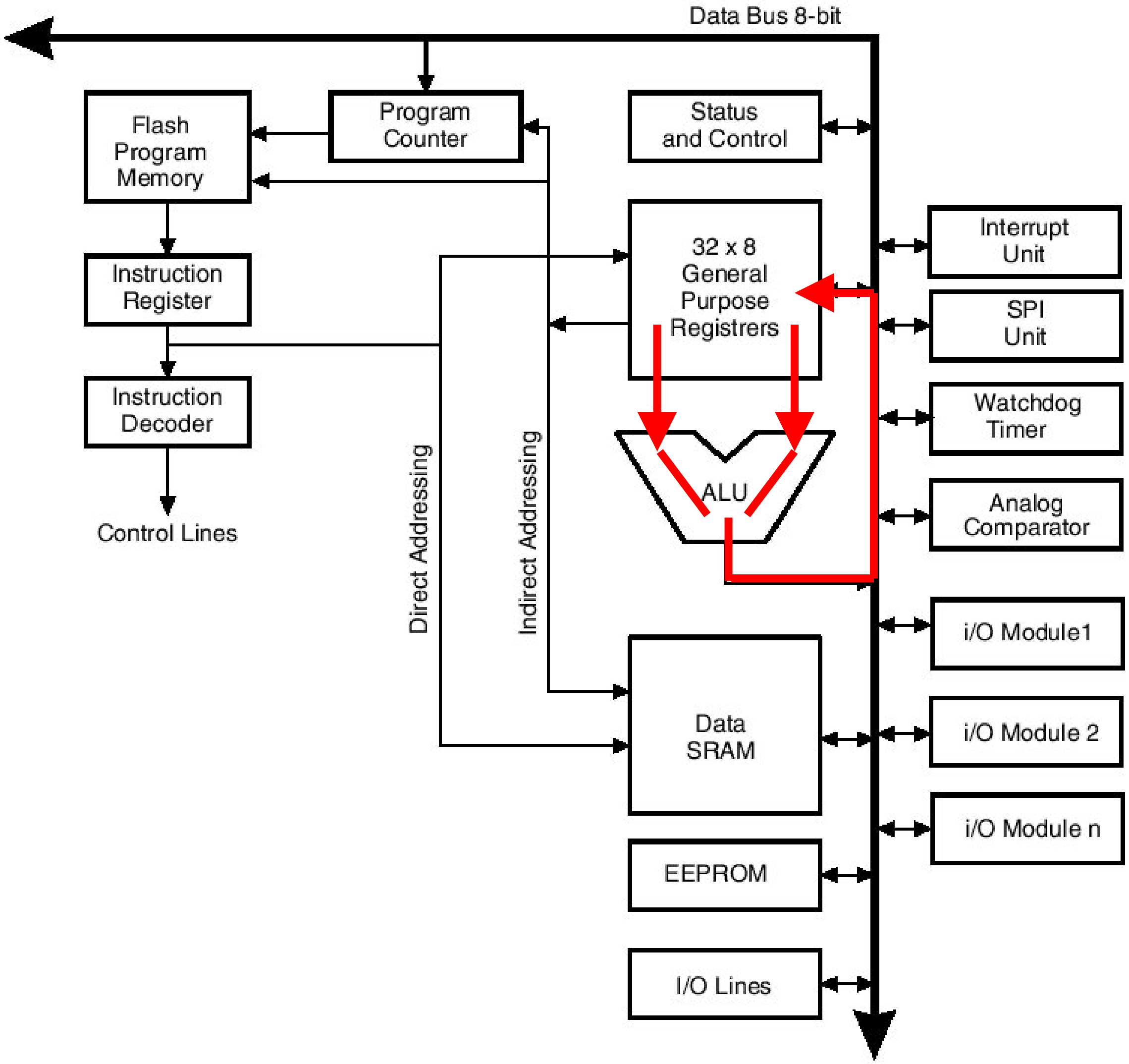
- Fetch register values
- ALU performs ADD



Add Two Register Values

ADD Rd, Rr

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



Some Mega8 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;
}
```

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

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

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;
}
```

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
……..
```

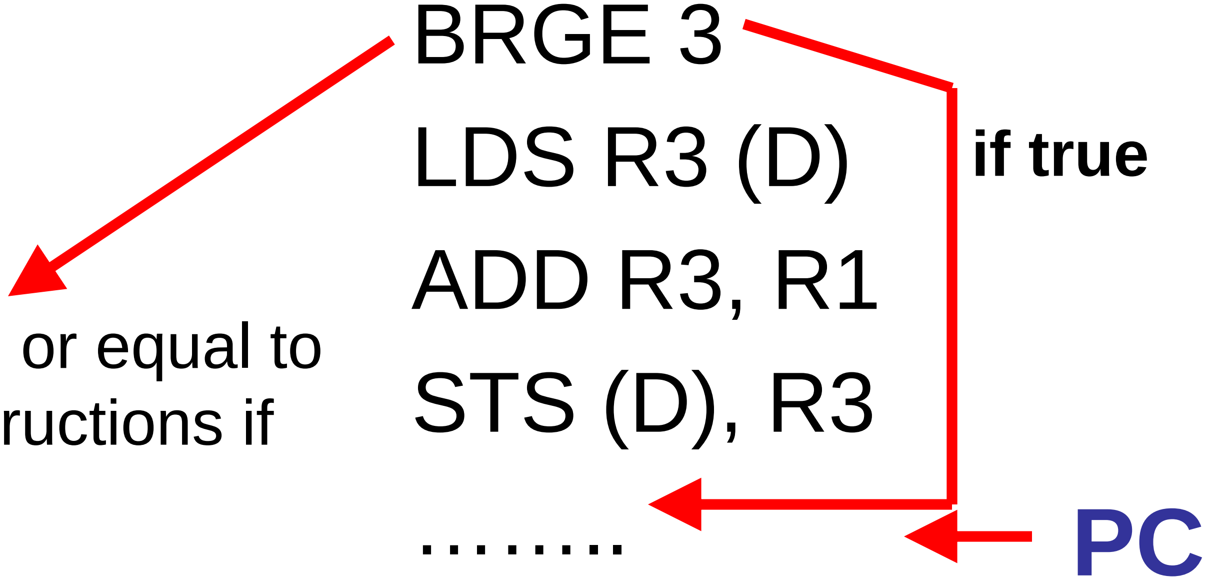
An Example

A C code snippet:

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

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

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;
}
```

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)    ← PC
ADD R3, R1
STS (D), R3
……..
```

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 ← PC
STS (D), R3
……..
```

