

The CS150 Grimoire



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Chapter 1

Introduction

1.1 Welcome!

Welcome to Computer Organization and Architecture (CS150) at the University of Idaho. We are certainly happy to have you in this course. CS150 is a multidisciplinary course, so you will rub shoulders with aspiring mages from fields such as Computer Science, Computer Engineering, Electrical Engineering, and usually a few others. Regardless of your background, we are glad that you've chosen to enroll in the course and we hope that you will discover interesting ingredients and incantations to enhance your repertoire. The passages ahead are twisty and difficult, but there is nothing in the course that you can't accomplish if you "put your mind to it" as the saying goes. So remember to keep your toad spittle warm and your mandrake root dry and enjoy the semester!

Chapter 2

CS150 AVR Instruction Subset

2.1 Preliminaries

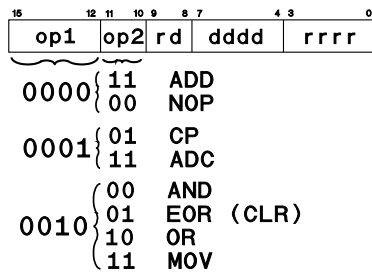
Although we study precepts that span all processors in this course, we apply these precepts to one processor in particular. That processor is the ATMEL ATmega328. The ATmega328 is a member of the AVR family of processors, and implements the AVR instruction set. The AVR instruction set is a set of instructions that are typically found on all processors in the AVR family.

The ATmega328 implements hundreds of instructions. In CS150 we only study (and use) a select subset of all instructions available on the ATmega328. This subset is referred to as the “CS150 AVR instruction subset” and is detailed in the remainder of this chapter. You are not required to understand or use any of the AVR instructions implemented by the ATmega328 that do not appear in the CS150 AVR instruction subset. Moreover, you are not permitted to use any of the AVR instructions available on the ATmega328 that do not appear in the CS150 AVR instruction subset. All work on assignments in this course must refer only to instructions contained within this subset.

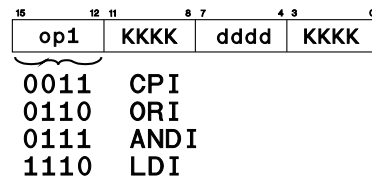
2.2 Instruction Encoding/Decoding Amulet

AVR Instruction Subset

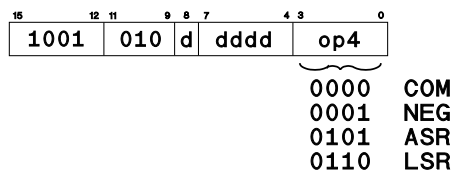
ALU Instructions



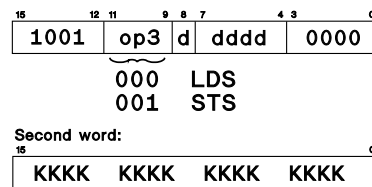
Immediate Instructions



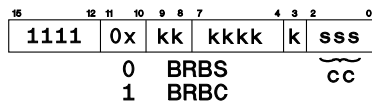
Unary Logical Instructions



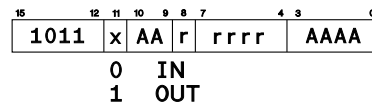
Load/Store Instructions



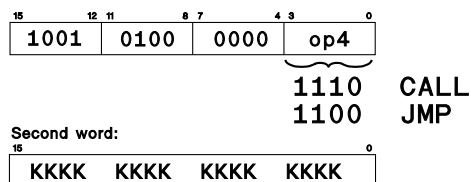
Branch Instructions



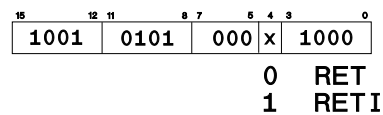
Input/Output Instructions



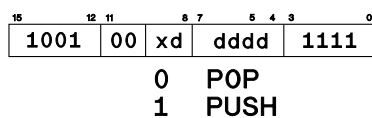
Call/Jump Instructions



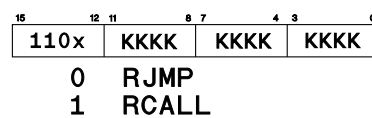
Return Instructions



Stack Instructions



Relative Jump Instructions



2.3 Instruction Legend

This section is a legend for understanding the instructions that appear in the remainder of this chapter. Each instruction is copied from the “ATMEL AVR Instruction Set Manual” reference which is on the course website, although there are minor modifications. The following terms and symbols are used in the narrative of these instructions:

