

to the use of load and store instructions when communicating between memory and CPU. All other instructions are executed within the registers of the CPU without referring to memory. A program for a RISC-type CPU consists of LOAD and STORE instructions that have one memory and one register address, and computational-type instructions that have three addresses with all three specifying processor registers. The following is a program to evaluate $X = (A + B) * (C + D)$.

LOAD	R1, A	$R1 \leftarrow M[A]$
LOAD	R2, B	$R2 \leftarrow M[B]$
LOAD	R3, C	$R3 \leftarrow M[C]$
LOAD	R4, D	$R4 \leftarrow M[D]$
ADD	R1, R1, R2	$R1 \leftarrow R1 + R2$
ADD	R3, R3, R2	$R3 \leftarrow R3 + R4$
MUL	R1, R1, R3	$R1 \leftarrow R1 * R3$
STORE	X, R1	$M[X] \leftarrow R1$

The load instructions transfer the operands from memory to CPU registers. The add and multiply operations are executed with data in the registers without accessing memory. The result of the computations is then stored in memory with a store instruction.

8-5 Addressing Modes

The operation field of an instruction specifies the operation to be performed. This operation must be executed on some data stored in computer registers or memory words. The way the operands are chosen during program execution is dependent on the addressing mode of the instruction. The addressing mode specifies a rule for interpreting or modifying the address field of the instruction before the operand is actually referenced. Computers use addressing mode techniques for the purpose of accommodating one or both of the following provisions:

1. To give programming versatility to the user by providing such facilities as pointers to memory, counters for loop control, indexing of data, and program relocation.
2. To reduce the number of bits in the addressing field of the instruction.

The availability of the addressing modes gives the experienced assembly language programmer flexibility for writing programs that are more efficient with respect to the number of instructions and execution time.

To understand the various addressing modes to be presented in this section, it is imperative that we understand the basic operation cycle of the

computer. The control unit of a computer is designed to go through an instruction cycle that is divided into three major phases:

1. Fetch the instruction from memory.
2. Decode the instruction.
3. Execute the instruction.

program counter
(PC)

There is one register in the computer called the program counter or *PC* that keeps track of the instructions in the program stored in memory. *PC* holds the address of the instruction to be executed next and is incremented each time an instruction is fetched from memory. The decoding done in step 2 determines the operation to be performed, the addressing mode of the instruction, and the location of the operands. The computer then executes the instruction and returns to step 1 to fetch the next instruction in sequence.

In some computers the addressing mode of the instruction is specified with a distinct binary code, just like the operation code is specified. Other computers use a single binary code that designates both the operation and the mode of the instruction. Instructions may be defined with a variety of addressing modes, and sometimes, two or more addressing modes are combined in one instruction.

mode field

An example of an instruction format with a distinct addressing mode field is shown in Fig. 8-6. The operation code specifies the operation to be performed. The mode field is used to locate the operands needed for the operation. There may or may not be an address field in the instruction. If there is an address field, it may designate a memory address or a processor register. Moreover, as discussed in the preceding section, the instruction may have more than one address field, and each address field may be associated with its own particular addressing mode.

Although most addressing modes modify the address field of the instruction, there are two modes that need no address field at all. These are the implied and immediate modes.

Implied Mode: In this mode the operands are specified implicitly in the definition of the instruction. For example, the instruction “complement accumulator” is an implied-mode instruction because the operand in the accumulator register is implied in the definition of the instruction. In fact, all register reference instructions that use an accumulator are implied-mode instructions. Zero-address

Figure 8-6 Instruction format with mode field.

Opcode	Mode	Address
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instructions in a stack-organized computer are implied-mode instructions since the operands are implied to be on top of the stack.

Immediate Mode: In this mode the operand is specified in the instruction itself. In other words, an immediate-mode instruction has an operand field rather than an address field. The operand field contains the actual operand to be used in conjunction with the operation specified in the instruction. Immediate-mode instructions are useful for initializing registers to a constant value.

It was mentioned previously that the address field of an instruction may specify either a memory word or a processor register. When the address field specifies a processor register, the instruction is said to be in the register mode.