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
……..
```

Summary

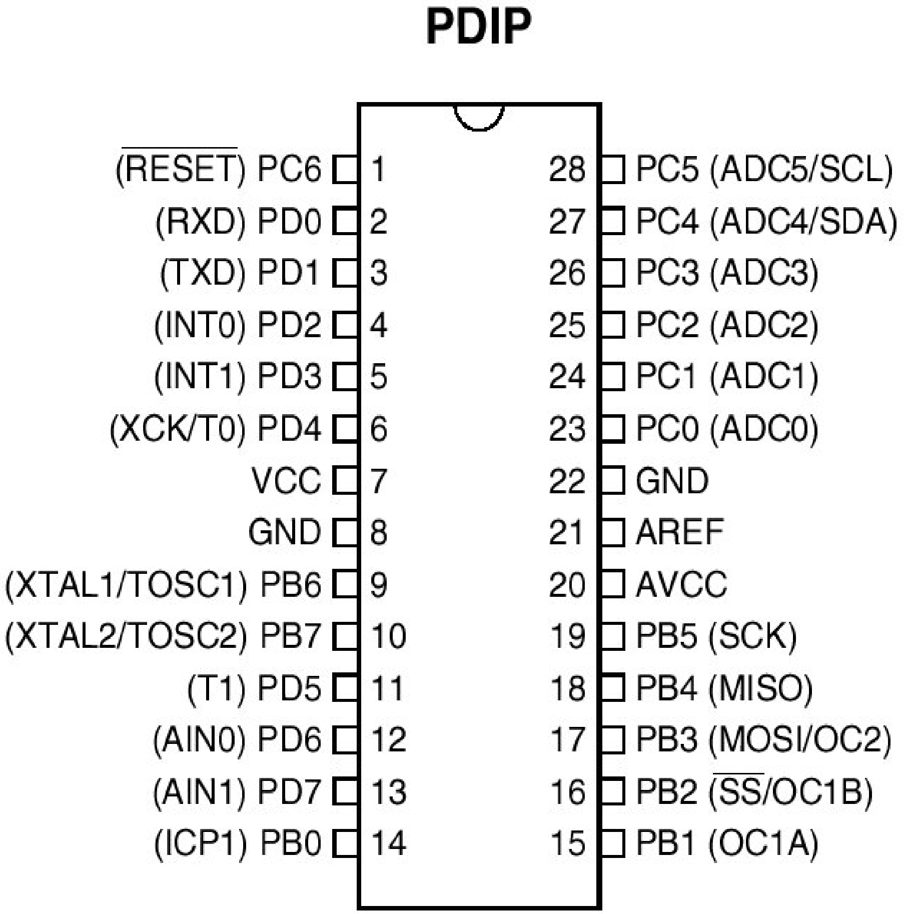
Instructions are the “atomic” actions that are taken by the processor

- One line of C code typically translates to a sequence of several instructions
- In the mega 8, 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

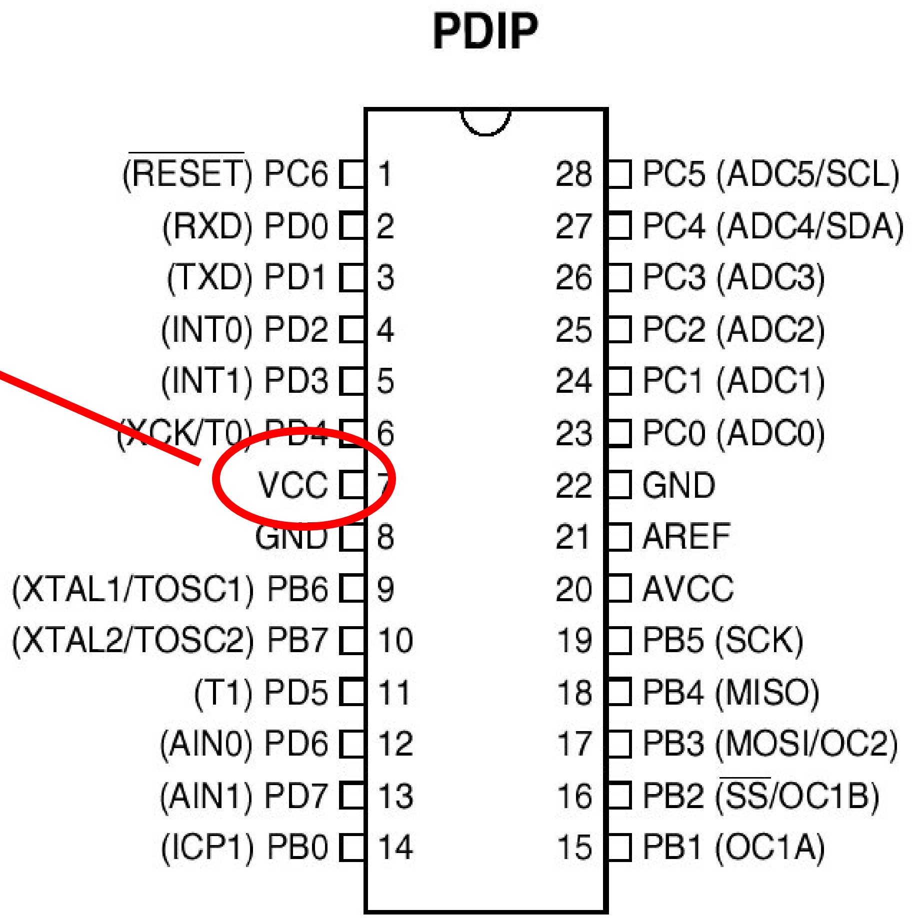
Atmel Mega8 Basics

- Complete, stand-alone computer
- Ours is a 28-pin package
- Most pins:
  - Are used for input/output
  - How they are used is configurable



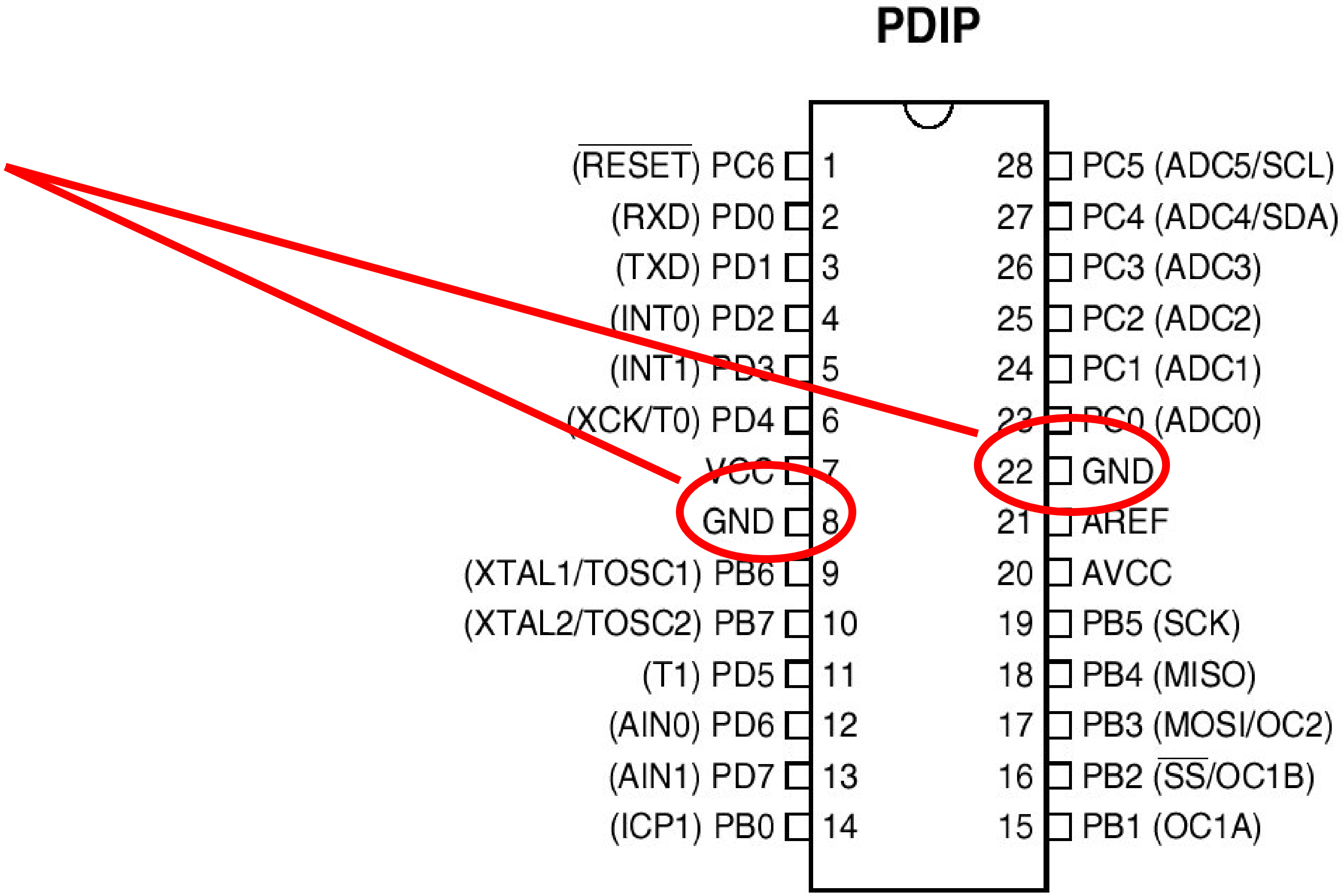
Atmel Mega8 Basics

Power (we will use +5V)



Atmel Mega8 Basics

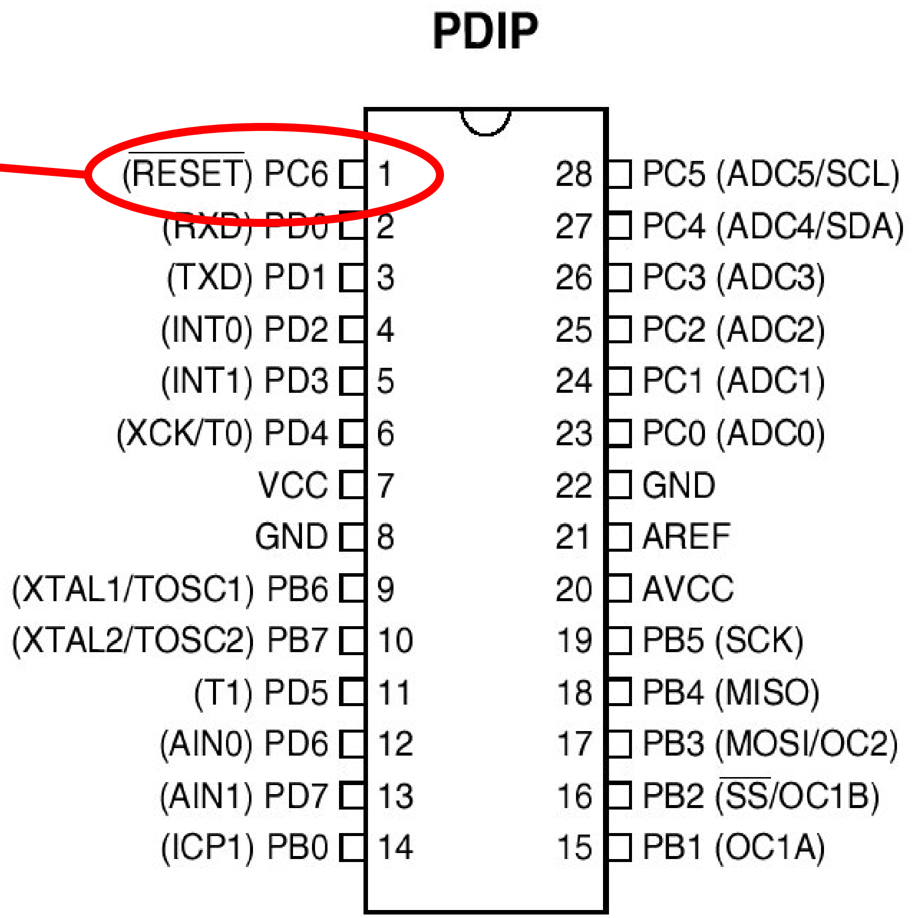
Ground



Atmel Mega8 Basics

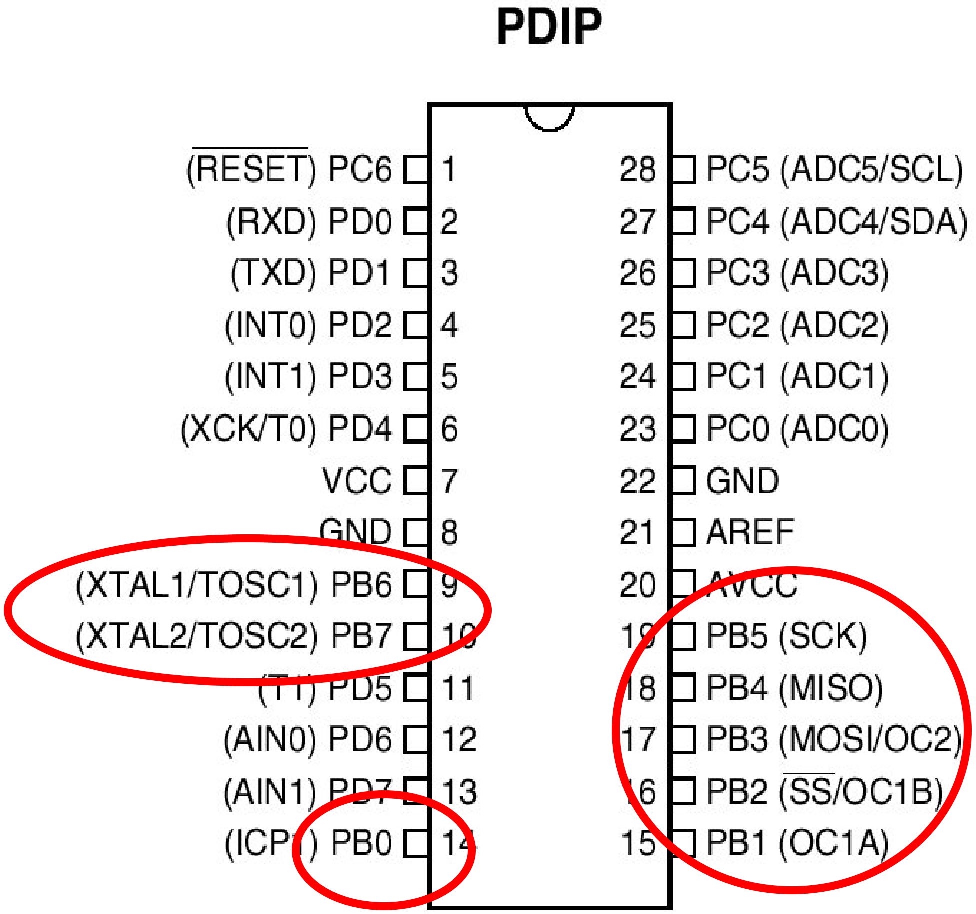
Reset

- Bring low to reset the processor
- In general, we will tie this pin to high through a pull-up resistor (10K ohm)



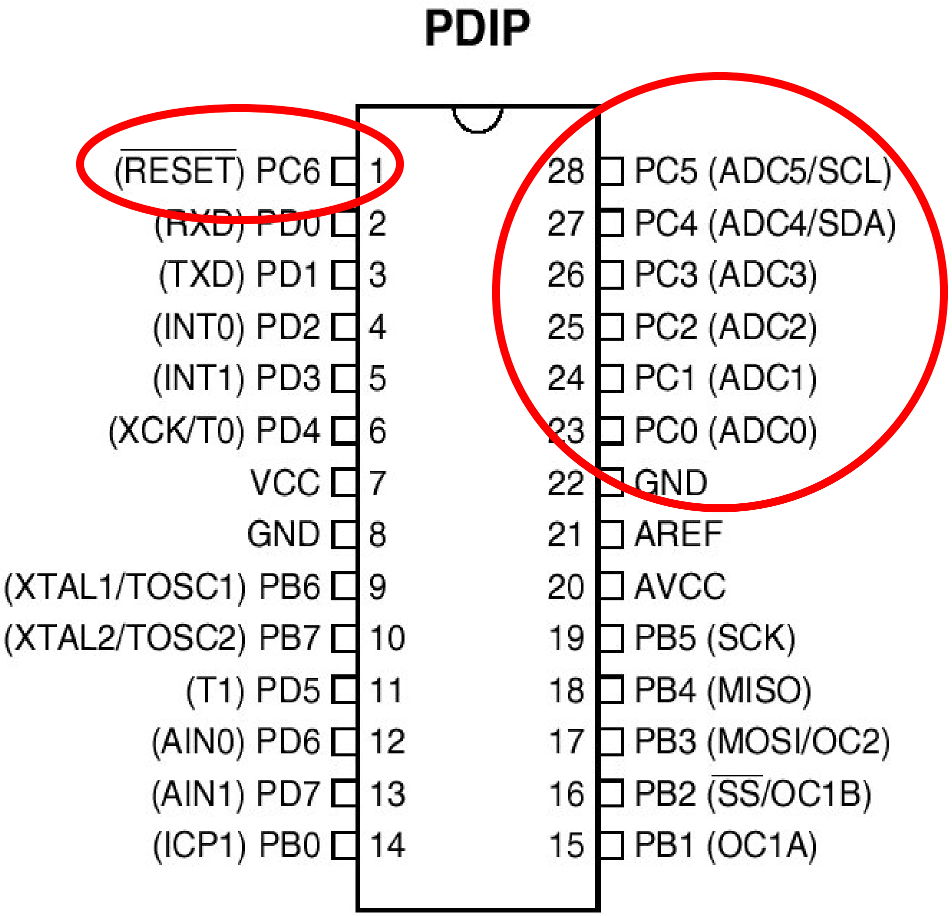
Atmel Mega8 Basics

PORT B



Atmel Mega8 Basics

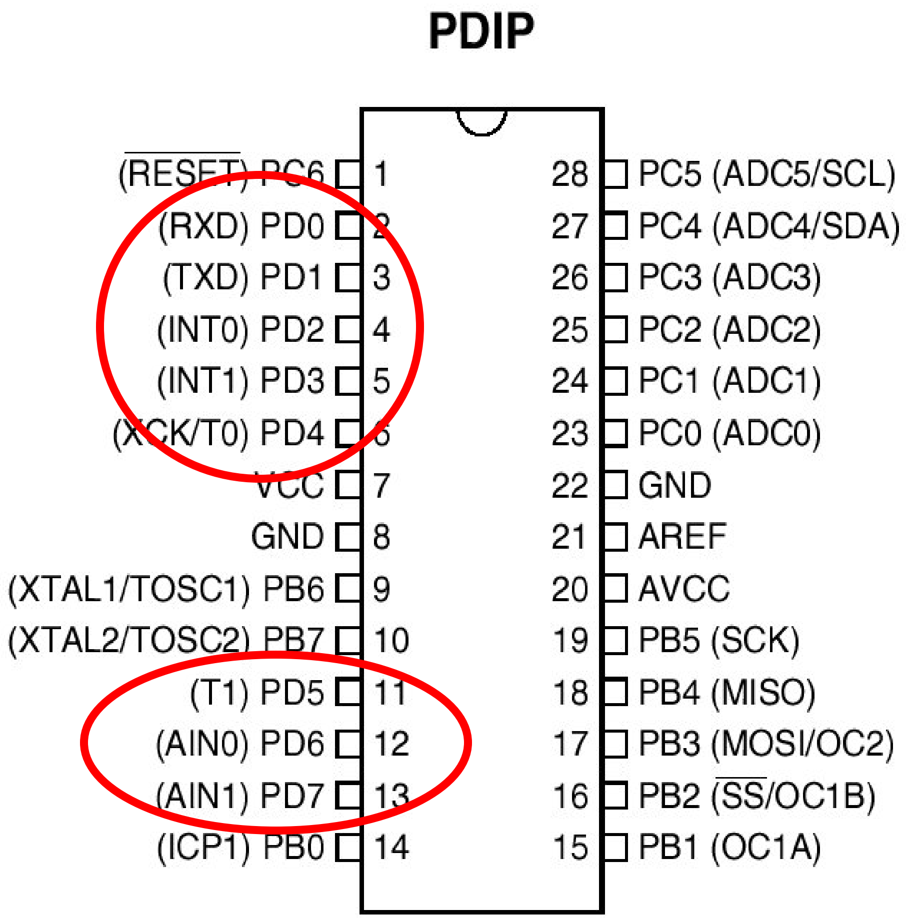
PORT C



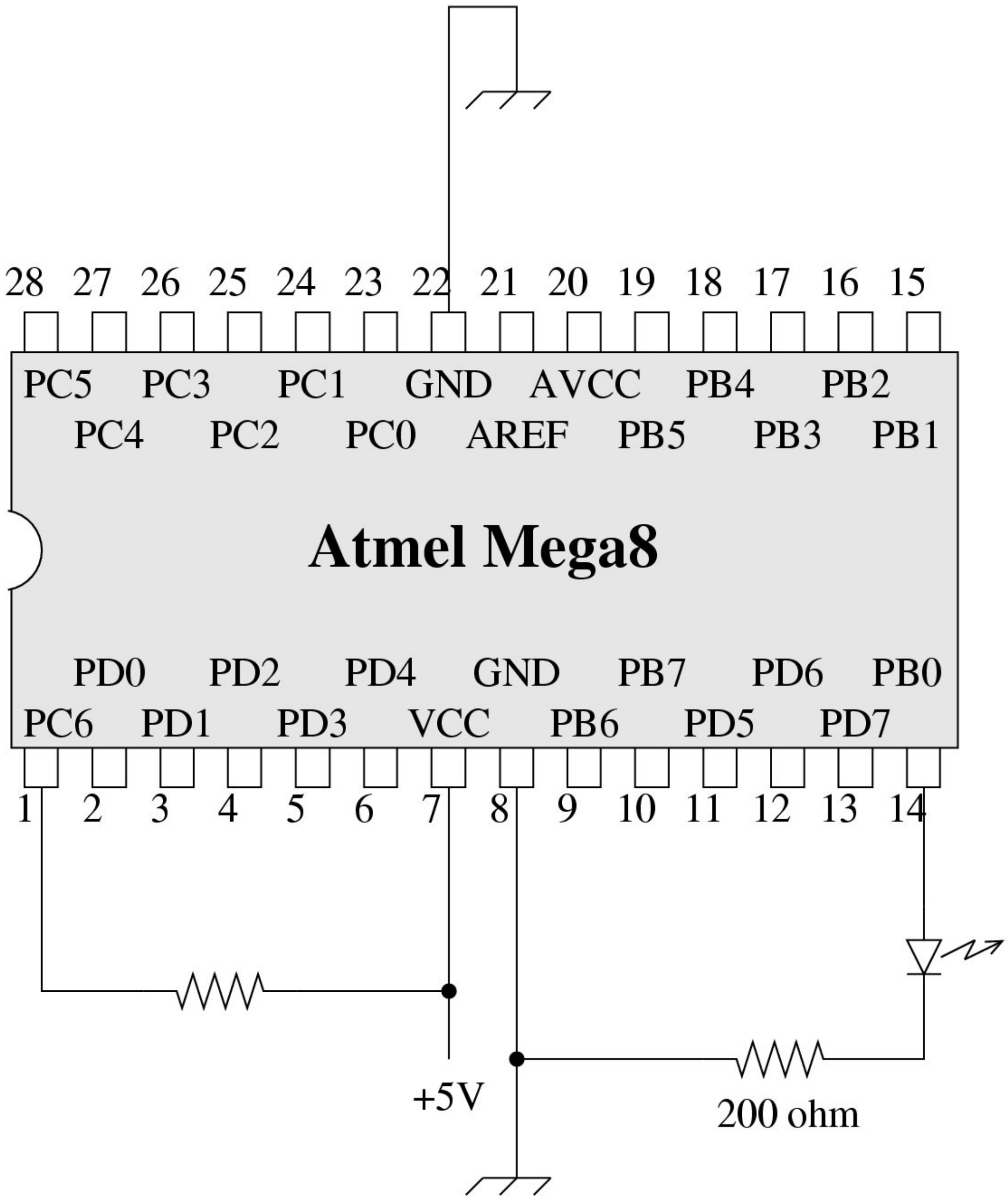
Atmel Mega8 Basics

PORT D

(all 8 bits are available)



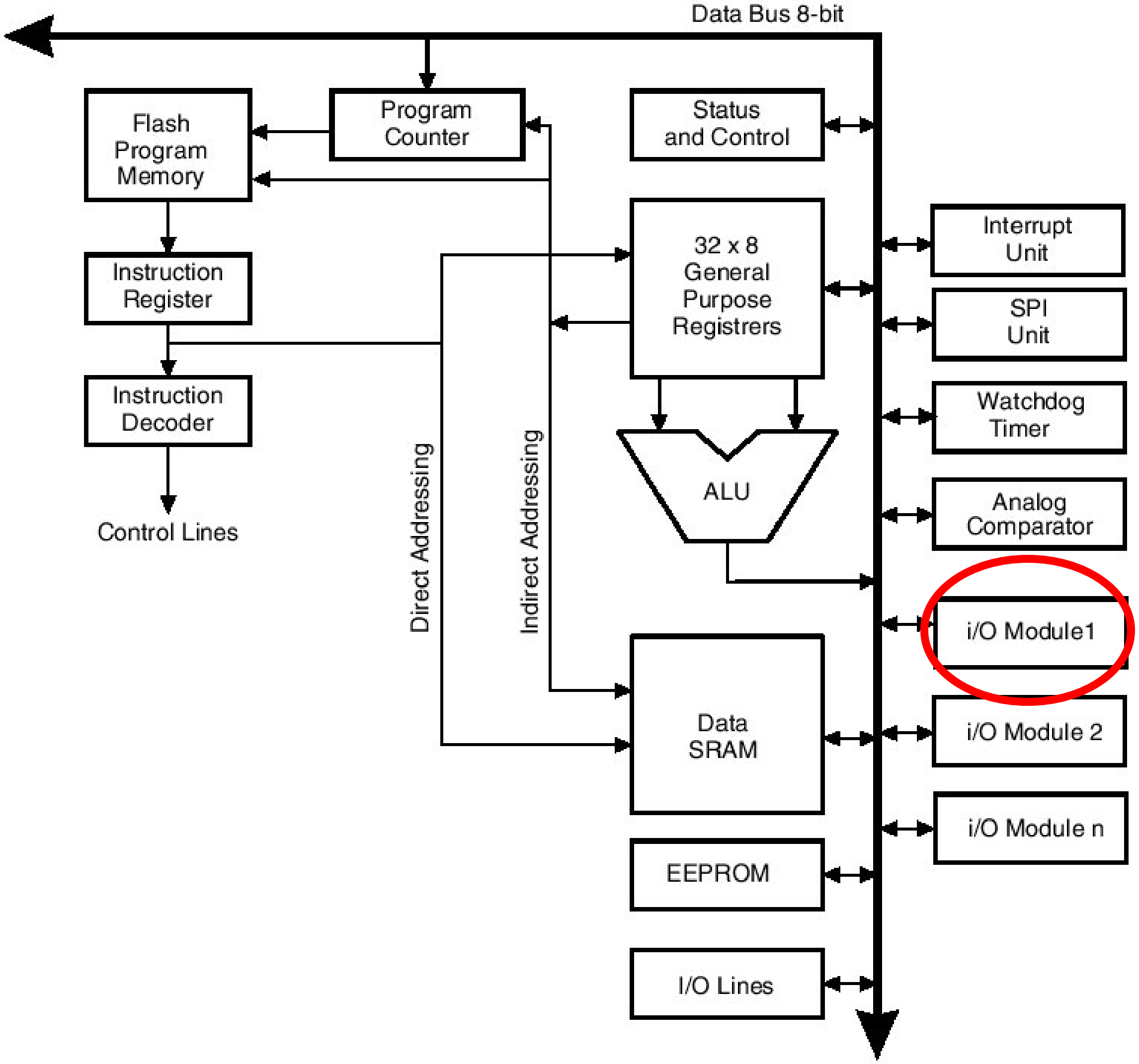
A First Circuit



Atmel Mega8

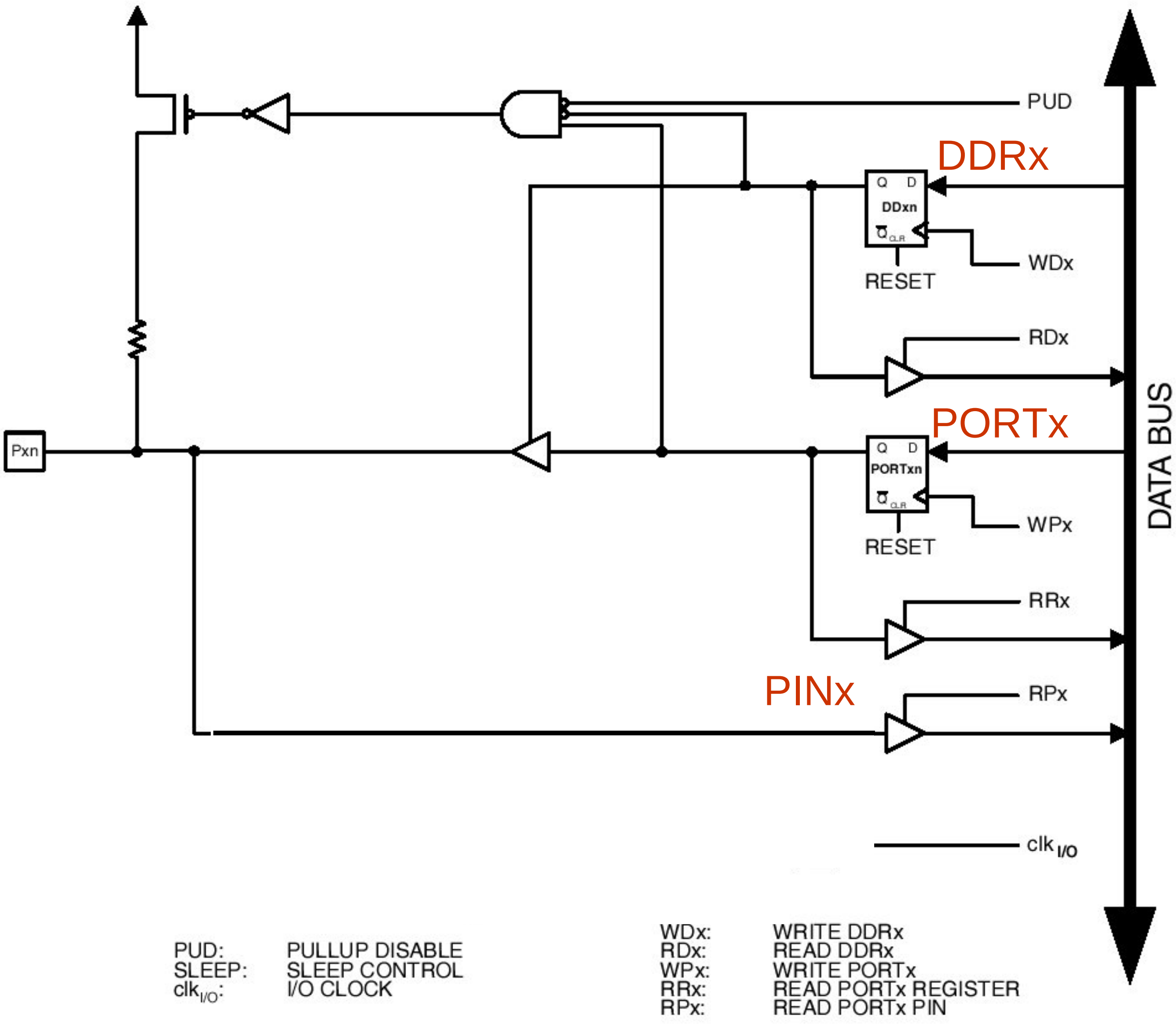
Control the pins through the I/O modules

- At the heart, these are registers … that are implemented using D flip-flops!

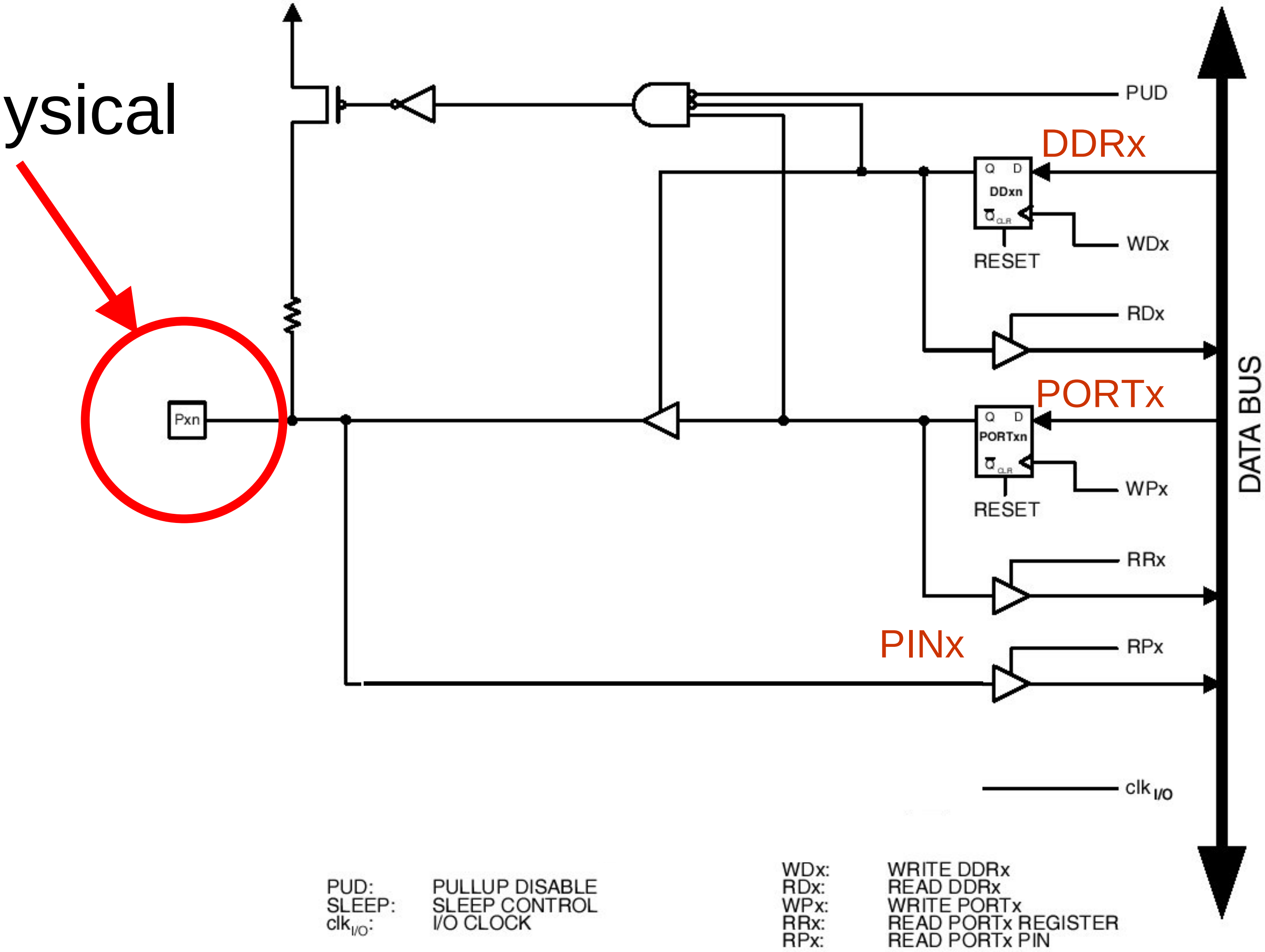


I/O Pin Implementation

Single bit of
PORT B



I/O Pin Implementation

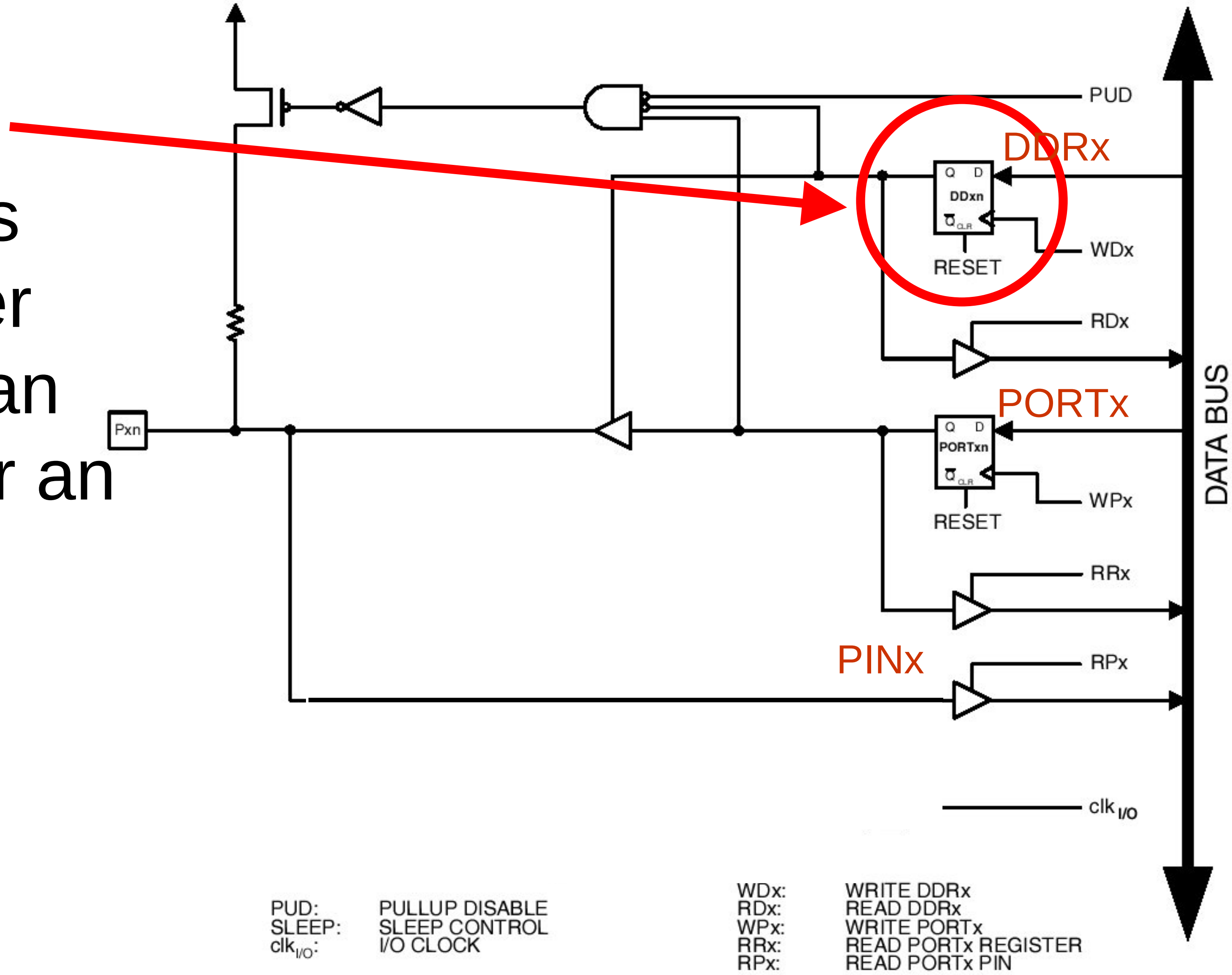


The physical pin

I/O Pin Implementation

DDRB

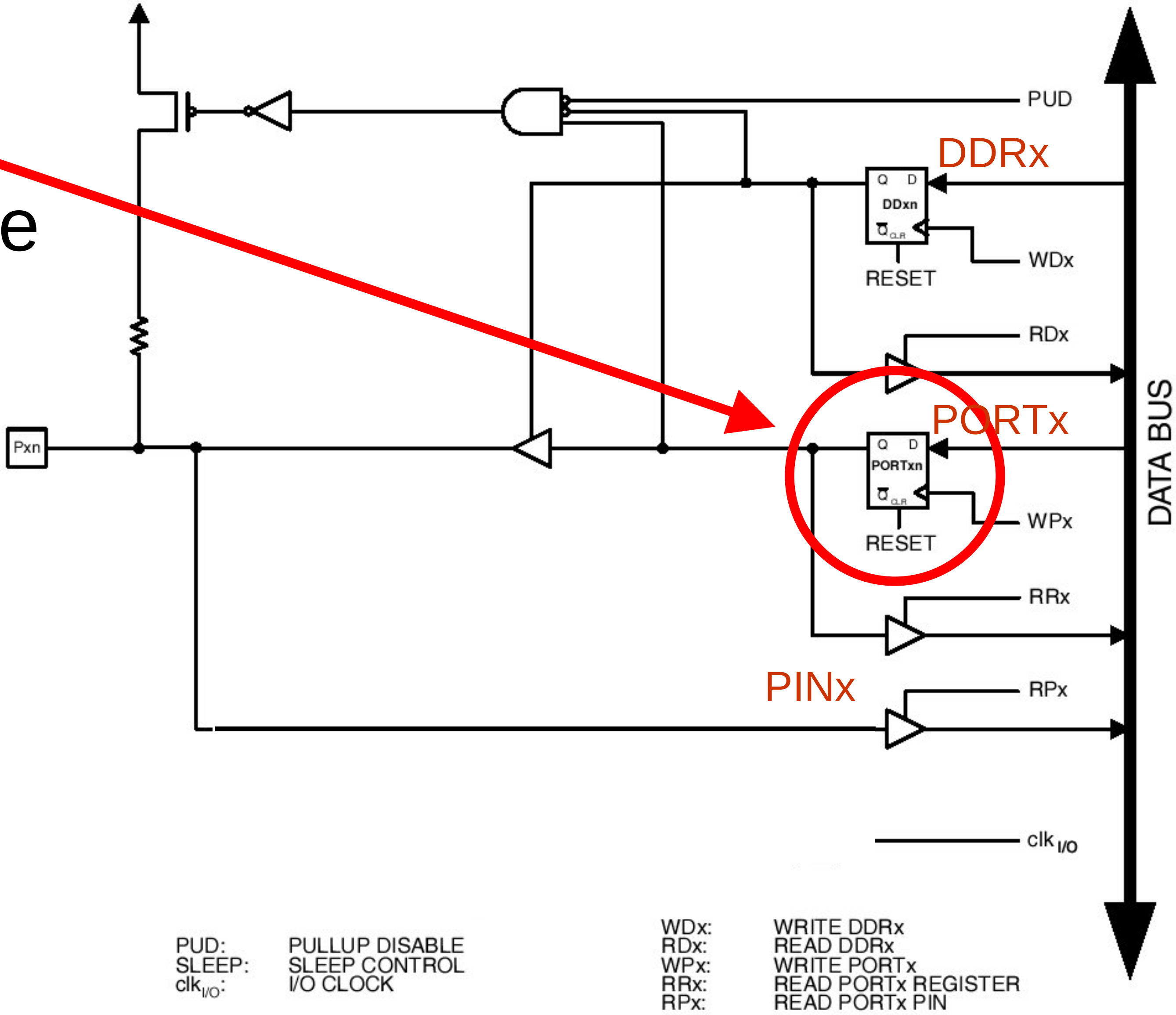
- Defines whether this is an input or an output



I/O Pin Implementation

PORTB

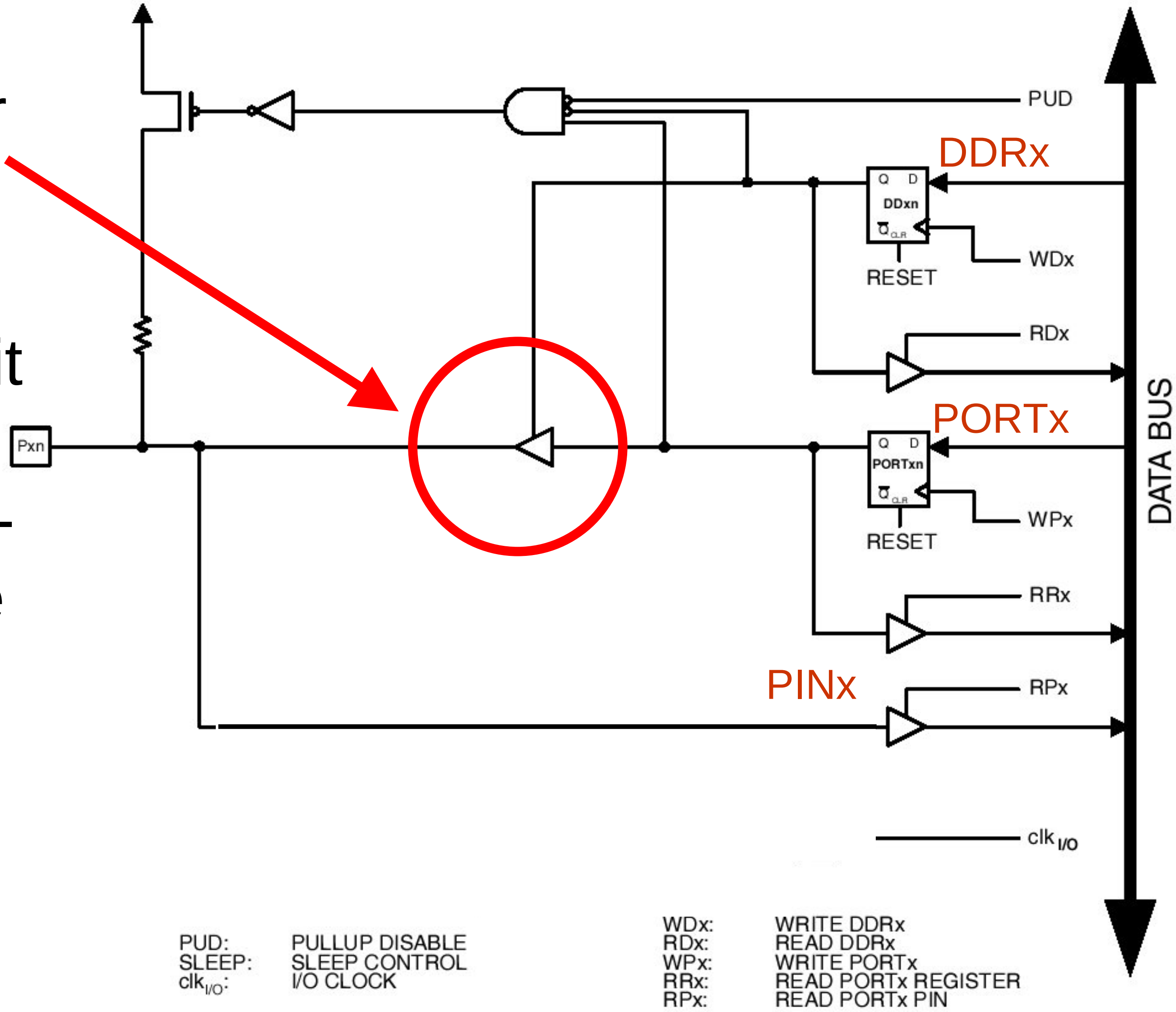
- Defines the value that is written out to the pin (if it is an output)



I/O Pin Implementation

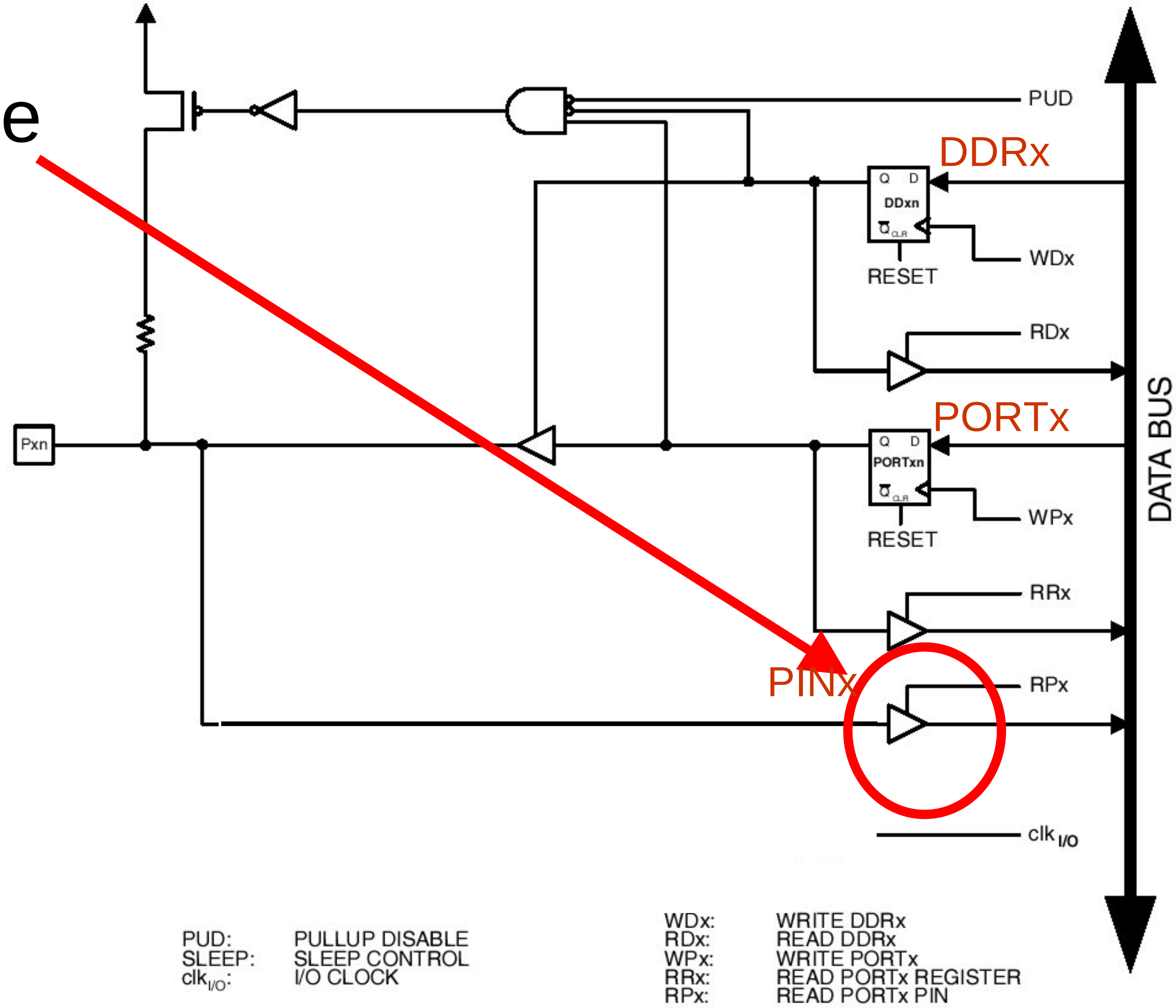
Tristate buffer

- When this pin is an output pin, it allows the PORTB flip-flop to drive the pin

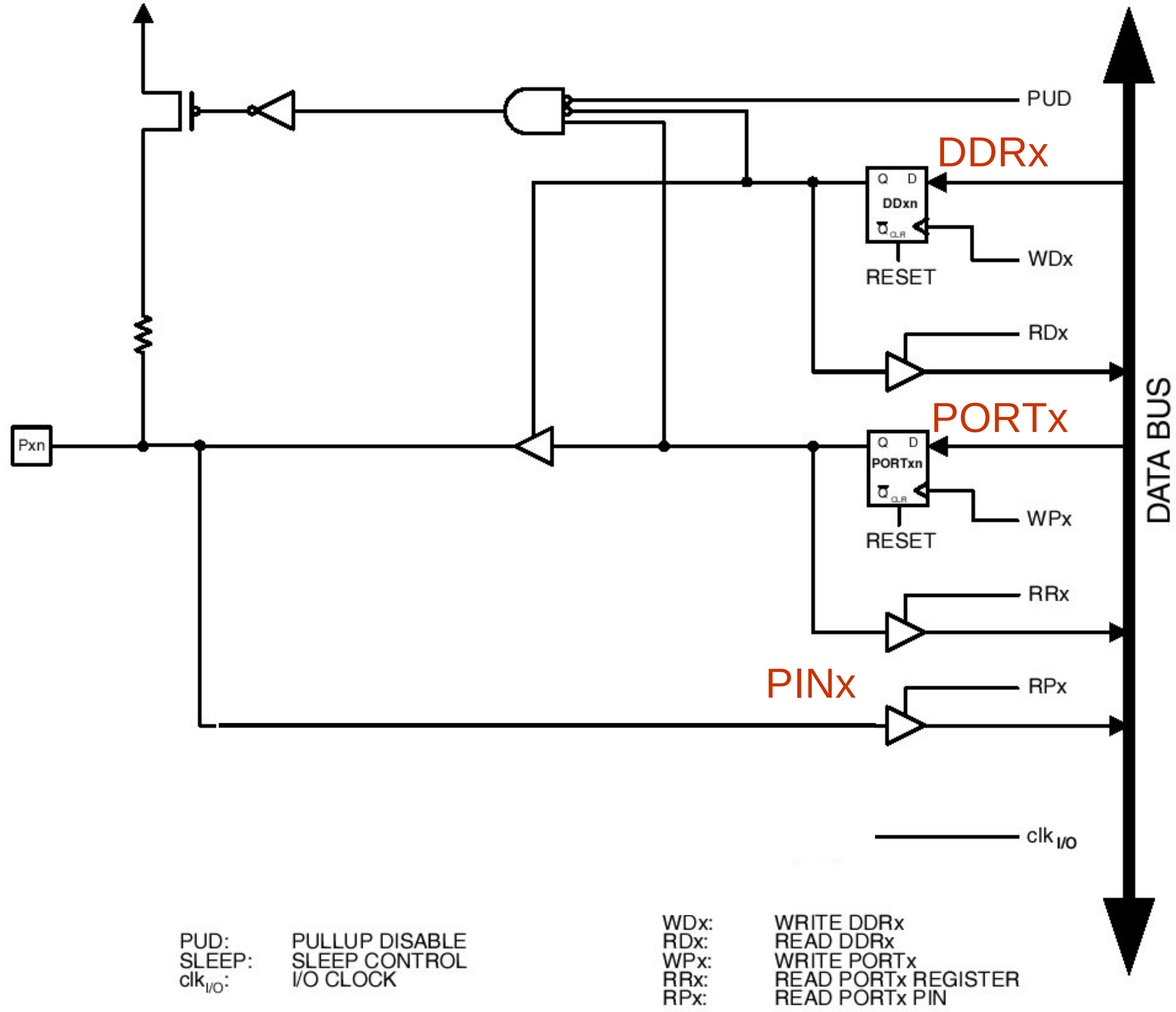


I/O Pin Implementation

Input tri-state buffer

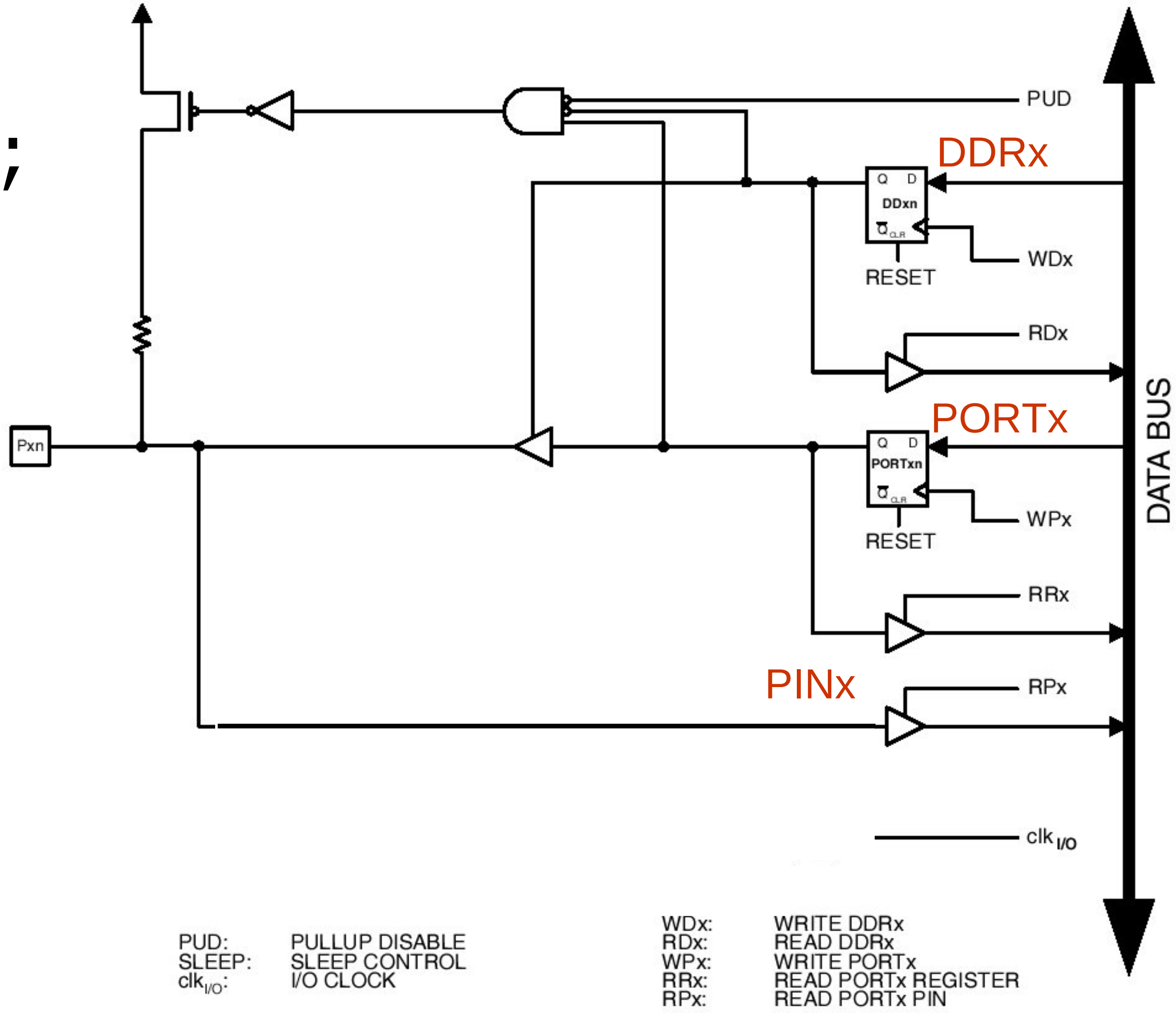


I/O Pin Implementation



I/O Pin Implementation

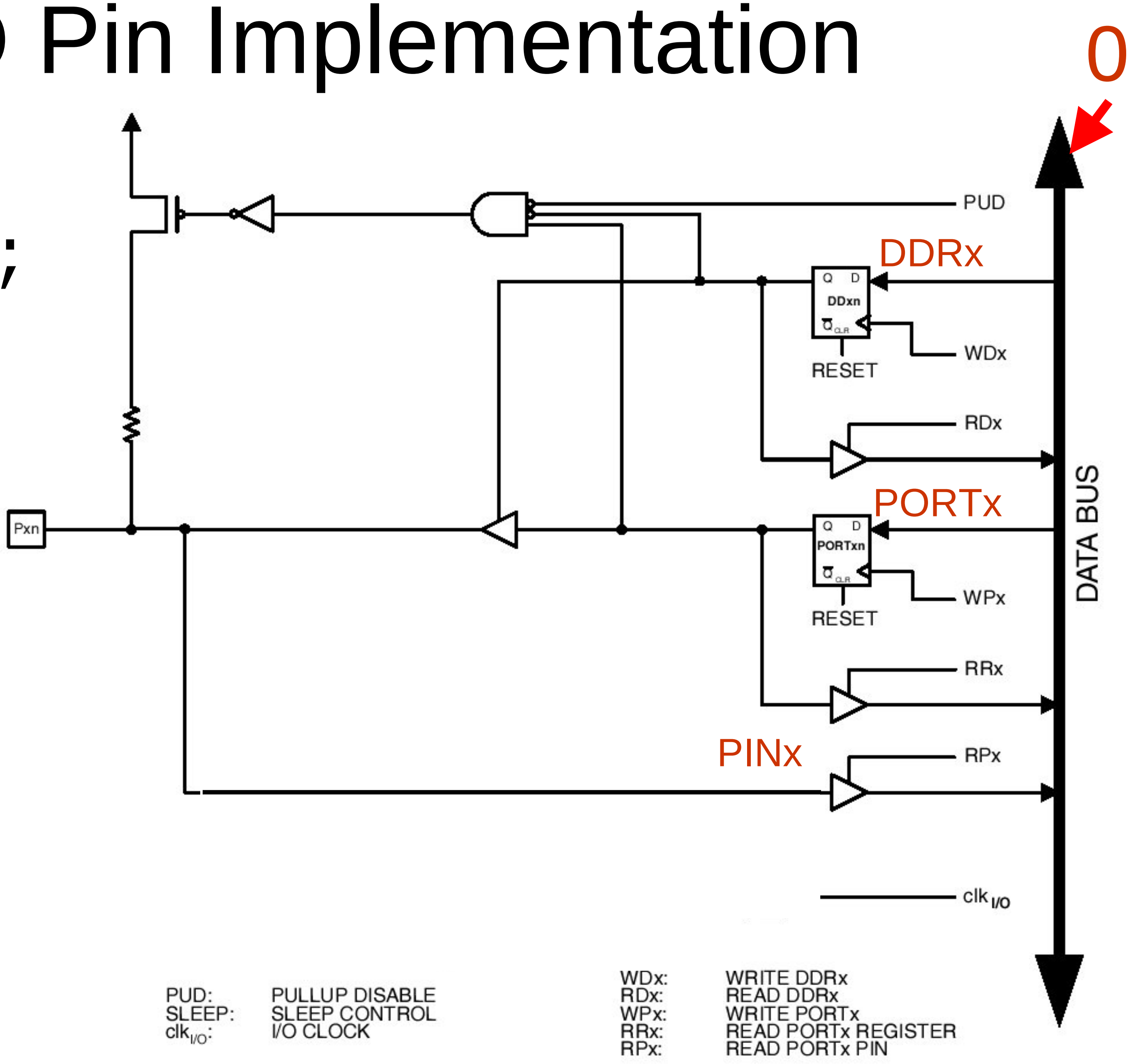
```
DDRB = 0;
```



I/O Pin Implementation