2.3.1 SREG: The ATmega328 status register

- C: The carry flag
- Z: The zero flag
- N: The negative flag
- V: The overflow flag
- S: The sign flag
- H: The half-carry flag
- T: The transfer flag
- I: The interrupt flag

2.3.2 Registers and Operands

- Rd: Destination register in the Register File
- Rr: Source register in the Register File
- R: Result after instruction has been executed
- ALU_RESULT: Register inside the ALU where a result is temporarily stored
- K: Constant data
- k: Constant address
- A: I/O space address
- s: Part of a 3-bit field indexing a bit in the status register

2.3.3 Stack

STACK: Location used for storing return address and pushed registers

SP: Stack Pointer (address of top of stack)

2.3.4 Flags

?: Flag is affected by a given instruction

-: Flag is unaffected by a given instruction

1: Flag is always set by a given instruction

0: Flag is always cleared by a given instruction

2.3.5 Boolean Equations

\Leftarrow : Concurrent assignment

\bullet : Logical AND

$+$: Logical OR

\oplus : Logical XOR

\overline{X} : Logical NOT (complement) of X

2.4 The Instructions

The rest of this chapter covers all the ATmega328 instructions that are members of the “CS150 AVR Instruction Subset.” Each of these instructions is also contained in the “ATMEL AVR Instruction Set Manual” reference which is on the course website. It is advisable to avail yourself of both these resources when studying these instructions.

ADC: Add with carry

Description

Adds two registers and the contents of the C bit in the SREG and places the result in the destination register Rd.

Operation

$$Rd \leftarrow Rd + Rr + C$$

Syntax

ADC Rd,Rr

Operands

$$0 \leq d \leq 31, 0 \leq r \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

0001 11rd dddd rrrr

Status Register Usage

I T H S V N Z C
- - ? ? ? ? ? ?

$$H \leftarrow Rd3 \bullet Rr3 + Rr3 \bullet \overline{R3} + Rd3 \bullet \overline{R3}$$

Set if there was a carry from bit 3.

$$S \leftarrow N \oplus V, \text{ for signed tests}$$

$$V \leftarrow Rd7 \bullet Rr7 \bullet \overline{R7} + \overline{Rd7} \bullet \overline{Rr7} \bullet R7$$

Set if two's complement overflow resulted from the operation.

$$N \leftarrow R7$$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

$$C \leftarrow Rd7 \bullet Rr7 + Rr7 \bullet \overline{R7} + Rd7 \bullet \overline{R7}$$

Set if there was a carry from the MSB of the result.

Example

```
; add r1:r0 to r3:r2
add r2,r0 ; add the low byte
adc r3,r1 ; add with carry the high byte
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

ADD: Add without carry**Description**

Adds two registers and places the result in the destination register Rd.

Operation

$$Rd \leftarrow Rd + Rr$$
Syntax

ADD Rd,Rr

Operands

$$0 \leq d \leq 31, 0 \leq r \leq 31$$
Program Counter

$$PC \leftarrow PC + 1$$
Instruction Format

0000 11rd dddd rrrr

Status Register Usage

I T H S V N Z C
- - ? ? ? ? ? ?

$$H \leftarrow Rd3 \bullet Rr3 + Rr3 \bullet \overline{R3} + Rd3 \bullet \overline{R3}$$

Set if there was a carry from bit 3.

$$S \leftarrow N \oplus V, \text{ for signed tests}$$

$$V \leftarrow Rd7 \bullet Rr7 \bullet \overline{R7} + \overline{Rd7} \bullet \overline{Rr7} \bullet R7$$

Set if two's complement overflow resulted from the operation.

$$N \leftarrow R7$$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

$$C \leftarrow Rd7 \bullet Rr7 + Rr7 \bullet \overline{R7} + Rd7 \bullet \overline{R7}$$

Set if there was a carry from the MSB of the result.

Example

```
add r1,r2 ; add r2 to r1
add r28,r28 ; add r28 to itself (shift left r28 by one)
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

AND: Logical AND

Description

Computes the logical and of the contents of register **Rd** and register **Rr** and stores the result in register **Rd**.

