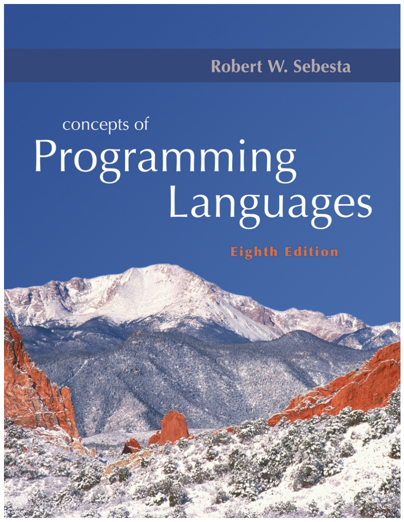
Chapter 6

Data Types



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Chapter 6 Topics

- Introduction
- Primitive Data Types
- Character String Types
- User-Defined Ordinal Types
- Array Types
- Associative Arrays
- Record Types
- Union Types
- Pointer and Reference Types

Introduction

- A data type defines a collection of data objects and a set of predefined operations on those objects
- A descriptor is the collection of the attributes of a variable
- An object represents an instance of a user-defined (abstract data) type
- One design issue for all data types: What operations are defined and how are they specified?

Primitive Data Types

- Almost all programming languages provide a set of primitive data types
- Primitive data types: Those not defined in terms of other data types
- Some primitive data types are merely reflections of the hardware
- Others require only a little non-hardware support for their implementation

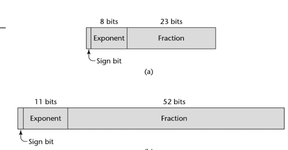
Primitive Data Types: Integer

- Almost always an exact reflection of the hardware so the mapping is trivial
- There may be as many as eight different integer types in a language
- Java's signed integer sizes: `byte`, `short`, `int`, `long`

Primitive Data Types: Floating Point

- Model real numbers, but only as approximations
- Languages for scientific use support at least two floating-point types (e.g., `float` and `double`; sometimes more
- Usually exactly like the hardware, but not always
- IEEE Floating-Point Standard 754

Figure 6.1
IEEE floating-point formats: (a) single precision, (b) double precision



Primitive Data Types: Complex

- Some languages support a complex type, e.g., Fortran and Python
- Each value consists of two floats, the real part and the imaginary part
- Literal form (in Python):

  `(7 + 3j)`, where `7` is the real part and `3` is the imaginary part

Primitive Data Types: Decimal

- For business applications (money)
  - Essential to COBOL
  - C# offers a decimal data type
- Store a fixed number of decimal digits, in coded form (BCD)
- Advantage: accuracy
- Disadvantages: limited range, wastes memory

Primitive Data Types: Boolean

- Simplest of all
- Range of values: two elements, one for "true" and one for "false"
- Could be implemented as bits, but often as bytes
  - Advantage: readability

Primitive Data Types: Character

- Stored as numeric codings
- Most commonly used coding: ASCII
- An alternative, 16-bit coding: Unicode
  - Includes characters from most natural languages
  - Originally used in Java
  - C# and JavaScript also support Unicode

Character String Types

- Values are sequences of characters
- Design issues:
  - Is it a primitive type or just a special kind of array?
  - Should the length of strings be static or dynamic?

Character String Types Operations

- Typical operations:
  - Assignment and copying
  - Comparison (=, >, etc.)
  - Catenation
  - Substring reference
  - Pattern matching

Character String Type in Certain Languages

- C and C++
  - Not primitive
  - Use **`char`** arrays and a library of functions that provide operations
- SNOBOL4 (a string manipulation language)
  - Primitive
  - Many operations, including elaborate pattern matching
- Fortran and Python
  - Primitive type with assignment and several operations
- Java
  - Primitive via the `String` class
- Perl, JavaScript, Ruby, and PHP
  - Provide built-in pattern matching, using regular expressions

Character String Length Options

- Static: COBOL, Java's `String` class
- Limited Dynamic Length: C and C++
  - In these languages, a special character is used to indicate the end of a string's characters, rather than maintaining the length
- Dynamic (no maximum): SNOBOL4, Perl, JavaScript
- Ada supports all three string length options

Character String Type Evaluation

- Aid to writability
- As a primitive type with static length, they are inexpensive to provide--why not have them?
- Dynamic length is nice, but is it worth the expense?

Character String Implementation

- Static length: compile-time descriptor
- Limited dynamic length: may need a run-time descriptor for length (but not in C and C++)
- Dynamic length: need run-time descriptor; allocation/de-allocation is the biggest implementation problem

Compile- and Run-Time Descriptors

Static string
Length
Address

Compile-time descriptor for static strings

Limited dynamic string
Maximum length
Current length
Address

Run-time descriptor for limited dynamic strings

User-Defined Ordinal Types

- An ordinal type is one in which the range of possible values can be easily associated with the set of positive integers
- Examples of primitive ordinal types in Java
  - `integer`
  - `char`
  - `boolean`

Enumeration Types

- All possible values, which are named constants, are provided in the definition
- C# example

```
enum days {mon, tue, wed, thu, fri, sat, sun};
```

- Design issues
  - Is an enumeration constant allowed to appear in more than one type definition, and if so, how is the type of an occurrence of that constant checked?
  - Are enumeration values coerced to integer?
  - Any other type coerced to an enumeration type?