```
DDRB = 0;
```

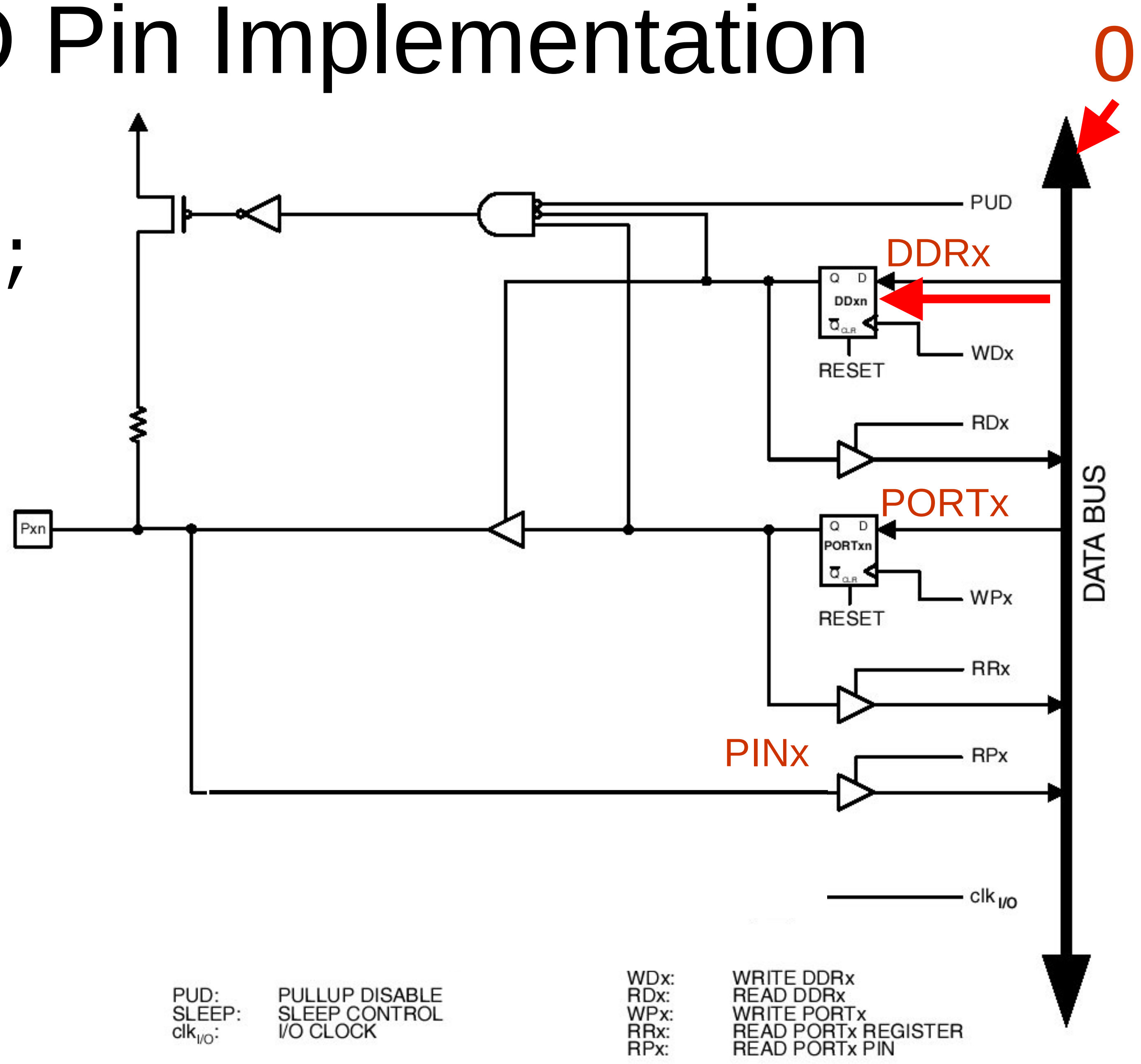
- “0” is written to the data bus



I/O Pin Implementation