Operation

$$Rd \leftarrow Rd \bullet Rr$$

Syntax

AND Rd,Rr

Operands

$$0 \leq d \leq 31, 0 \leq r \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

0010 00rd dddd rrrr

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	0	?	?	-

$S \leftarrow N \oplus V$, for signed tests

$V \leftarrow 0$

V is always cleared by this instruction.

$N \leftarrow R7$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

Example

```
and r2,r3 ; bitwise and r2 and r3, result in r2
ldi r16,1 ; load bitmask 0000 0001 into r16
and r2,r16 ; isolate bit 0 in r2
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

ANDI: Logical AND with Immediate

Description

Computes the logical and of the contents of register *Rd* and constant *K* and stores the result in register *Rd*.

Operation

$$Rd \leftarrow Rd \bullet K$$

Syntax

ANDI *Rd*,*K*

Operands

$$16 \leq d \leq 31, 0 \leq K \leq 255$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

0111 KKKK dddd KKKK

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	0	?	?	-

$S \leftarrow N \oplus V$, for signed tests

$V \leftarrow 0$

V is always cleared by this instruction.

$N \leftarrow R7$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

Example

```
andi r17,$0f ; clear upper nibble of r17
andi r18,$10 ; isolate bit 4 in r18
andi r19,$aa ; clear bits 0, 2, 4, and 6 in r19
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

ASR: Arithmetic Shift Right

Description

Shifts all bits in Rd one place to the right. Bit 7 of Rd is held constant. Bit 0 of Rd is loaded into the C flag of the $SREG$. This operation effectively divides a signed value by 2 without changing its sign. The C flag can be used to round the result.

Operation

$$C \leftarrow Rd[0] \leftarrow Rd[1] \leftarrow Rd[2] \leftarrow Rd[3] \leftarrow Rd[4] \leftarrow Rd[5] \leftarrow Rd[6] \leftarrow Rd[7]$$

Syntax

ASR Rd

Operands

$$0 \leq d \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

1001 010d dddd 0101

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	?	?	?	?

$S \leftarrow N \oplus V$, for signed tests

$V \leftarrow N \oplus C$ (for N and C *after* the shift)

$N \leftarrow R7$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

$C \leftarrow Rd0$

Set if the LSB of Rd was set before the shift.

Example

```
ldi r16,$10 ; load 16 into r16
asr r16      ; r16 = r16 / 2
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

BRBC: Branch if Bit is Clear

Description

Conditional relative branch predicated by a single bit in the status register (SREG). This instruction tests a single bit in SREG specified by the programmer. If the specified bit in the SREG is clear, this instruction branches to an instruction relative to the PC. If the specified bit in the SREG is set, no branch is taken. This instruction branches relative to the PC in either direction ($PC - 63 \leq \text{destination} \leq PC + 64$). The parameter k is the offset from the PC and is represented in two's complement form.

Operation

if $SREG[s] = 0$ then $PC \leftarrow PC + k$

Syntax

BRBC s, k

Operands

$0 \leq s \leq 7, -64 \leq k \leq 63$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

1111 01kk kkkk ksss

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```

cpi r20,0      ; does r20 contain the value 0?
brbc 1,IsFalse ; branch to IsFalse if the Z flag is clear
...
IsFalse: nop   ; branch destination

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 2 machine cycles to complete if the predicate is true, or 1 if the predicate is false.

BRBS: Branch if Bit is Set

Description

Conditional relative branch predicated by a single bit in the status register (SREG). This instruction tests a single bit in SREG specified by the programmer. If the specified bit in the SREG is set, this instruction branches to an instruction relative to the PC. If the specified bit in the SREG is clear, no branch is taken. This instruction branches relative to the PC in either direction ($PC - 63 \leq \text{destination} \leq PC + 64$). The parameter k is the offset from the PC and is represented in two's complement form.

Operation

if $SREG[s] = 1$ then $PC \leftarrow PC + k$

Syntax

BRBS s, k

Operands

$0 \leq s \leq 7, -64 \leq k \leq 63$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

1111 00kk kkkk ksss

Status Register Usage

I T H S V N Z C

- - - - -

This instruction does not modify any SREG bits.

Example

```

cpi r20,0      ; does r20 contain the value 0?
brbs 1,IsTrue ; branch to IsTrue if the Z flag is set
...
IsTrue: nop    ; branch destination

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 2 machine cycles to complete if the predicate is true, or 1 if the predicate is false.