Register Mode: In this mode the operands are in registers that reside within the CPU. The particular register is selected from a register field in the instruction. A k -bit field can specify any one of 2^k registers.

Register Indirect Mode: In this mode the instruction specifies a register in the CPU whose contents give the address of the operand in memory. In other words, the selected register contains the address of the operand rather than the operand itself. Before using a register indirect mode instruction, the programmer must ensure that the memory address of the operand is placed in the processor register with a previous instruction. A reference to the register is then equivalent to specifying a memory address. The advantage of a register indirect mode instruction is that the address field of the instruction uses fewer bits to select a register than would have been required to specify a memory address directly.

Autoincrement or Autodecrement Mode: This is similar to the register indirect mode except that the register is incremented or decremented after (or before) its value is used to access memory. When the address stored in the register refers to a table of data in memory, it is necessary to increment or decrement the register after every access to the table. This can be achieved by using the increment or decrement instruction. However, because it is such a common requirement, some computers incorporate a special mode that automatically increments or decrements the content of the register after data access.

The address field of an instruction is used by the control unit in the CPU to obtain the operand from memory. Sometimes the value given in the address field is the address of the operand, but sometimes it is just an address from which the address of the operand is calculated. To differentiate among the various addressing modes it is necessary to distinguish between the address part of the instruction and the effective address used by the control when executing the instruction. The *effective address* is defined to be the memory address obtained from the computation dictated by the given addressing mode. The effective address is the address of the operand in a computational-type instruction. It is

effective address

the address where control branches in response to a branch-type instruction. We have already defined two addressing modes in Chap. 5. They are summarized here for reference.

Direct Address Mode: In this mode the effective address is equal to the address part of the instruction. The operand resides in memory and its address is given directly by the address field of the instruction. In a branch-type instruction the address field specifies the actual branch address.

Indirect Address Mode: In this mode the address field of the instruction gives the address where the effective address is stored in memory. Control fetches the instruction from memory and uses its address part to access memory again to read the effective address. The indirect address mode is also explained in Sec. 5-1 in conjunction with Fig. 5-2.

A few addressing modes require that the address field of the instruction be added to the content of a specific register in the CPU. The effective address in these modes is obtained from the following computation:

$$\text{effective address} = \text{address part of instruction} + \text{content of CPU register}$$

The CPU register used in the computation may be the program counter, an index register, or a base register. In either case we have a different addressing mode which is used for a different application.

Relative Address Mode: In this mode the content of the program counter is added to the address part of the instruction in order to obtain the effective address. The address part of the instruction is usually a signed number (in 2's complement representation) which can be either positive or negative. When this number is added to the content of the program counter, the result produces an effective address whose position in memory is relative to the address of the next instruction. To clarify with an example, assume that the program counter contains the number 825 and the address part of the instruction contains the number 24. The instruction at location 825 is read from memory during the fetch phase and the program counter is then incremented by one to 826. The effective address computation for the relative address mode is $826 + 24 = 850$. This is 24 memory locations forward from the address of the next instruction. Relative addressing is often used with branch-type instructions when the branch address is in the area surrounding the instruction word itself. It results in a shorter address field in the instruction format since the relative address can be specified with a smaller number of bits compared to the number of bits required to designate the entire memory address.

Indexed Addressing Mode: In this mode the content of an index register is added to the address part of the instruction to obtain the effective address.

The index register is a special CPU register that contains an index value. The address field of the instruction defines the beginning address of a data array in memory. Each operand in the array is stored in memory relative to the beginning address. The distance between the beginning address and the address of the operand is the index value stored in the index register. Any operand in the array can be accessed with the same instruction provided that the index register contains the correct index value. The index register can be incremented to facilitate access to consecutive operands. Note that if an index-type instruction does not include an address field in its format, the instruction converts to the register indirect mode of operation.

Some computers dedicate one CPU register to function solely as an index register. This register is involved implicitly when, the index-mode instruction is used. In computers with many processor registers, any one of the CPU registers can contain the index number. In such a case the register must be specified explicitly in a register field within the instruction format.