```
DDRB = 0;
```

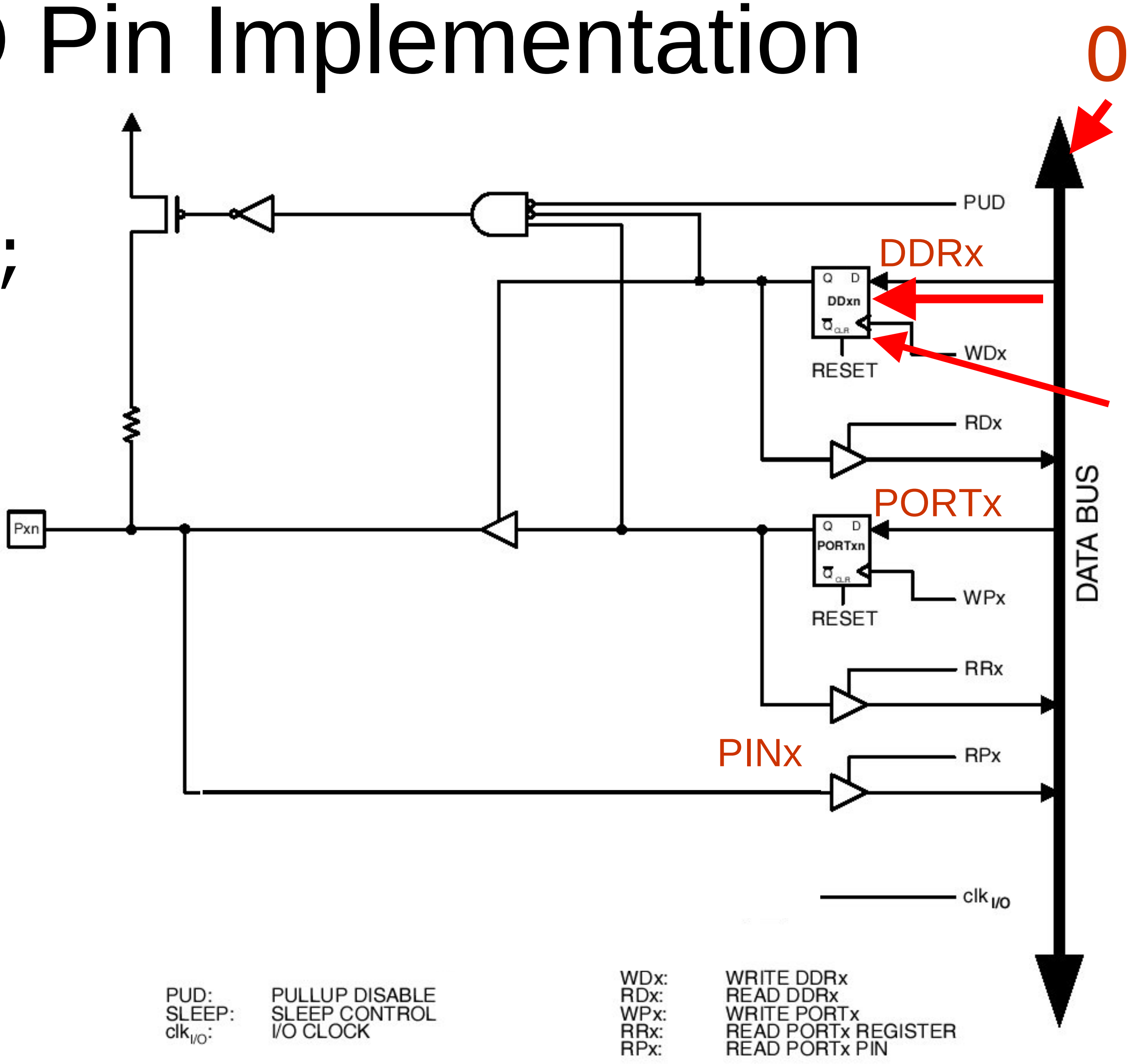
- “0” is written to the data bus
- This is input to the DDRB register



I/O Pin Implementation

```
DDRB = 0;
```

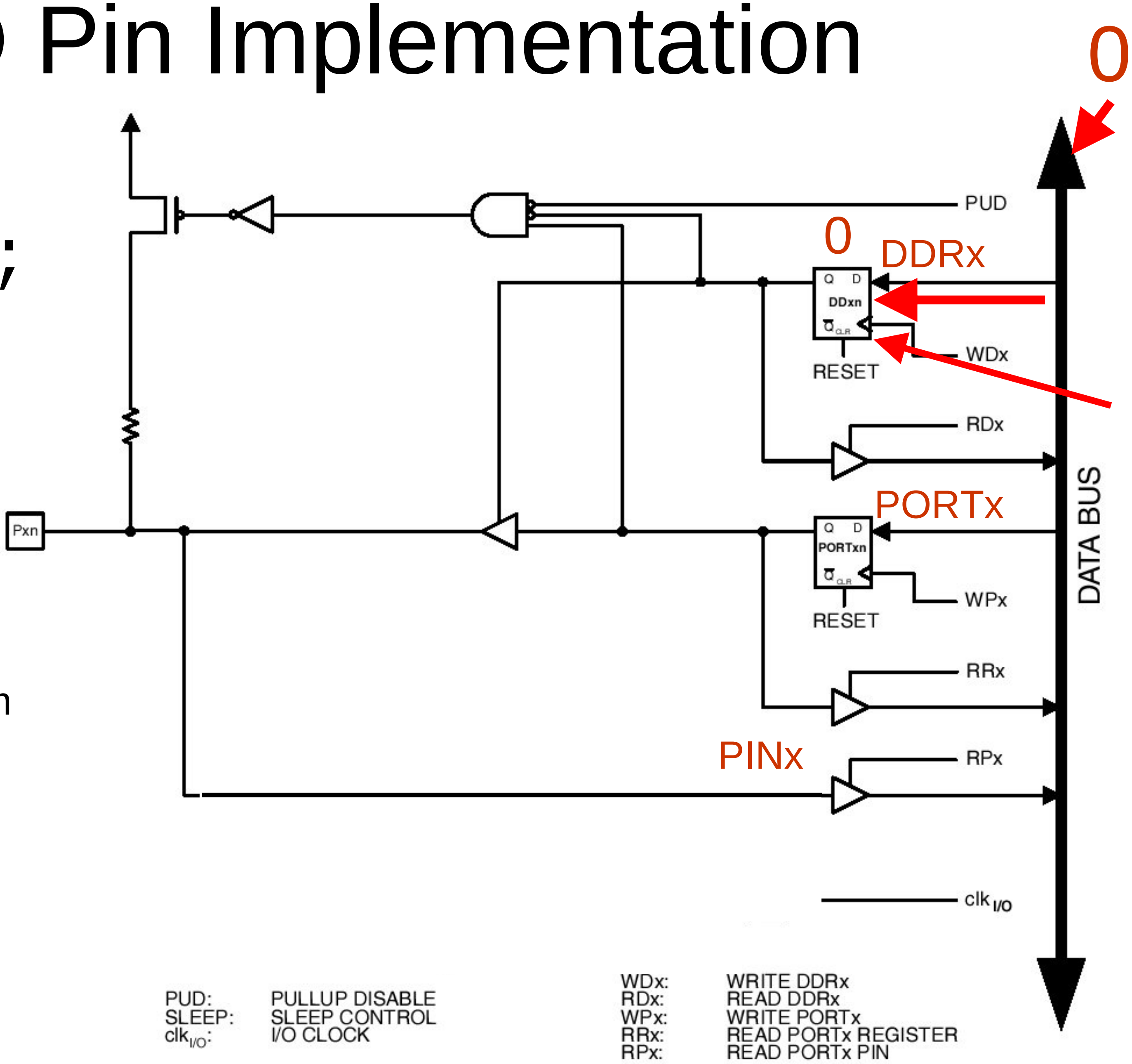
- “0” is written to the data bus
- This is input to the DDRB register
- WDB is clocked from high to low



I/O Pin Implementation

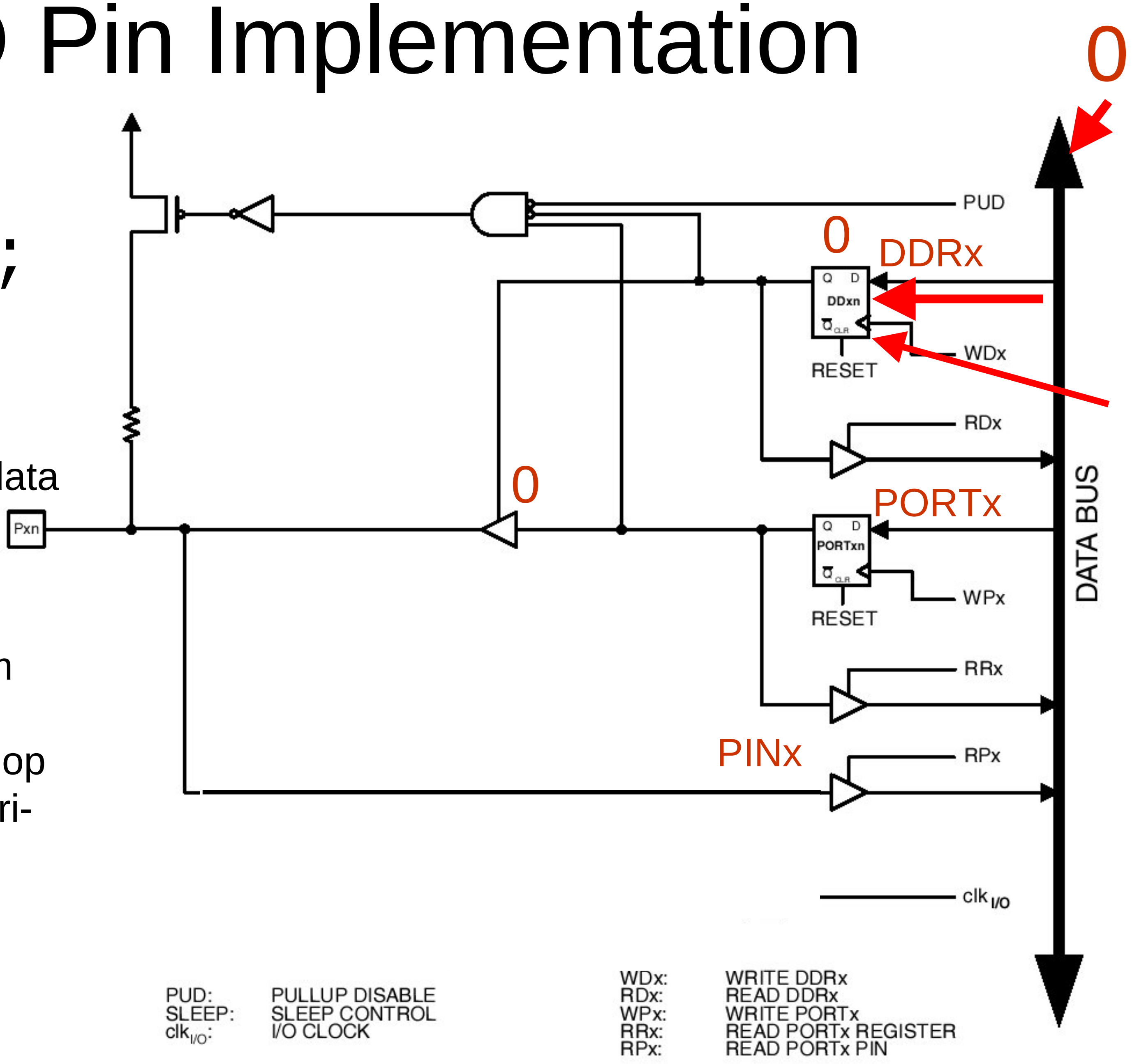
```
DDRB = 0;
```

- “0” is written to the data bus
- This is input to the DDRB register
- WDB is clocked from high to low
- “0” is stored by the flip-flop



I/O Pin Implementation