CALL: Call to a Subroutine

Description

This instruction makes an unconditional absolute branch to a subroutine located anywhere within Program Memory. This instruction stores the return address (the address of the instruction immediately after the `CALL`) on the stack. After the return address is stored on the stack, this instruction decrements the stack pointer by 2 (uses a *post-decrement* scheme).

Operation

$PC \leftarrow k$

Syntax	Operands	Program Counter	Stack
<code>CALL k</code>	$0 \leq k \leq 32K$	$PC \leftarrow k$	$STACK \leftarrow PC$ $SP \leftarrow SP - 2$

Instruction Format

```
1001 010k kkkk 111k
kkkk kkkk kkkk kkkk
```

Status Register Usage

```
I T H S V N Z C
- - - - -
```

This instruction does not modify any SREG bits.

Example

```
ldi r16,$a5      ; load r16 with sanity value
call CheckSanity ; check for sanity
nop
...
CheckSanity:
  cpi r16,$a5      ; does r16 contain the value 0xa5?
  brbc 1,Insane   ; if it doesn't something is very wrong
  ret
  ...
Insane:
  rjmp Insane     ; stay right here cause we're loopy
```

Space/Time

This instruction is 2 instruction words (4 bytes) wide and takes 4 machine cycles to complete.

COM: One's Complement

Description

This instruction computes the one's complement of the value in Rd and stores the result in Rd.

Operation

$$Rd \leftarrow \$FF - Rd$$

Syntax

COM Rd

Operands

$$0 \leq d \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

1001 010d dddd 0000

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	0	?	?	1

$S \leftarrow N \oplus V$, for signed tests

$V \leftarrow 0$

V is always cleared by this instruction.

$N \leftarrow R7$

Set if MSB of the result is set.

$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$

Set if the result of the operation was 0.

$C \leftarrow 1$

C is always set by this instruction.

Example

```

    com r4          ; take one's complement of r4
    brbs 1,IsZero ; branch if result is zero
    ...
IsZero: nop       ; branch destination

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

CP: Compare Registers

Description

This instruction compares the values of registers **Rd** and **Rr**. The values in **Rd** and **Rr** are not modified by this instruction.

Operation

$ALU_Result \leftarrow Rd - Rr$

Syntax

CP Rd,Rr

Operands

$0 \leq d \leq 31, 0 \leq r \leq 31$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

0001 01rd dddd rrrr

Status Register Usage

I T H S V N Z C

- - ? ? ? ? ? ?

$$H \leftarrow \overline{Rd3} \bullet Rr3 + Rr3 \bullet R3 + R3 \bullet \overline{Rd3}$$

Set if there was a borrow from bit 3.

$$S \leftarrow N \oplus V, \text{ for signed tests}$$

$$V \leftarrow Rd7 \bullet Rr7 \bullet \overline{R7} + \overline{Rd7} \bullet \overline{Rr7} \bullet R7$$

Set if two's complement overflow resulted from the operation.

$$N \leftarrow R7$$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

$$C \leftarrow \overline{Rd7} \bullet Rr7 + Rr7 \bullet R7 + R7 \bullet \overline{Rd7}$$

Set if the absolute value of the contents of **Rr** is greater than the absolute value of the contents of **Rd**.

Example

```
cp r4,r19      ; compare r4 with r19
```

```
brbc 1,NotEqual ; branch if r4 != r19
```

```
...
```

```
NotEqual: nop      ; branch destination
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

CPI: Compare Register with Immediate

Description

This instruction compares the value of register Rd and a constant value. The value in Rd is not modified by this instruction.