Base Register Addressing Mode: In this mode the content of a base register is added to the address part of the instruction to obtain the effective address. This is similar to the indexed addressing mode except that the register is now called a base register instead of an index register. The difference between the two modes is in the way they are used rather than in the way that they are computed. An index register is assumed to hold an index number that is relative to the address part of the instruction. A base register is assumed to hold a base address and the address field of the instruction gives a displacement relative to this base address. The base register addressing mode is used in computers to facilitate the relocation of programs in memory. When programs and data are moved from one segment of memory to another, as required in multiprogramming systems, the address values of instructions must reflect this change of position. With a base register, the displacement values of instructions do not have to change. Only the value of the base register requires updating to reflect the beginning of a new memory segment.

Numerical Example

To show the differences between the various modes, we will show the effect of the addressing modes on the instruction defined in Fig. 8-7. The two-word instruction at address 200 and 201 is a “load to *AC*” instruction with an address field equal to 500. The first word of the instruction specifies the operation code and mode, and the second word specifies the address part. *PC* has the value 200 for fetching this instruction. The content of processor register *R1* is 400, and the content of an index register *XR* is 100. *AC* receives the operand after the instruction is executed. The figure lists a few pertinent addresses and shows the memory content at each of these addresses.

Memory	
Address	Mode
200	Load to <i>AC</i>
201	Address = 500
202	Next instruction
399	450
400	700
500	800
600	900
702	325
800	300

Figure 8-7 Numerical example for addressing modes.

The mode field of the instruction can specify any one of a number of modes. For each possible mode we calculate the effective address and the operand that must be loaded into *AC*. In the direct address mode the effective address is the address part of the instruction 500 and the operand to be loaded into *AC* is 800. In the immediate mode the second word of the instruction is taken as the operand rather than an address, so 500 is loaded into *AC*. (The effective address in this case is 201.) In the indirect mode the effective address is stored in memory at address 500. Therefore, the effective address is 800 and the operand is 300. In the relative mode the effective address is $500 + 202 = 702$ and the operand is 325. (Note that the value in *PC* after the fetch phase and during the execute phase is 202.) In the index mode the effective address is $XR + 500 = 100 + 500 = 600$ and the operand is 900. In the register mode the operand is in *R1* and 400 is loaded into *AC*. (There is no effective address in this case.) In the register indirect mode the effective address is 400, equal to the content of *R1* and the operand loaded into *AC* is 700. The autoincrement mode is the same as the register indirect mode except that *R1* is incremented to 401 after the execution of the instruction. The autodecrement mode decrements *R1* to 399 prior to the execution of the instruction. The operand loaded into *AC* is now 450. Table 8-4 lists the values of the effective address and the operand loaded into *AC* for the nine addressing modes.

TABLE 8-4 Tabular List of Numerical Example

Addressing Mode	Effective Address	Content of <i>AC</i>
Direct address	500	800
Immediate operand	201	500
Indirect address	800	300
Relative address	702	325
Indexed address	600	900
Register	—	400
Register indirect	400	700
Autoincrement	400	700
Autodecrement	399	450

8-6 Data Transfer and Manipulation

Computers provide an extensive set of instructions to give the user the flexibility to carry out various computational tasks. The instruction set of different computers differ from each other mostly in the way the operands are determined from the address and mode fields. The actual operations available in the instruction set are not very different from one computer to another. It so happens that the binary code assignments in the operation code field is different in different computers, even for the same operation. It may also happen that the symbolic name given to instructions in the assembly language notation is different in different computers, even for the same instruction. Nevertheless, there is a set of basic operations that most, if not all, computers include in their instruction repertoire. The basic set of operations available in a typical computer is the subject covered in this and the next section.