```
DDRB = 0;
```



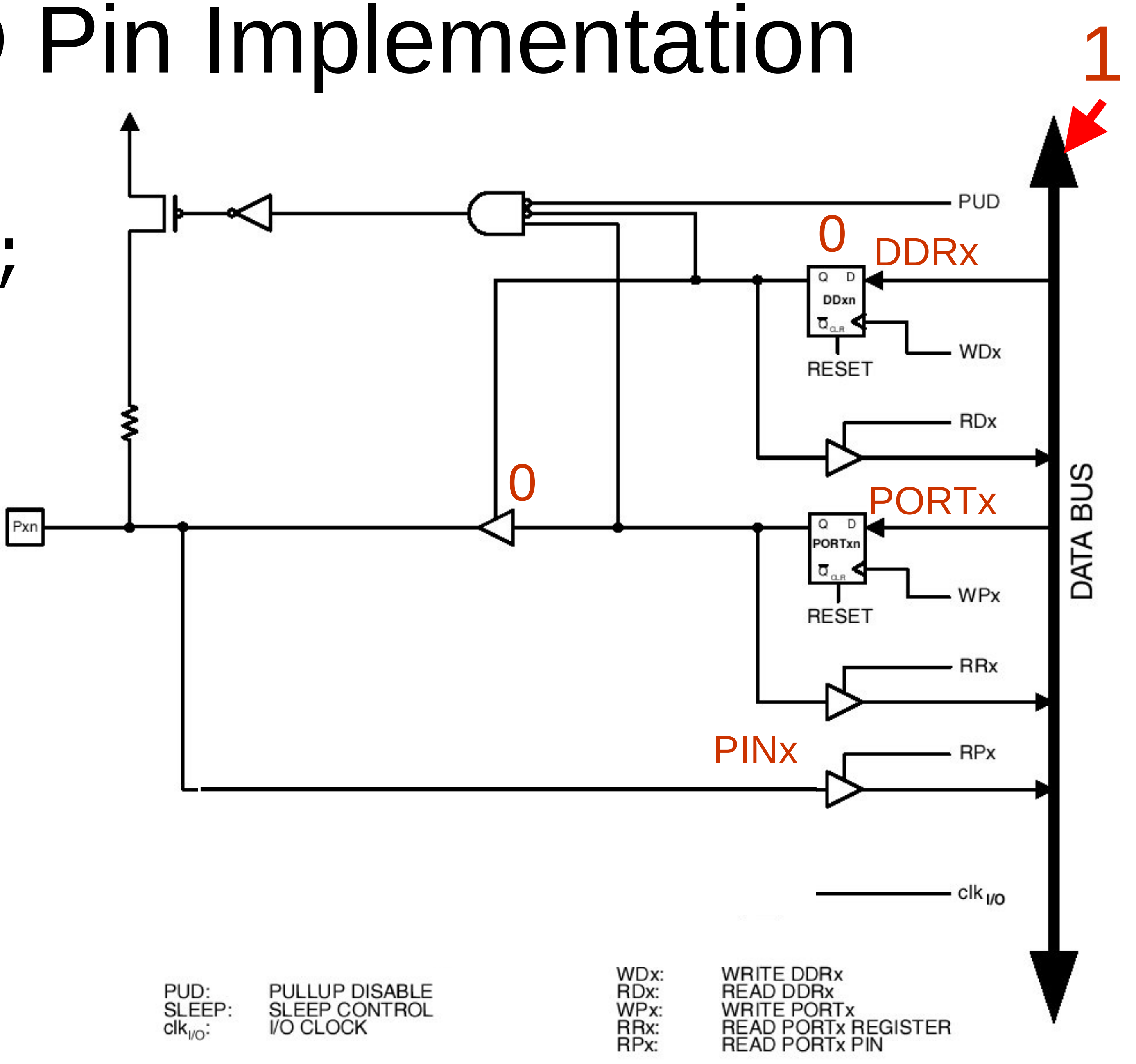
- “0” is written to the data bus
- This is input to the DDRB register
- WDB is clocked from high to low
- “0” is stored by flip-flop
- Which turns off the tri-state buffer

-> this is an input pin

I/O Pin Implementation

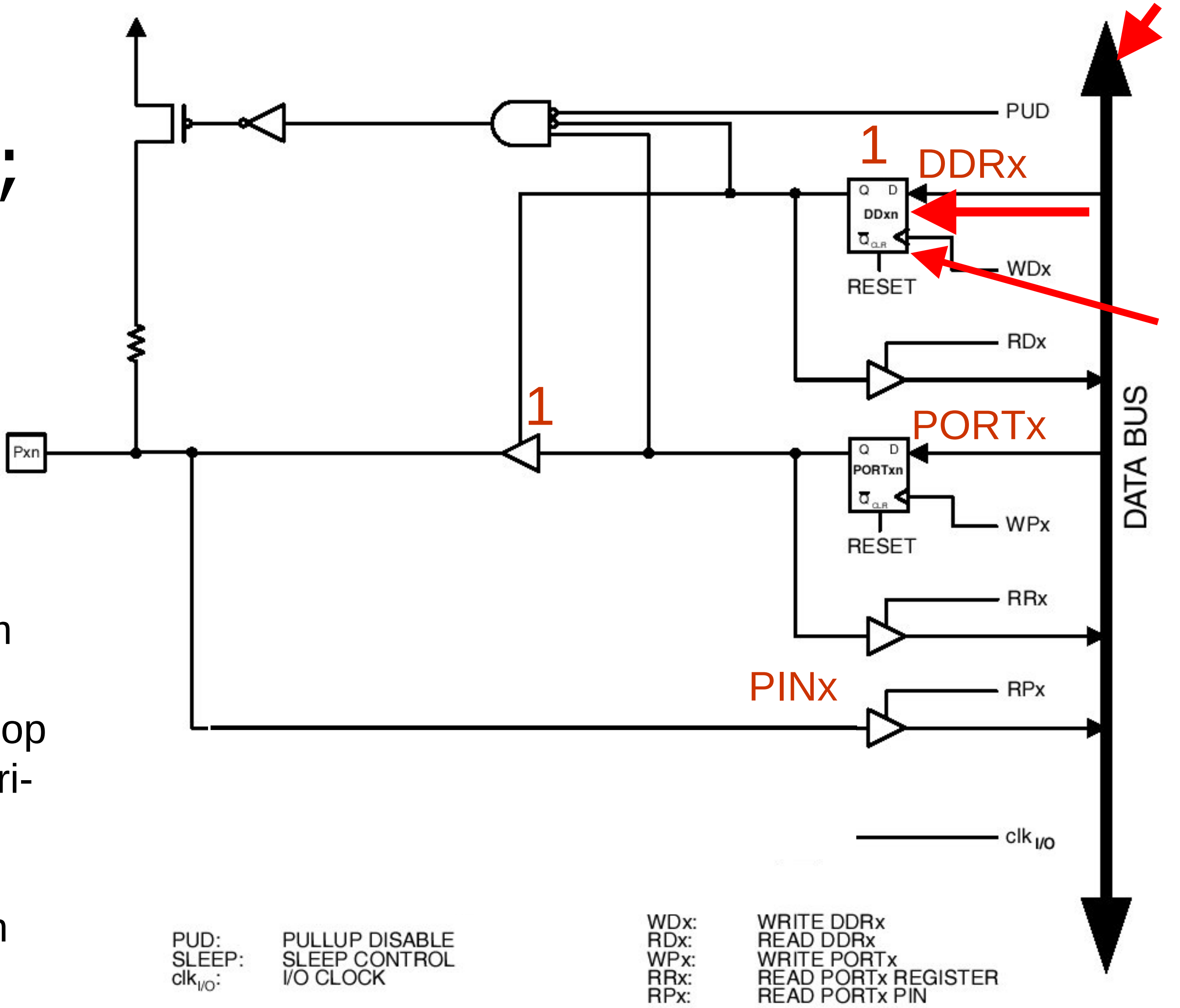
```
DDRB = 1;
```

- “1” is written to the data bus



I/O Pin Implementation

```
DDRB = 1;
```

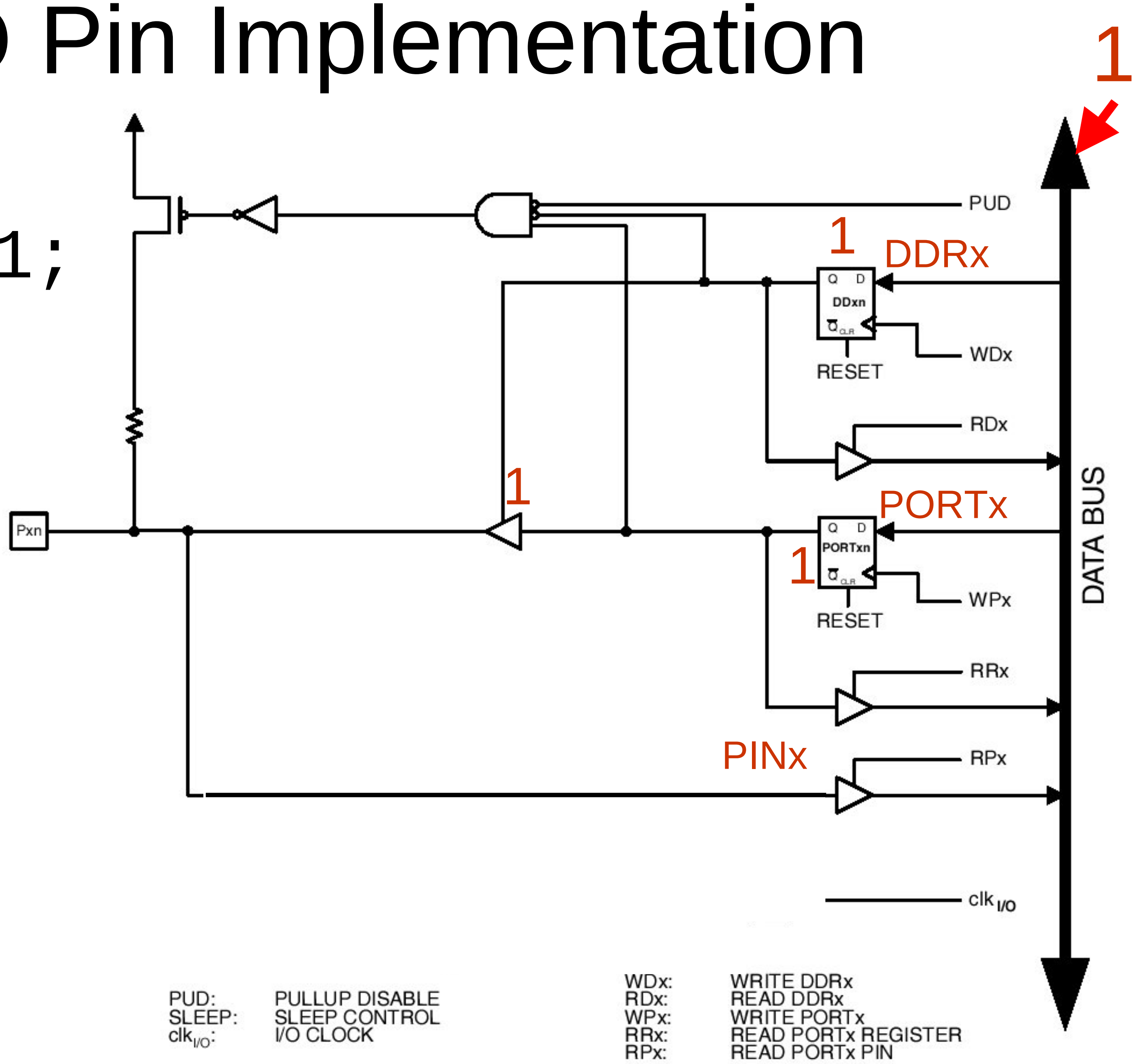


- “1” is written to the data bus
- This is input to the DDRB register
- WDB is clocked from high to low
- “1” is stored by flip-flop
- Which turns on the tri-state buffer

-> this is an output pin

I/O Pin Implementation

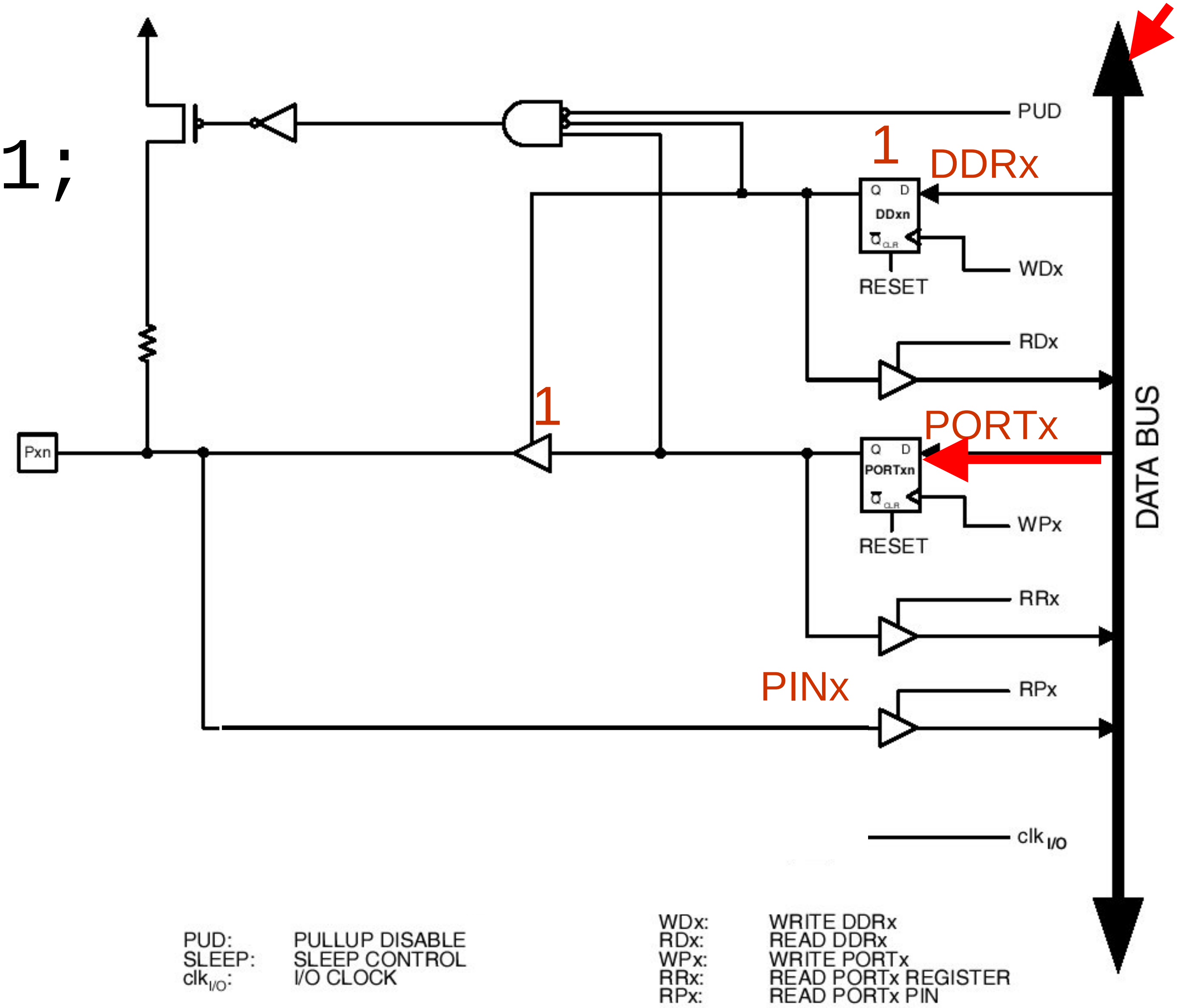
```
PORTB = 1;
```



I/O Pin Implementation

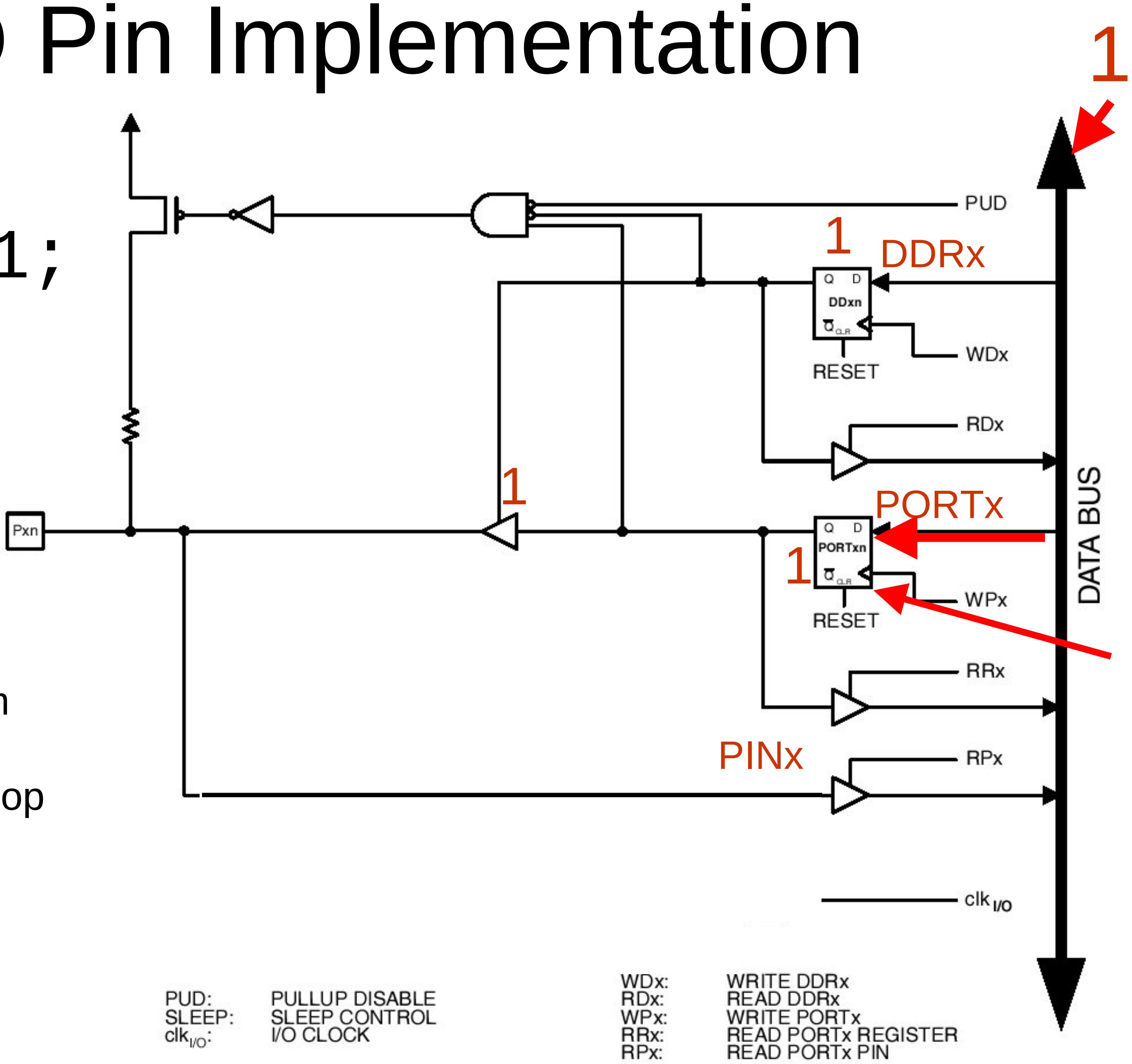
```
PORTB = 1;
```

- “1” is written to the data bus
- This is input to the PORTB register



I/O Pin Implementation

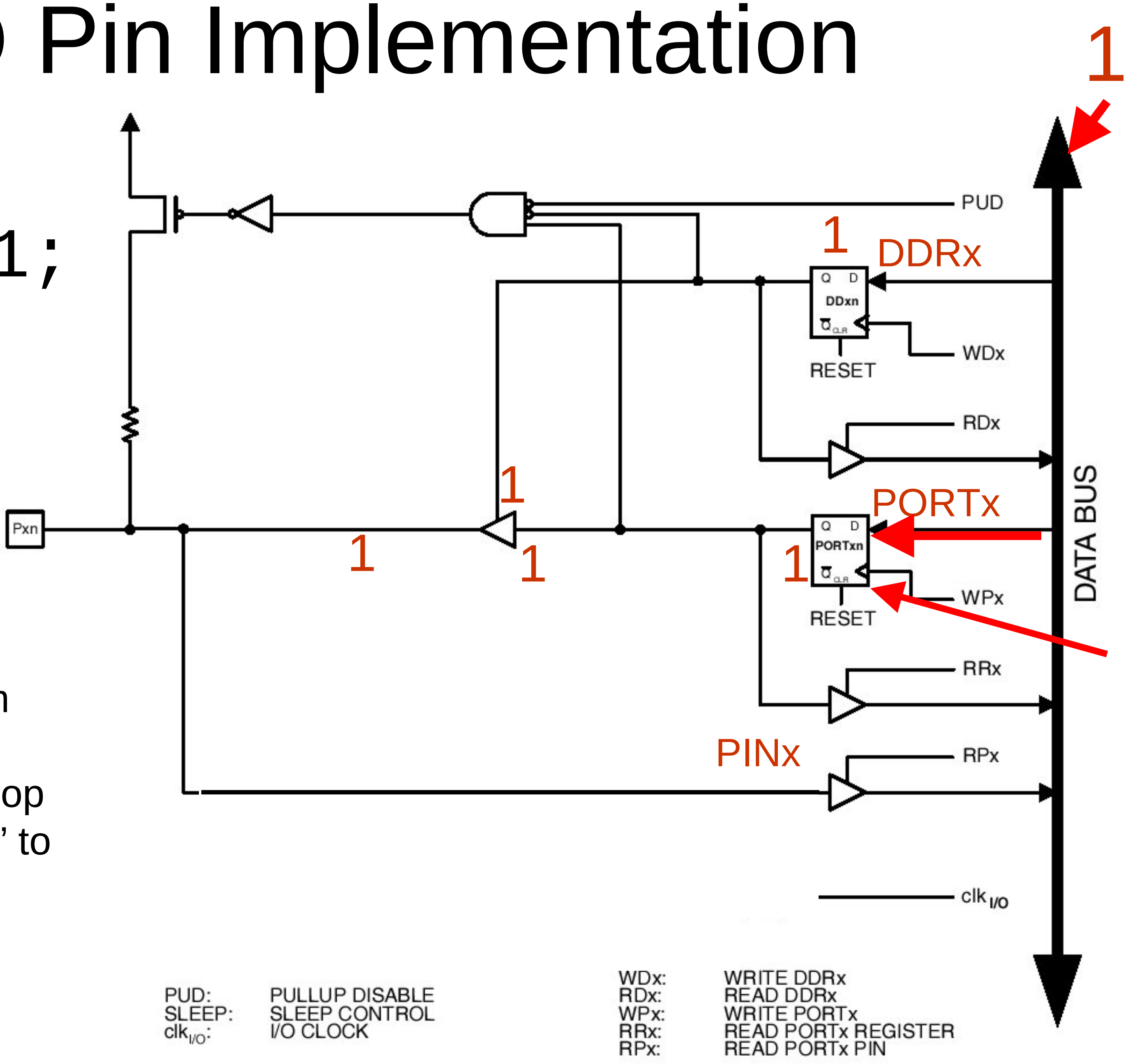
```
PORTB = 1;
```



- “1” is written to the data bus
- This is input to the PORTB register
- WPB is clocked from high to low
- “1” is stored by flip-flop

I/O Pin Implementation