Operation

$ALU_Result \leftarrow Rd - K$

Syntax

CPI Rd,K

Operands

$16 \leq d \leq 31, 0 \leq K \leq 255$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

0011 KKKK dddd KKKK

Status Register Usage

I T H S V N Z C

- - ? ? ? ? ? ?

$$H \leftarrow \overline{Rd3} \bullet K3 + K3 \bullet R3 + R3 \bullet \overline{Rd3}$$

Set if there was a borrow from bit 3.

$$S \leftarrow N \oplus V, \text{ for signed tests}$$

$$V \leftarrow Rd7 \bullet \overline{K7} \bullet \overline{R7} + \overline{Rd7} \bullet K7 \bullet R7$$

Set if two's complement overflow resulted from the operation.

$$N \leftarrow R7$$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

$$C \leftarrow \overline{Rd7} \bullet K7 + K7 \bullet R7 + R7 \bullet \overline{Rd7}$$

Set if the absolute value of the contents of K is greater than the absolute value of the contents of Rd.

Example

```
cpi r19,$CC ; compare r19 with 0xCC
```

```
brbs 1,Equal ; branch if r19 = 0xCC
```

```
...
```

```
Equal: nop ; branch destination
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

EOR: Exclusive OR

Description

This instruction computes the logical exclusive-or of register *Rd* and register *Rr* and places the result in the destination register *Rd*.

Operation

$$Rd \leftarrow Rd \oplus Rr$$

Syntax

EOR *Rd*,*Rr*

Operands

$$0 \leq d \leq 31, 0 \leq r \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

0010 01rd dddd rrrr

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	0	?	?	-

$$S \leftarrow N \oplus V, \text{ for signed tests}$$

$$V \leftarrow 0$$

V is always cleared by this instruction.

$$N \leftarrow R7$$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

Example

```
eor r4,r4    ; clear all bits in r4
eor r0,r22   ; bitwise xor of r0 and r22
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

IN: Load an I/O Location into a Register**Description**

This instruction loads the data at an address in I/O space into register Rd.

Operation

$Rd \leftarrow I/O(A)$

Syntax

IN Rd,A

Operands

$0 \leq d \leq 31, 0 \leq A \leq 63$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

1011 0AA d dddd AAAA

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```
in  r16,5      ; load value of PORTB into r16
cpi r16,$ff    ; check if all bits in r16 are set
brbs 1,AllSet ; branch if all bits are set in r16
...
AllSet: nop    ; branch destination
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

JMP: Jump

Description

This instruction makes an unconditional absolute branch to a location anywhere within Program Memory.

Operation

$PC \leftarrow k$

Syntax

JMP k

Operands

$0 \leq k \leq 32K$

Program Counter

$PC \leftarrow k$

Instruction Format

```
1001 0100 0000 1100
0kkk kkkk kkkk kkkk
```

Status Register Usage

```
I T H S V N Z C
- - - - -
```

This instruction does not modify any SREG bits.

Example

```
mov r1,r0 ; copy r0 into r1
jmp farplc ; unconditional branch
...
farplc: nop ; branch destination
```

Space/Time

This instruction is 2 instruction words (4 bytes) wide and takes 3 machine cycles to complete.

LDI: Load Immediate**Description**

This instruction loads an 8-bit constant into register Rd.

Operation

$Rd \leftarrow K$

Syntax

LDI Rd,K

Operands

$16 \leq d \leq 31, 0 \leq K \leq 255$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

1110 KKKK dddd KKKK

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```
ldi r31,$1f ; load 31 into r31
ldi r30,30  ; load 30 into r30
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

LDS: Load Direct from Data Space

Description

This instruction loads one byte from data space into register *Rd*. The data space consists of the register file, I/O memory, and internal SRAM.

Operation

$Rd \leftarrow (k)$

Syntax

LDS *Rd*,*k*

Operands

$0 \leq d \leq 31, 0 \leq k \leq 65535$

Program Counter

$PC \leftarrow PC + 2$

Instruction Format

```
1001 000d dddd 0000
kkkk kkkk kkkk kkkk
```

Status Register Usage

```
I T H S V N Z C
- - - - - - - -
```

This instruction does not modify any SREG bits.

Example

```
lds r22,$ff00 ; load r22 with contents of data space location $ff00
andi r22,$fe  ; clear bit 0 in r22
sts $ff00,r22 ; write modified data back to where it came from
```

Space/Time

This instruction is 2 instruction words (4 bytes) wide and takes 2 machine cycles to complete.