Most computer instructions can be classified into three categories:

1. Data transfer instructions
2. Data manipulation instructions
3. Program control instructions

Data transfer instructions cause transfer of data from one location to another without changing the binary information content. Data manipulation instructions are those that perform arithmetic, logic, and shift operations. Program control instructions provide decision-making capabilities and change the path taken by the program when executed in the computer. The instruction set of a particular computer determines the register transfer operations and control decisions that are available to the user.

set of basic operations

Data Transfer Instructions

Data transfer instructions move data from one place in the computer to another without changing the data content. The most common transfers are between memory and processor registers, between processor registers and input or output, and between the processor registers themselves. Table 8-5 gives a list of eight data transfer instructions used in many computers. Accompanying each instruction is a mnemonic symbol. It must be realized that different computers use different mnemonics for the same instruction name.

The *load* instruction has been used mostly to designate a transfer from memory to a processor register, usually an accumulator. The *store* instruction designates a transfer from a processor register into memory. The *move* instruction has been used in computers with multiple CPU registers to designate a transfer from one register to another. It has also been used for data transfers between CPU registers and memory or between two memory words. The *exchange* instruction swaps information between two registers or a register and a memory word. The *input* and *output* instructions transfer data among processor registers and input or output terminals. The *push* and *pop* instructions transfer data between processor registers and a memory stack.

It must be realized that the instructions listed in Table 8-5, as well as in subsequent tables in this section, are often associated with a variety of addressing modes. Some assembly language conventions modify the mnemonic symbol to differentiate between the different addressing modes. For example, the mnemonic for *load immediate* becomes LDI. Other assembly language conventions use a special character to designate the addressing mode. For example, the immediate mode is recognized from a pound sign # placed before the operand. In any case, the important thing is to realize that each instruction can occur with a variety of addressing modes. As an example, consider the *load to accumulator* instruction when used with eight

TABLE 8-5 Typical Data Transfer Instructions

Name	Mnemonic
Load	LD
Store	ST
Move	MOV
Exchange	XCH
Input	IN
Output	OUT
Push	PUSH
Pop	POP

TABLE 8-6 Eight Addressing Modes for the Load Instruction

Mode	Assembly Convention	Register Transfer
Direct address	LD <i>ADR</i>	$AC \leftarrow M[ADR]$
Indirect address	LD @ <i>ADR</i>	$AC \leftarrow M[M[ADR]]$
Relative address	LD \$ <i>ADR</i>	$AC \leftarrow M[PC + ADR]$
Immediate operand	LD # <i>NBR</i>	$AC \leftarrow NBR$
Index addressing	LD <i>ADR</i> (<i>X</i>)	$AC \leftarrow M[ADR + XR]$
Register	LD <i>R1</i>	$AC \leftarrow R1$
Register indirect	LD (<i>R1</i>)	$AC \leftarrow M[R1]$
Autoincrement	LD (<i>R1</i>) +	$AC \leftarrow M[R1], R1 \leftarrow R1 + 1$

different addressing modes. Table 8-6 shows the recommended assembly language convention and the actual transfer accomplished in each case. *ADR* stands for an address, *NBR* is a number or operand, *X* is an index register, *R1* is a processor register, and *AC* is the accumulator register. The @ character symbolizes an indirect address. The \$ character before an address makes the address relative to the program counter *PC*. The # character precedes the operand in an immediate-mode instruction. An indexed mode instruction is recognized by a register that is placed in parentheses after the symbolic address. The register mode is symbolized by giving the name of a processor register. In the register indirect mode, the name of the register that holds the memory address is enclosed in parentheses. The autoincrement mode is distinguished from the register indirect mode by placing a plus after the parenthesized register. The autodecrement mode would use a minus instead. To be able to write assembly language programs for a computer, it is necessary to know the type of instructions available and also to be familiar with the addressing modes used in the particular computer.

Data Manipulation Instructions

Data manipulation instructions perform operations on data and provide the computational capabilities for the computer. The data manipulation instructions in a typical computer are usually divided into three basic types:

1. Arithmetic instructions
2. Logical and bit manipulation instructions
3. Shift instructions

A list of data manipulation instructions will look very much like the list of micro-operations given in Chap. 4. It must be realized, however, that each instruction when executed in the computer must go through the fetch phase to read its binary