```
PORTB = 1;
```



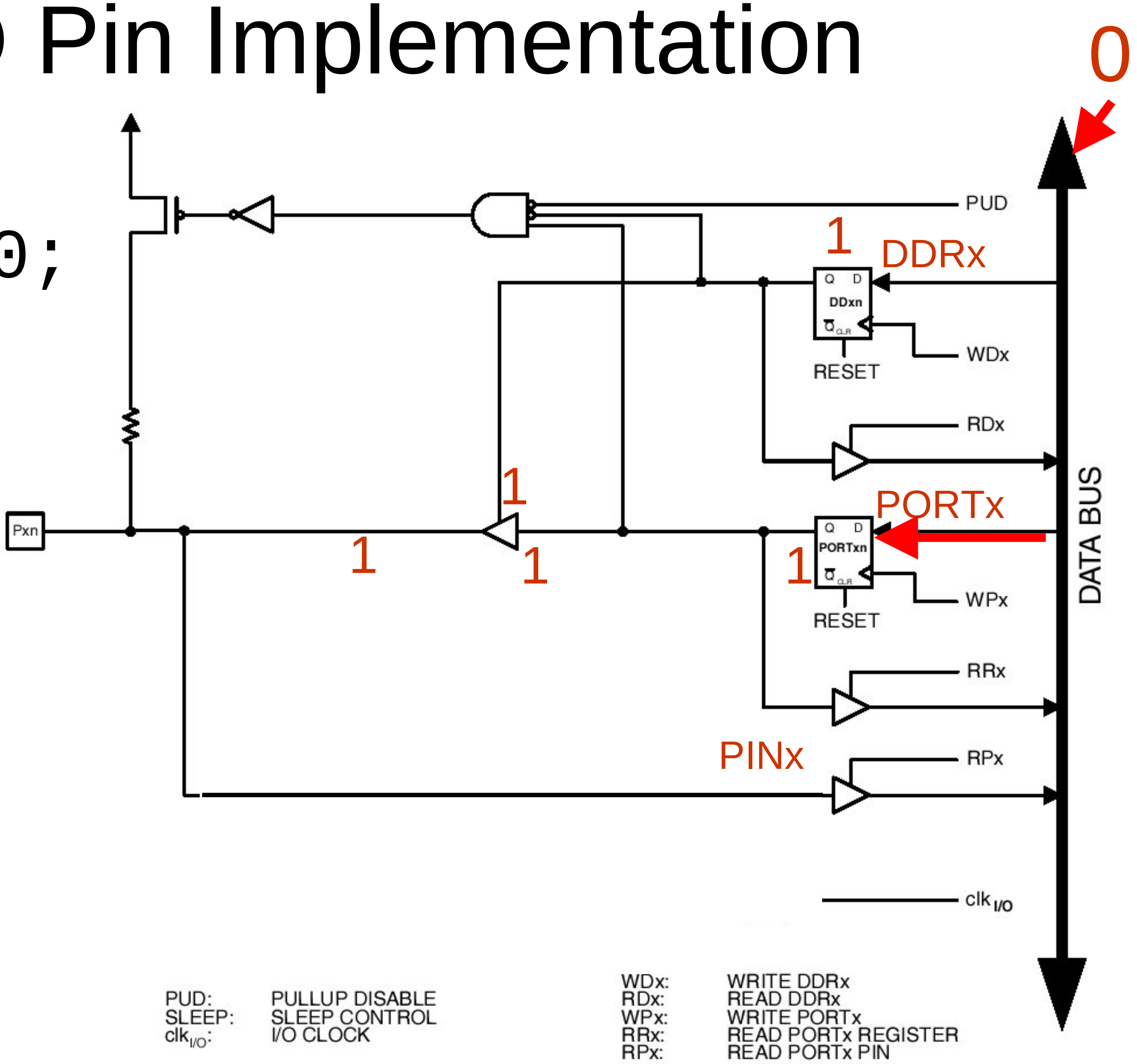
- “1” is written to the data bus
- This is input to the PORTB register
- WPB is clocked from high to low
- “1” is stored by flip-flop
- Which provides a “1” to the tri-state buffer

-> output a “1”

I/O Pin Implementation

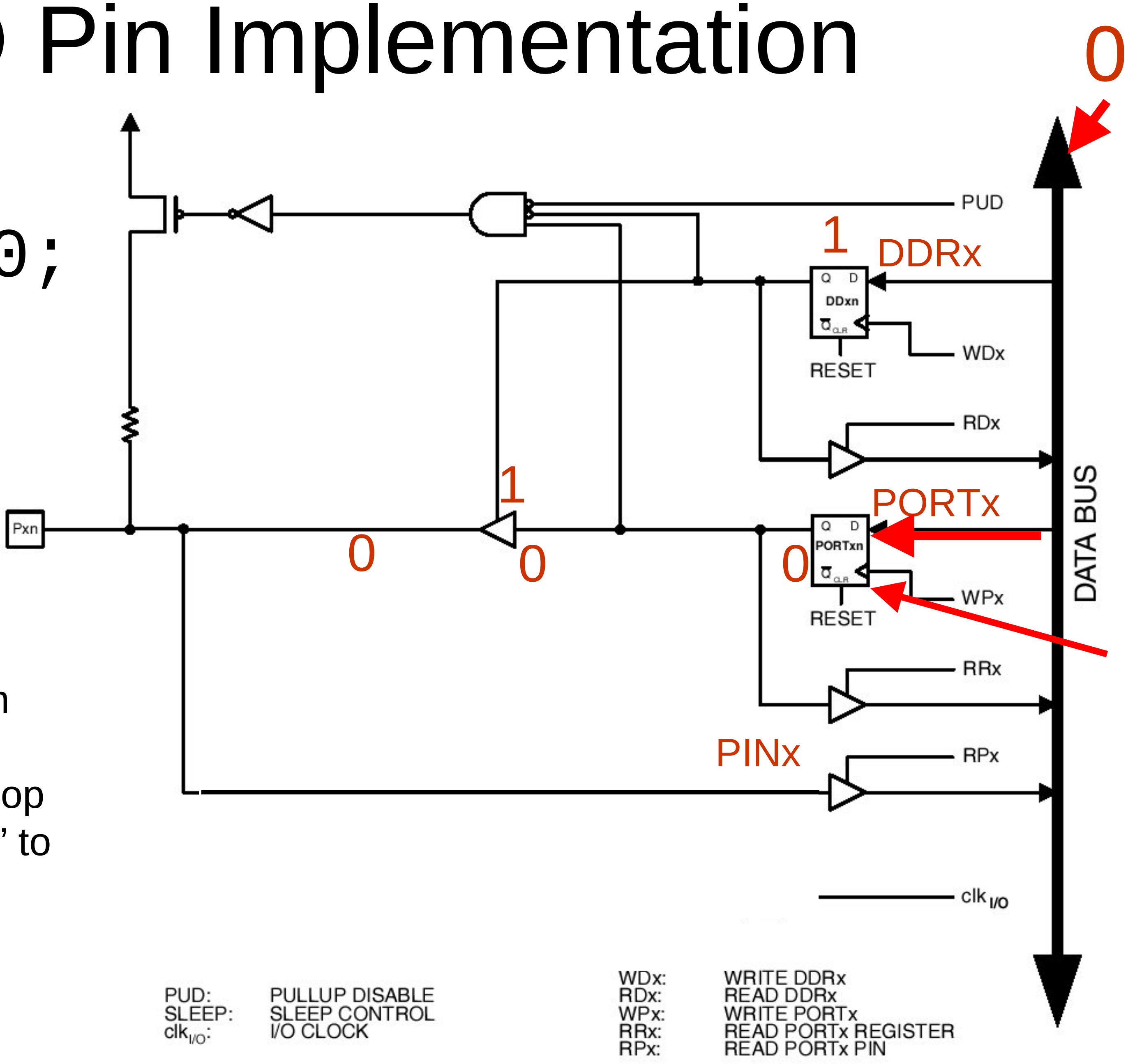
```
PORTB = 0;
```

- “0” is written to the data bus



I/O Pin Implementation

```
PORTB = 0;
```

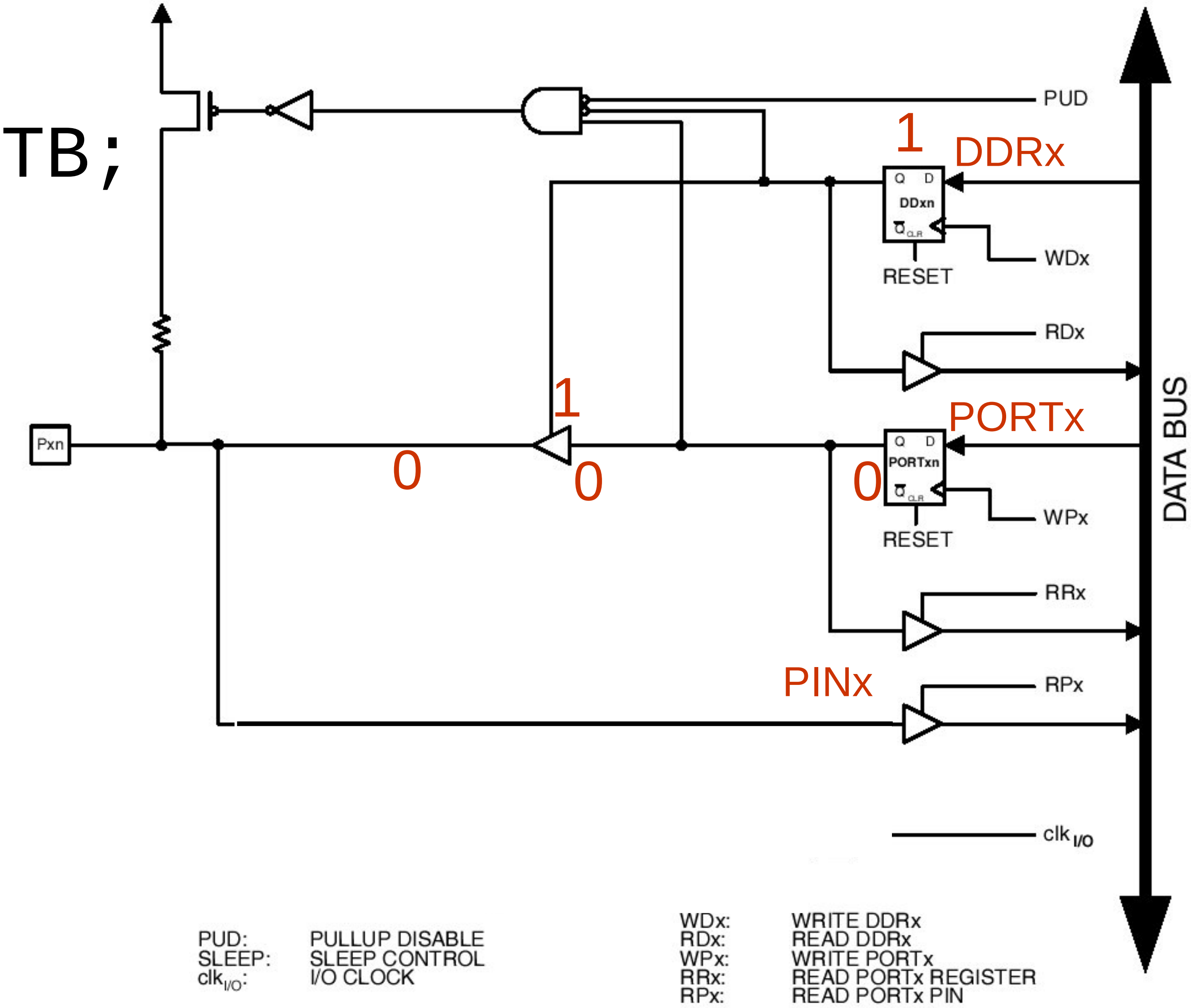


- “0” is written to the data bus
- This is input to the PORTB register
- WPB is clocked from high to low
- “0” is stored by flip-flop
- Which provides a “0” to the tri-state buffer

-> output a “0”

I/O Pin Implementation

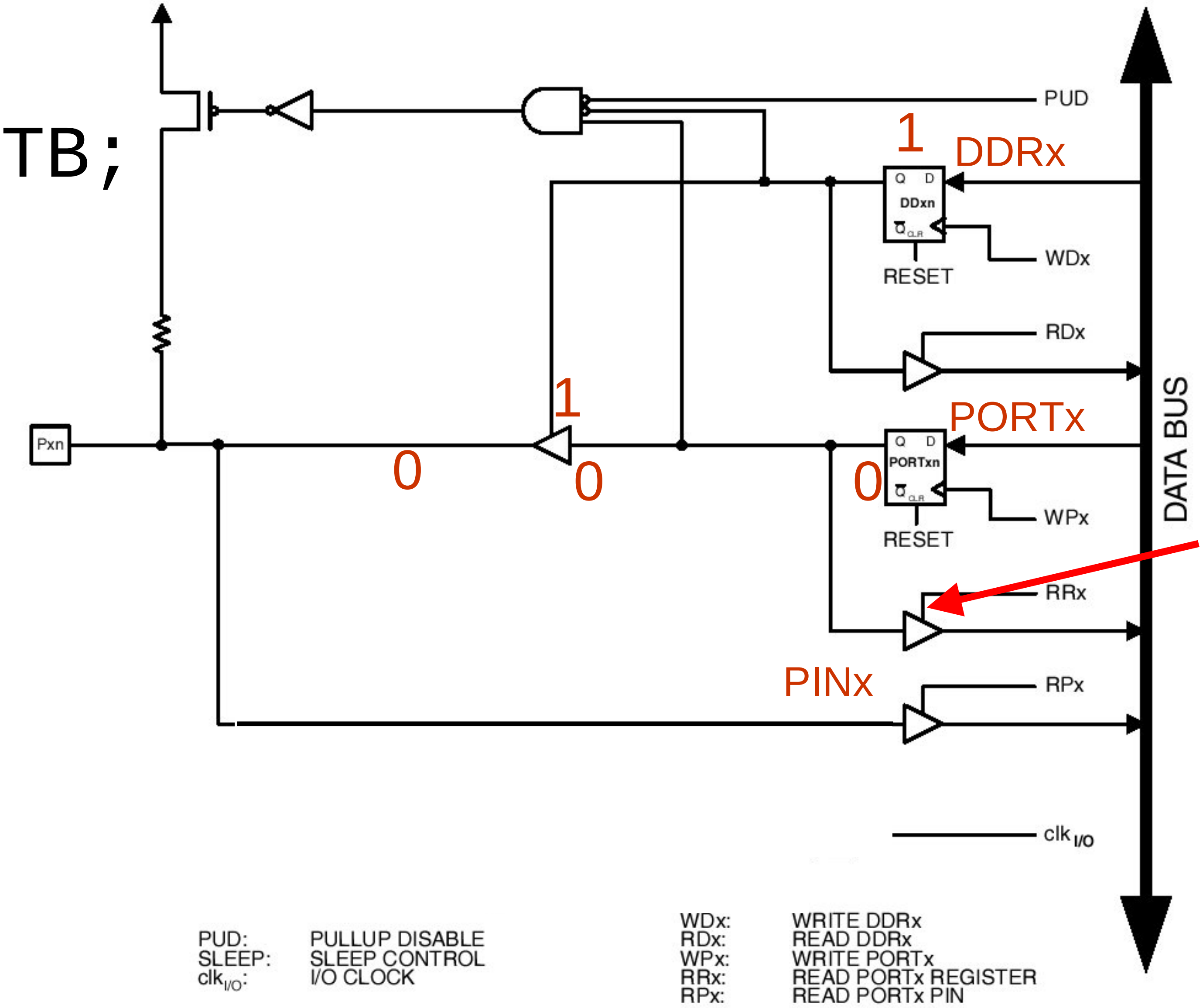
```
foo = PORTB;
```



I/O Pin Implementation