LSR: Logical Shift Right

Description

Shifts all bits in Rd one place to the right. Bit 7 of Rd is cleared. Bit 0 of Rd is loaded into the C flag of the **SREG**. This operation effectively divides an unsigned value by two. The C flag can be used to round the result.

Operation

$$C \leftarrow Rd[0] \leftarrow Rd[1] \leftarrow Rd[2] \leftarrow Rd[3] \leftarrow Rd[4] \leftarrow Rd[5] \leftarrow Rd[6] \leftarrow Rd[7] \leftarrow 0$$

Syntax

LSR Rd

Operands

$$0 \leq d \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

1001 010d dddd 0110

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	?	0	?	?

$S \leftarrow N \oplus V$, for signed tests

$V \leftarrow N \oplus C$ (for N and C *after* the shift)

$N \leftarrow 0$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

$C \leftarrow Rd0$

Set if the LSB of Rd was set before the shift.

Example

```

lsr r8           ; shift r8 right, putting bit 0 into the C flag
brbs 0,BitWasOne ; if bit 0 was a 1, branch to BitWasOne
...
BitWasOne: nop   ; branch destination

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

MOV: Move Value From Register

Description

This instruction moves the value in **Rr** into **Rd**. The value in **Rr** remains unchanged, while the destination register **Rd** is loaded with a copy of **Rr**.

Operation

$Rd \leftarrow Rr$

Syntax

MOV Rd,Rr

Operands

$0 \leq d \leq 31, 0 \leq r \leq 31$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

0010 11rd dddd rrrr

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any **SREG** bits.

Example

```
mov r16,r0 ; copy r0 into r16
call check ; call subroutine
...
check:
  cpi r16,$11 ; compare r16 to 17
  ...
  ret          ; return from subroutine
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

NEG: Two's Complement

Description

This instruction replaces the contents of register Rd with its two's complement; the value $\$80$ is left unchanged.

Operation

$$Rd \leftarrow \$00 - Rd$$

Syntax

NEG Rd

Operands

$$0 \leq d \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

1001 010d dddd 0001

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	?	?	?	?	?	?

$$H \leftarrow R3 + Rd3$$

Set if there was a borrow from bit 3.

$$S \leftarrow N \oplus V, \text{ for signed tests}$$

$$V \leftarrow R7 \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if there is a two's complement overflow from the implied subtraction from $\$00$.

A two's complement overflow will occur if and only if the result is $\$80$.

$$N \leftarrow R7$$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

$$C \leftarrow R7 + R6 + R5 + R4 + R3 + R2 + R1 + R0$$

Set if there is a borrow in the implied subtraction from $\$00$. The C flag will always be set unless the result is $\$00$.

Example

```
neg r19
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

NOP: No Operation**Description**

This instruction performs a single-cycle No Operation.

Operation

none

Syntax

NOP

Operands

none

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

0000 0000 0000 0000

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```

    call DelaySevenCycles
    ...
DelaySevenCycles:
    nop
    nop
    nop
    ret          ; return takes 4 cycles

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

OR: Logical OR

Description

Computes the bitwise logical OR of the contents of registers *Rd* and *Rr* and places the result in *Rd*.

Operation

$$Rd \leftarrow Rd \vee Rr$$

Syntax

OR *Rd*,*Rr*

Operands

$$0 \leq d \leq 31, 0 \leq r \leq 31$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

0010 10rd dddd rrrr

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	0	?	?	-

$S \leftarrow N \oplus V$, for signed tests

$V \leftarrow 0$

V is always cleared by this instruction.

$N \leftarrow R7$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

Example

```
or r16,r1 ; perform OR of r16 with r1
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

ORI: Logical OR with Immediate

Description

Computes the bitwise logical OR of the contents of register *Rd* and a constant and places the result in *Rd*.

Operation

$$Rd \leftarrow Rd \vee K$$

Syntax

ORI *Rd*,*K*

Operands

$$16 \leq d \leq 31, 0 \leq K \leq 255$$

Program Counter

$$PC \leftarrow PC + 1$$

Instruction Format

0110 KKKK dddd KKKK

Status Register Usage

I	T	H	S	V	N	Z	C
-	-	-	?	0	?	?	-

$S \leftarrow N \oplus V$, for signed tests

$V \leftarrow 0$

V is always cleared by this instruction.