```
foo = PORTB;
```

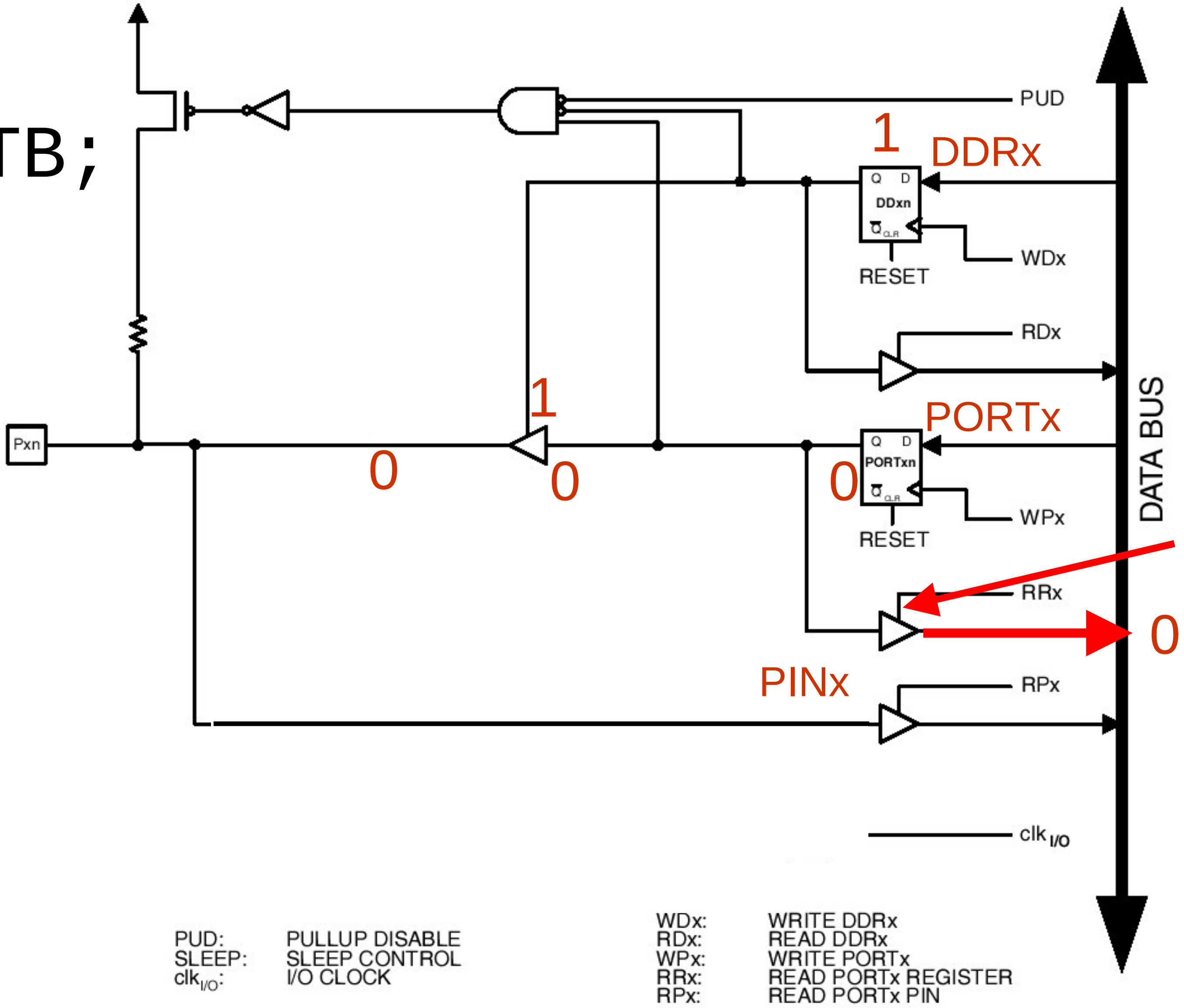
- RPB is set high



I/O Pin Implementation

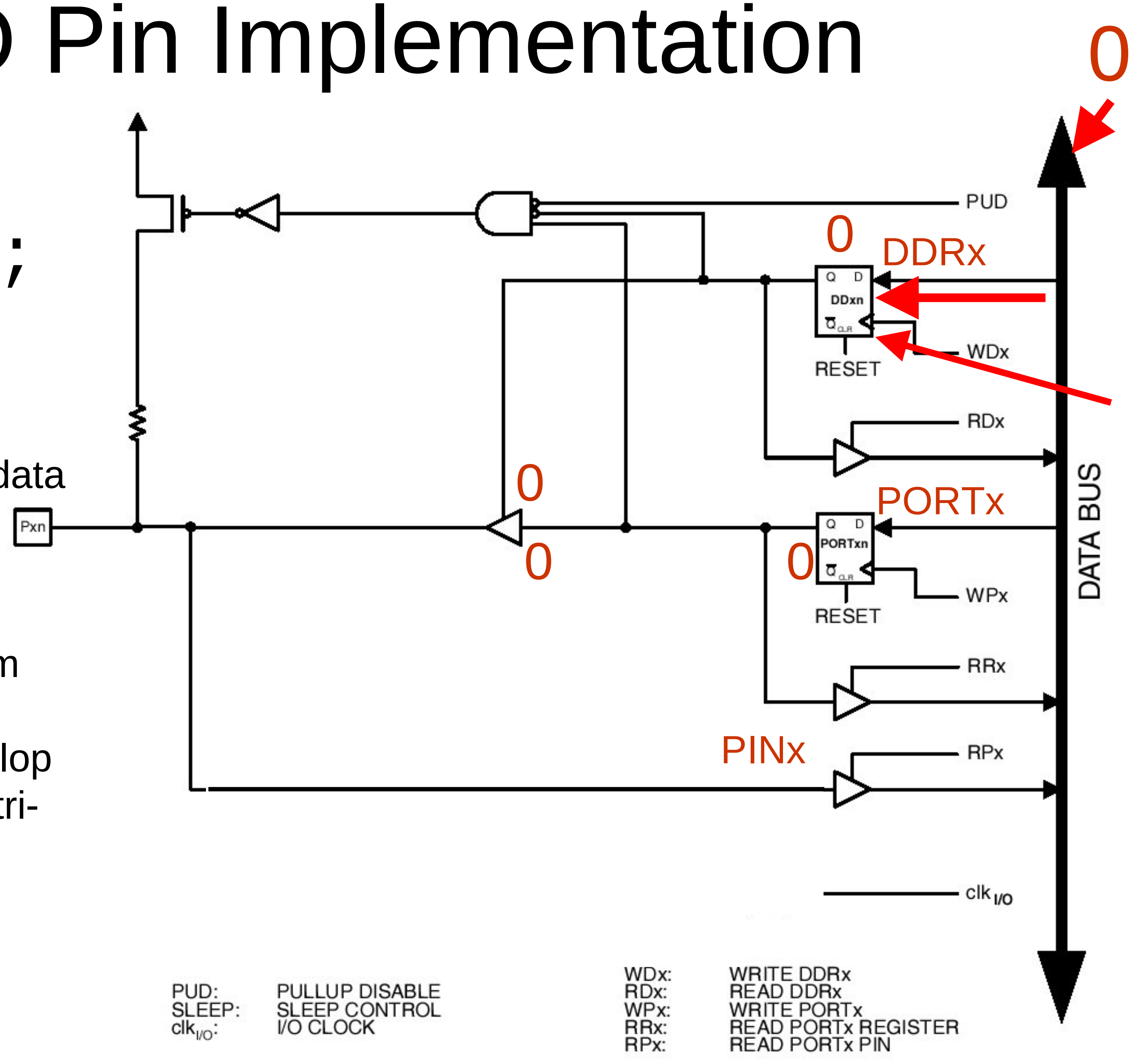
```
foo = PORTB;
```

- RPB is clocked from high to low
- “0” is written to the data bus



I/O Pin Implementation

```
DDRB = 0;
```

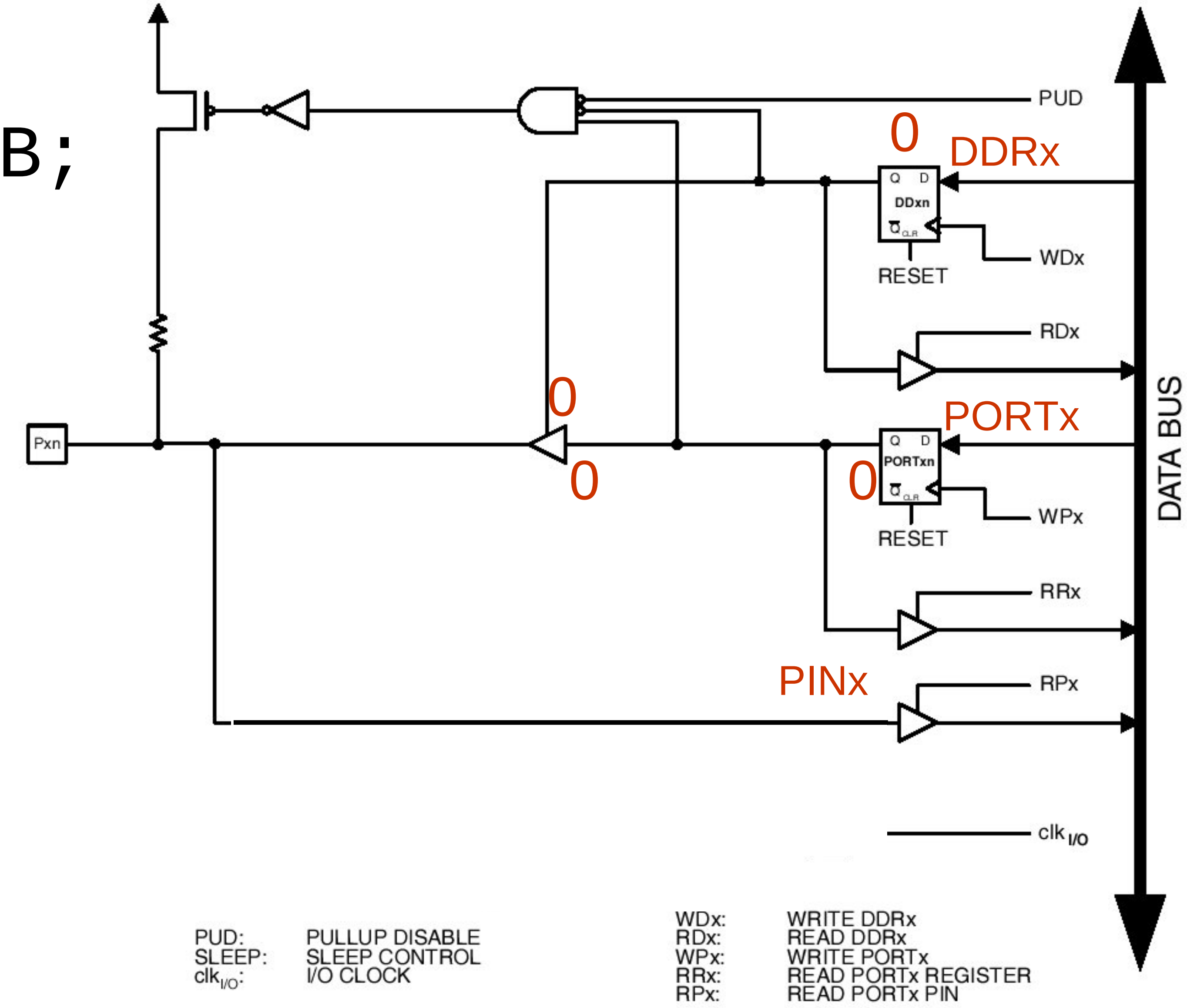


- “0” is written to the data bus
- This is input to the DDRB register
- WDB is clocked from high to low
- “0” is stored by flip-flop
- Which turns off the tri-state buffer

-> this is an input pin

I/O Pin Implementation

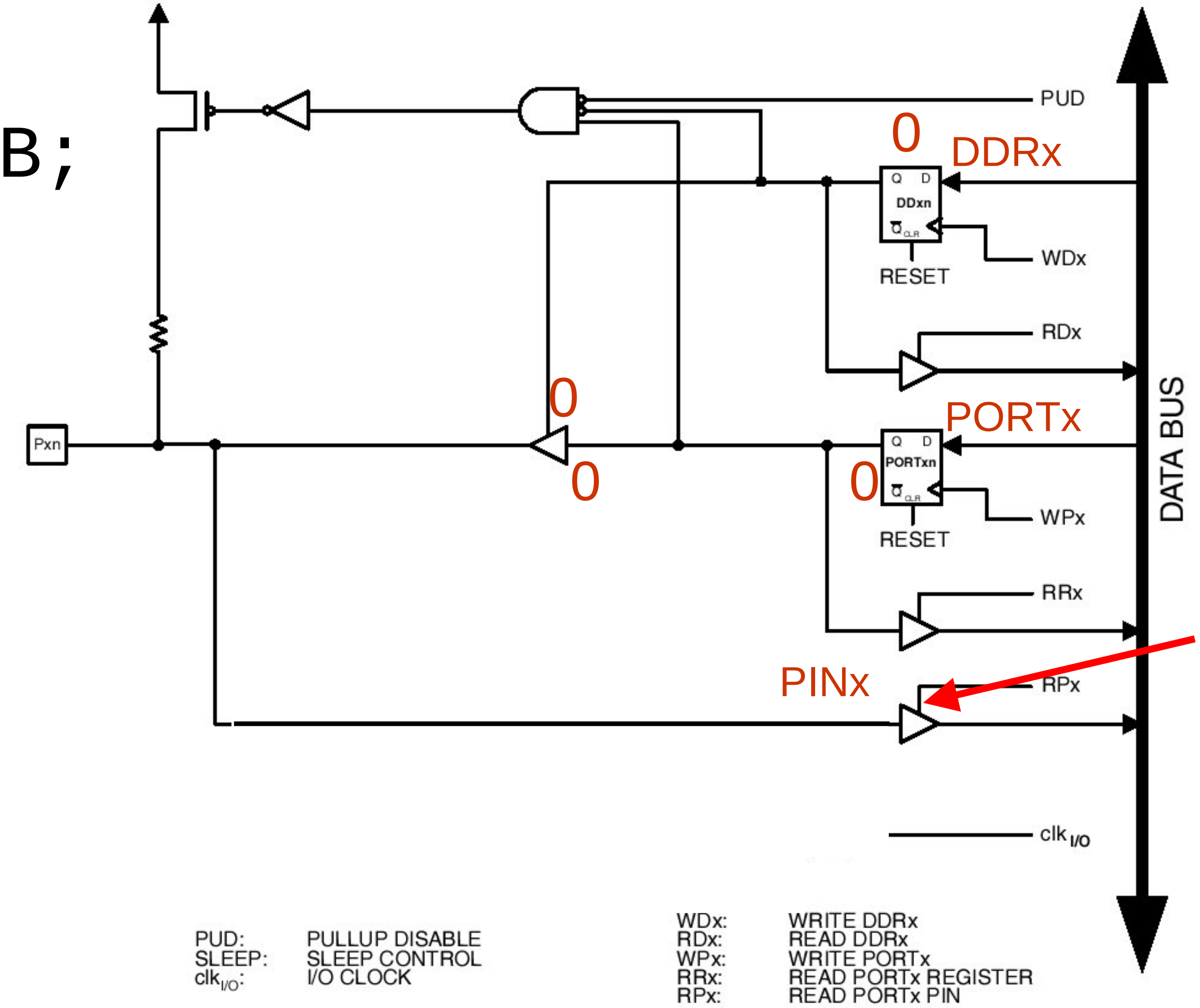
```
foo = PINB;
```



I/O Pin Implementation

```
foo = PINB;
```

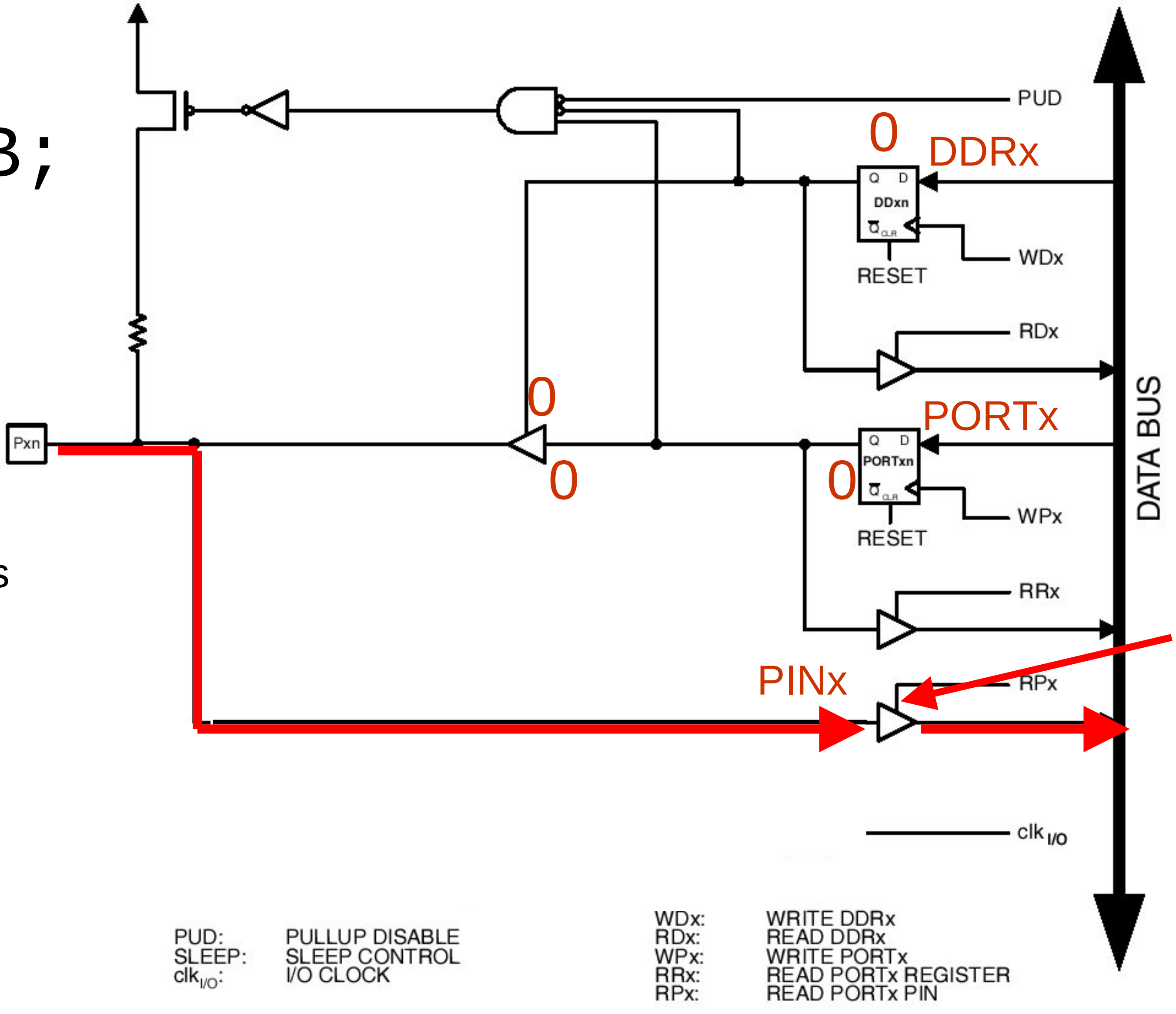
- RPB is set high



I/O Pin Implementation

`foo = PINB;`

- RPB is clocked from high to low
- The pin state is copied to the data bus



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

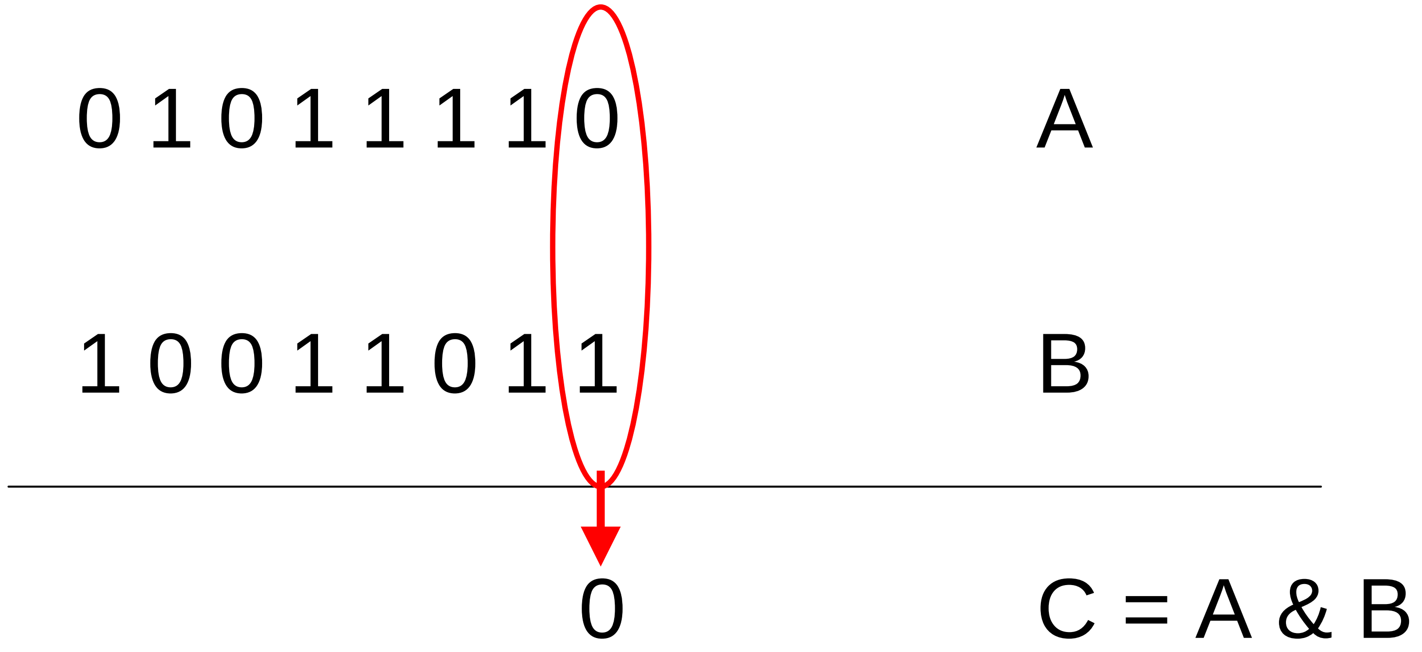
Bit-Wise Operators

0 1 0 1 1 1 1 0 A

1 0 0 1 1 0 1 1 B

C = A & B

Bit-Wise Operators

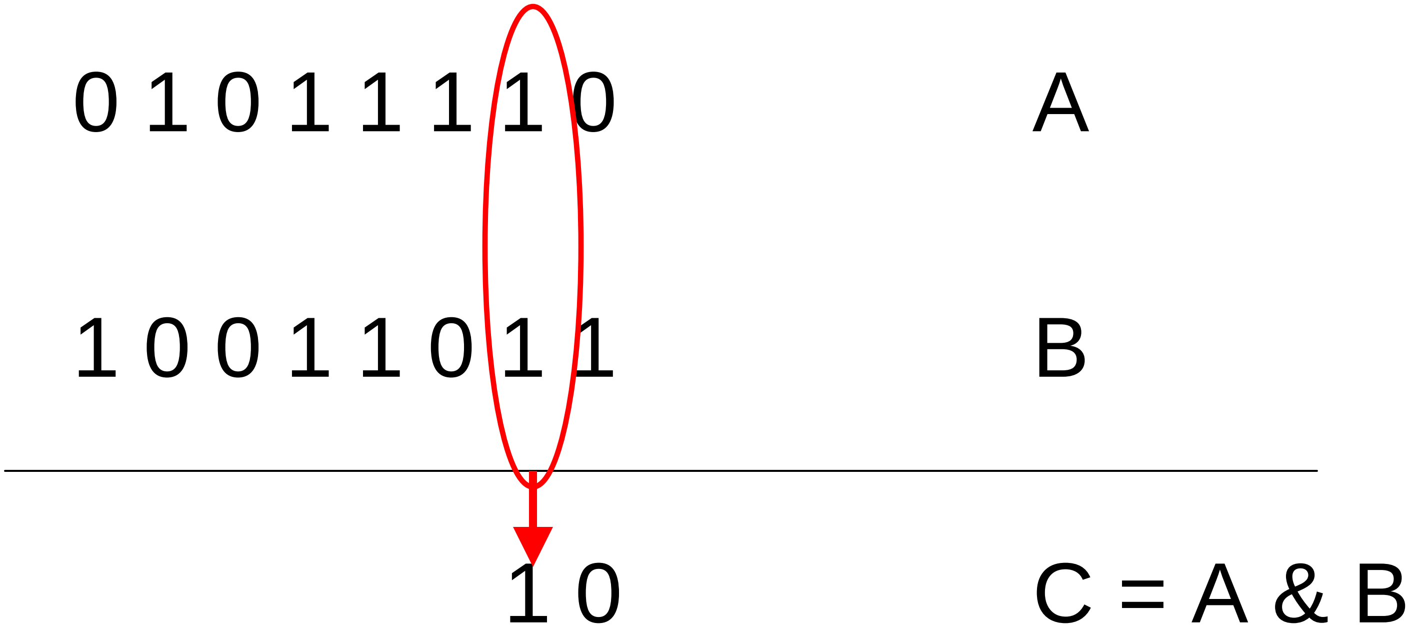


0 1 0 1 1 1 1 0 A

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?

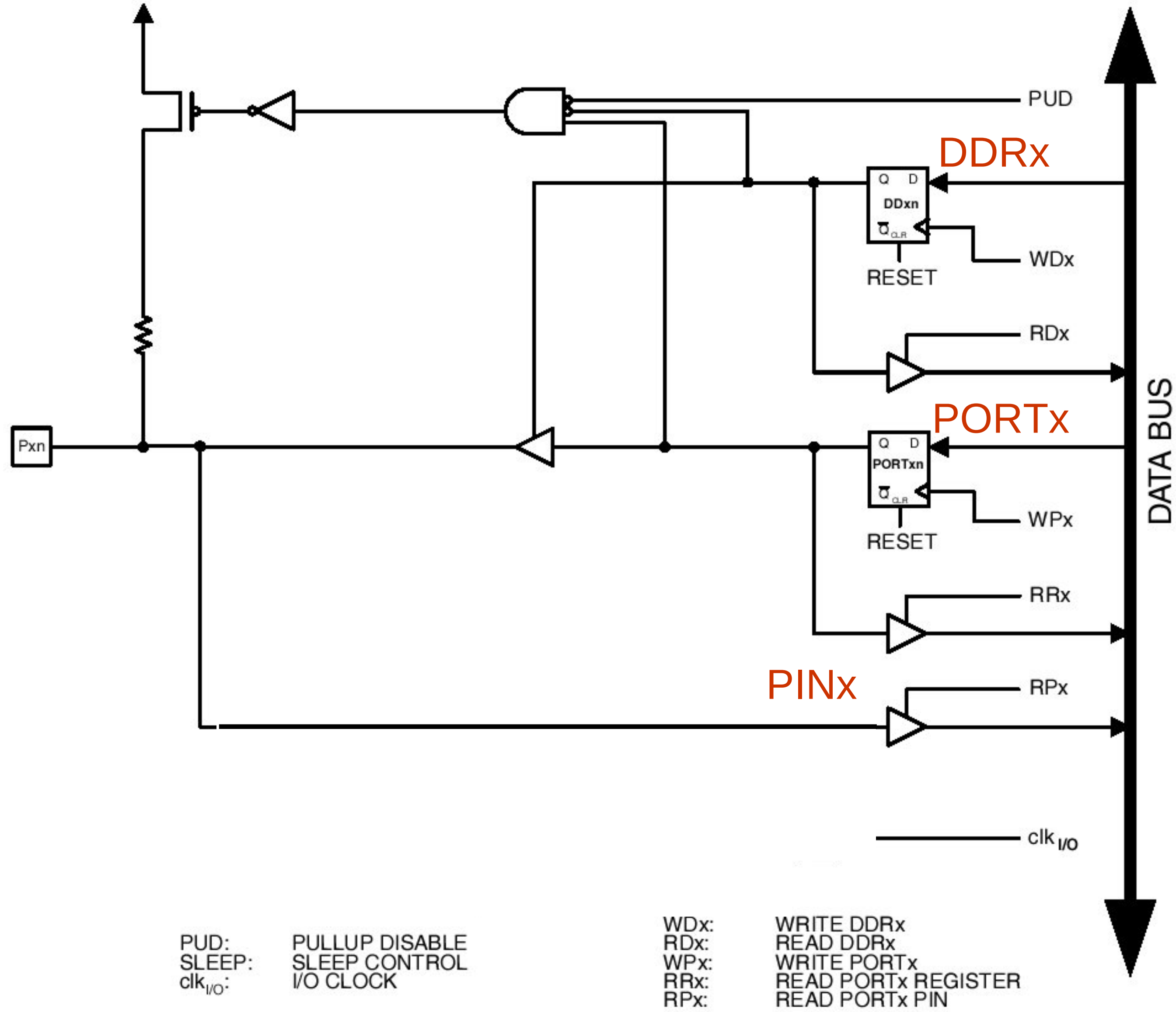
```
A = A & 0xFB;
```

or

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

I/O Pin Implementation

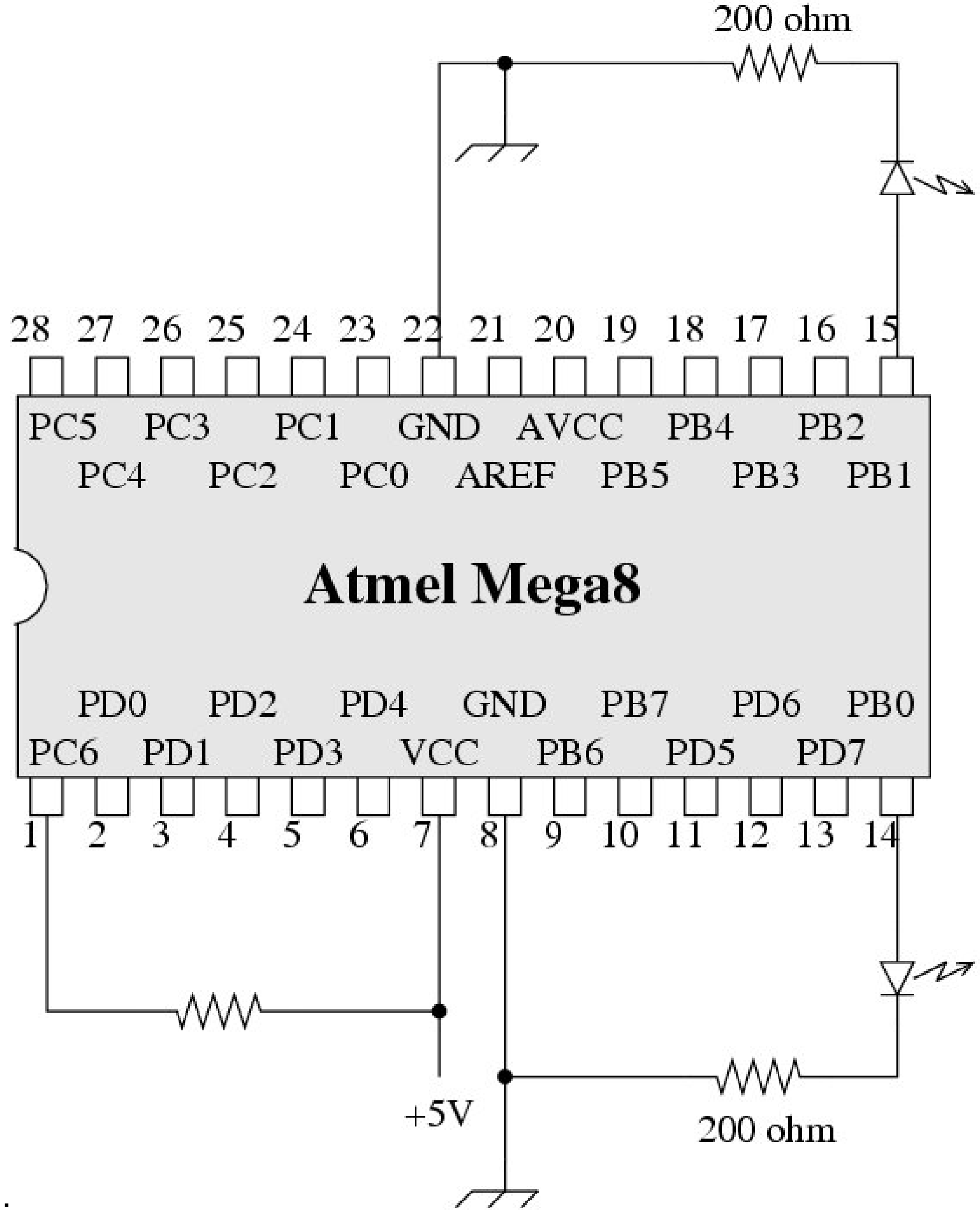
Single bit of
PORT B



A First Program

Flash the LEDs at a regular interval

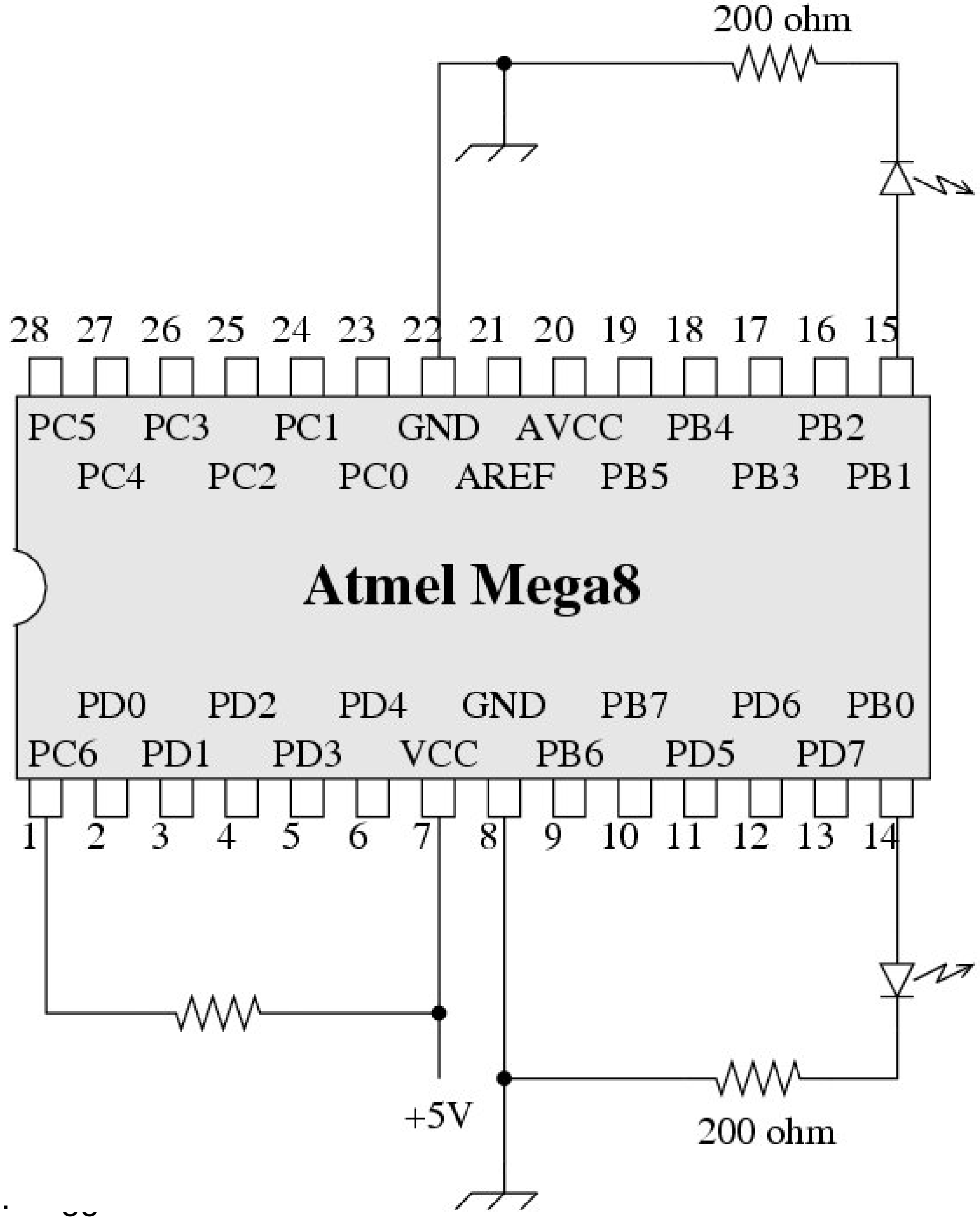
- How do we do this?



A First Program

How do we flash the LED at a regular interval?

- We toggle the state of PB0



A First Program

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

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

A Second Program

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

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

What does this program do?

A Second Program

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

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

Flashes LED on PB1 at 1 Hz
on PB0: 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 = (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 = PINB;

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

A Note About the C/Atmel Book

The book uses C syntax that looks like this:

```
PORTA.0 = 0;     // Set bit 0 to 0
```

This syntax is not available with our C compiler. Instead, you will need to use:

```
PORTA &= 0xFE;
```

or

```
PORTA &= ~1;
```

or

```
PORTA = PORTA & ~1;
```

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