$N \leftarrow R7$

Set if MSB of the result is set.

$$Z \leftarrow \overline{R7} \bullet \overline{R6} \bullet \overline{R5} \bullet \overline{R4} \bullet \overline{R3} \bullet \overline{R2} \bullet \overline{R1} \bullet \overline{R0}$$

Set if the result of the operation was 0.

Example

```
ori r16,$F0 ; set high nibble of r16
ori r17,1   ; set bit 0 of r17
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

OUT: Store Register Value to I/O Location**Description**

This instruction stores the value of register `Rr` into an address in I/O space.

Operation

$I/O(A) \leftarrow Rr$

Syntax

`OUT A,Rr`

Operands

$0 \leq r \leq 31, 0 \leq A \leq 63$

Program Counter

$PC \leftarrow PC + 1$

Instruction Format

1011 1AAr rrrr AAAA

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```
ldi r16,$08 ; load 0000 1000 into r16
out $05,r16 ; set PORTB pin 3 (PORTB[3])
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

POP: Pop Value from Stack into Register

Description

This instruction loads register *Rd* with a value from the stack. The stack pointer (*SP*) is incremented by 1 *before* the pop. The stack is not scrubbed as a result of this operation.

Operation

$Rd \leftarrow \text{STACK}(SP)$

Syntax	Operands	Program Counter	Stack
POP <i>Rd</i>	$0 \leq d \leq 31$	$PC \leftarrow PC + 1$	$SP \leftarrow SP + 1$

Instruction Format

1001 000d dddd 1111

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```

    call MyFunction
    ...
MyFunction:
    push r31 ; save r31
    push r30 ; save r30

    ...      ; more work here...

    pop r30  ; restore r30
    pop r31  ; restore r31
    ret

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

PUSH: Push Register Value onto Stack

Description

This instruction stores the value of register **Rr** on the stack. The stack pointer (**SP**) is decremented by 1 *after* the push. The value in register **Rr** is not affected by this instruction.

Operation

STACK(SP) \leftarrow Rr

Syntax	Operands	Program Counter	Stack
PUSH Rr	$0 \leq r \leq 31$	PC \leftarrow PC + 1	SP \leftarrow SP - 1

Instruction Format

1001 001r rrrr 1111

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```

    call MyFunction
    ...
MyFunction:
    push r31 ; save r31
    push r30 ; save r30

    ...      ; more work here...

    pop r30 ; restore r30
    pop r31 ; restore r31
    ret

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 1 machine cycle to complete.

RCALL: Relative Call to Subroutine

Description

This instruction makes a relative call to an address within $PC - 2K + 1$ and $PC + 2K$ instruction words. The address of the instruction after the **RCALL** is stored onto the stack as the return address. The stack pointer (**SP**) is decremented by two bytes (one instruction word) *after* the return address is stored.

Operation

$PC \leftarrow PC + k$

Syntax	Operands	Program Counter	Stack
RCALL k	$-2K \leq k \leq K$	$PC \leftarrow PC + 1$	$STACK \leftarrow PC$ $SP \leftarrow SP - 2$
.			

Instruction Format

1101 kkkk kkkk kkkk

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any **SREG** bits.

Example

```

rcall MyFunction
...
MyFunction:
push r31 ; save r31
push r30 ; save r30

...      ; more work here...

pop r30 ; restore r30
pop r31 ; restore r31
ret

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 3 machine cycles to complete.

RET: Return from Subroutine

Description

This instruction actualizes a return from a subroutine. The return address is loaded from the stack. The stack pointer (SP) is incremented by two bytes (one instruction word) *before* the return address is retrieved from the stack.

Operation

$PC \leftarrow \text{STACK}(SP)$

Syntax

RET

Operands

This instruction has no operands

Stack

$SP \leftarrow SP + 2$

Instruction Format

1001 0101 0000 1000

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```

    rcall MyFunction
    ...
MyFunction:
    push r31 ; save r31
    push r30 ; save r30

    ...      ; more work here...

    pop r30 ; restore r30
    pop r31 ; restore r31
    ret

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 4 machine cycles to complete.

RETI: Return from Interrupt

Description

This instruction actualizes a return from an interrupt. The return address is loaded from the stack. The stack pointer (SP) is incremented by two bytes (one instruction word) *before* the return address is retrieved from the stack. This instruction sets the Global Interrupt flag in SREG to permit further interrupts.

Operation

$PC \leftarrow \text{STACK}(SP)$

Syntax

RETI

Operands

This instruction has no operands

Stack

$SP \leftarrow SP + 2$

Instruction Format

1001 0101 0001 1000

Status Register Usage

I	T	H	S	V	N	Z	C
1	-	-	-	-	-	-	-

$I \leftarrow 1$

I is always set by this instruction.

Example

```
ISR_0:
    push r0 ; save r0

    ...    ; more work here...

    pop r0 ; restore r0
    reti
```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 4 machine cycles to complete.

RJMP: Relative Jump

Description

This instruction makes an unconditional absolute branch to a location within PC - 2K + 1 and PC + 2K instruction words in Program Memory.

Operation

$PC \leftarrow PC + k$

Syntax

RJMP k

Operands

$-2K \leq k \leq 2K$

Program Counter

$PC \leftarrow PC + k$

Instruction Format

1100 kkkk kkkk kkkk

Status Register Usage

I T H S V N Z C
- - - - -

This instruction does not modify any SREG bits.

Example

```

    cpi r16,$42 ; compare r16 to 66
    brbs 1,error ; if not equal, error
    rjmp ok
error:
    add r16,r17
    inc r16
ok: nop

```

Space/Time

This instruction is 1 instruction word (2 bytes) wide and takes 2 machine cycles to complete.

STS: Store Direct to Data Space

Description

This instruction stores one byte from register `Rr` into data space. The data space consists of the register file, I/O memory, and internal SRAM.

Operation

$(k) \leftarrow Rr$

Syntax

STS `k, Rr`

Operands

$0 \leq r \leq 31, 0 \leq k \leq 65535$

Program Counter

$PC \leftarrow PC + 2$

Instruction Format

```
1001 001r rrrr 0000
kkkk kkkk kkkk kkkk
```

Status Register Usage

```
I T H S V N Z C
- - - - -
```

This instruction does not modify any SREG bits.

Example

```
lds r22,$ff00 ; load r22 with contents of data space location $ff00
andi r22,$fe  ; clear bit 0 in r22
sts $ff00,r22 ; write modified data back to where it came from
```

Space/Time

This instruction is 2 instruction words (4 bytes) wide and takes 2 machine cycles to complete.

Chapter 3

ATmega328 Ports

The AVR family of processors contains a set of 8-bit *ports*. These ports are essentially pins that are tied to 8-bit registers, and are used to communicate with the world outside the processor. Ports on AVR processors are reconfigurable and are mapped into data memory. Ports must be configured before they are used. Figure 3.1 shows the ports on the ATmega328 and the addresses to which they are mapped.

I/O Space Address	Data Space Address	Register Name
0x0B	0x2B	PORTD
0x0A	0x2A	DDRD
0x09	0x29	PIND
0x08	0x28	PORTC
0x07	0x27	DDRC
0x06	0x26	PINC
0x05	0x25	PORTB
0x04	0x24	DDRB
0x03	0x23	PINB

Figure 3.1: Memory-Mapped ATmega328 Ports

Individual pins associated with a given port can be configured to be either an input or an output at any given time. The role of an individual pin (or all of the pins) associated with a given port can be changed at runtime. Figure 3.2 shows assembly language code for configuring pin 2 of PORTD (or PORTD[2]) as an input. This sample code configures the data direction of PORTD[2] without changing the data direction associated with any of the other pins. This sample uses data space

instructions (`lds` and `sts`), and therefore must use the “Data Space Address” of DDRD as depicted in Figure 3.1 in order to configure the data direction of PORTD pin 2.

```
.equ _ddrd = $2a

lds r24,_ddrd ; load r24 with DDRD
andi r24,$fb ; clear Pin 2 (to make it an input)
sts _ddrd,r24 ; write back to DDRD
```

Figure 3.2: Configuring PORTD Pin 2 as Input