Evaluation of Enumerated Type

- Aid to readability, e.g., no need to code a color as a number
- Aid to reliability, e.g., compiler can check:
  - operations (don't allow colors to be added)
  - No enumeration variable can be assigned a value outside its defined range
  - Ada, C#, and Java 5.0 provide better support for enumeration than C++ because enumeration type variables in these languages are not coerced into integer types

Subrange Types

- An ordered contiguous subsequence of an ordinal type
  - Example: 12..18 is a subrange of integer type
- Ada's design

```
type Days is (mon, tue, wed, thu, fri, sat, sun);
subtype Weekdays is Days range mon..fri;
subtype Index is Integer range 1..100;

Day1: Days;
Day2: Weekday;
Day2 := Day1;
```


Subrange Evaluation

- Aid to readability
  - Make it clear to the readers that variables of subrange can store only certain range of values
- Reliability
  - Assigning a value to a subrange variable that is outside the specified range is detected as an error

Implementation of User-Defined Ordinal Types

- Enumeration types are implemented as integers
- Subrange types are implemented like the parent types with code inserted (by the compiler) to restrict assignments to subrange variables

Array Types

- An array is an aggregate of homogeneous data elements in which an individual element is identified by its position in the aggregate, relative to the first element.

Array Design Issues

- What types are legal for subscripts?
- Are subscripting expressions in element references range checked?
- When are subscript ranges bound?
- When does allocation take place?
- What is the maximum number of subscripts?
- Can array objects be initialized?
- Are any kind of slices supported?

Array Indexing

- Indexing (or subscripting) is a mapping from indices to elements

  `array_name (index_value_list) → an element`
- Index Syntax
  - FORTRAN, PL/I, Ada use parentheses
    - Ada explicitly uses parentheses to show uniformity between array references and function calls because both are mappings
  - Most other languages use brackets

Arrays Index (Subscript) Types

- FORTRAN, C: integer only
- Ada: integer or enumeration (includes Boolean and char)
- Java: integer types only
- Index range checking
  - C, C++, Perl, and Fortran do not specify range checking
  - Java, ML, C# specify range checking
  - In Ada, the default is to require range checking, but it can be turned off

Subscript Binding and Array Categories

- Static: subscript ranges are statically bound and storage allocation is static (before run-time)
  - Advantage: efficiency (no dynamic allocation)
- Fixed stack-dynamic: subscript ranges are statically bound, but the allocation is done at declaration time
  - Advantage: space efficiency

Subscript Binding and Array Categories (cont.)

- Stack-dynamic: subscript ranges are dynamically bound and the storage allocation is dynamic (done at run-time)
  - Advantage: flexibility (the size of an array need not be known until the array is to be used)
- Fixed heap-dynamic: similar to fixed stack-dynamic: storage binding is dynamic but fixed after allocation (i.e., binding is done when requested and storage is allocated from heap, not stack)

Subscript Binding and Array Categories (cont.)

- Heap-dynamic: binding of subscript ranges and storage allocation is dynamic and can change any number of times
  - Advantage: flexibility (arrays can grow or shrink during program execution)

Subscript Binding and Array Categories (cont.)

- C and C++ arrays that include `static` modifier are static
- C and C++ arrays without `static` modifier are fixed stack-dynamic
- C and C++ provide fixed heap-dynamic arrays
- C# includes a second array class `ArrayList` that provides fixed heap-dynamic
- Perl, JavaScript, Python, and Ruby support heap-dynamic arrays

Heterogeneous Arrays

- A heterogeneous array is one in which the elements need not be of the same type
- Supported by Perl, Python, JavaScript, and Ruby

Array Initialization

- Some language allow initialization at the time of storage allocation
  - C, C++, Java, C# example

```
int list [] = {4, 5, 7, 83}
```

  - Character strings in C and C++

```
char name [] = "freddie";
```

  - Arrays of strings in C and C++

```
char *names [] = {"Bob", "Jake", "Joe"];
```

  - Java initialization of String objects

```
String[] names = {"Bob", "Jake", "Joe"};
```


Arrays Operations

- APL provides the most powerful array processing operations for vectors and matrixes as well as unary operators (for example, to reverse column elements)
- Ada allows array assignment but also catenation
- Python's array assignments, but they are only reference changes. Python also supports array catenation and element membership operations
- Ruby also provides array catenation
- Fortran provides elemental operations because they are between pairs of array elements
  - For example, + operator between two arrays results in an array of the sums of the element pairs of the two arrays

Rectangular and Jagged Arrays

- A rectangular array is a multi-dimensioned array in which all of the rows have the same number of elements and all columns have the same number of elements
- A jagged matrix has rows with varying number of elements
  - Possible when multi-dimensioned arrays actually appear as arrays of arrays
- C, C++, and Java support jagged arrays
- Fortran, Ada, and C# support rectangular arrays (C# also supports jagged arrays)

Slices

- A slice is some substructure of an array; nothing more than a referencing mechanism
- Slices are only useful in languages that have array operations

Slice Examples

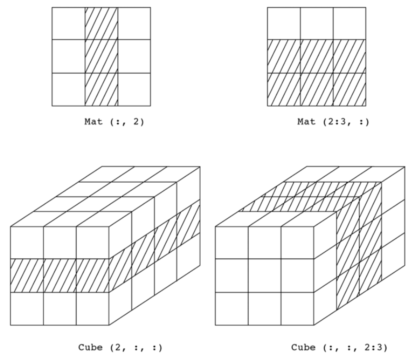
- Fortran 95

```
Integer, Dimension (10) :: Vector
Integer, Dimension (3, 3) :: Mat
Integer, Dimension (3, 3) :: Cube
```

`Vector (3:6)` is a four element array

Slices Examples in Fortran 95

Figure 6.4
Example slices in Fortran 95

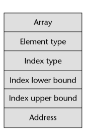


Implementation of Arrays

- Access function maps subscript expressions to an address in the array
- Access function for single-dimensioned arrays:

```
address(list[k]) = address (list[lower_bound]) +
                   ((k-lower_bound) * element_size)
```

Figure 6.5
Compile-time description for single-dimensioned arrays

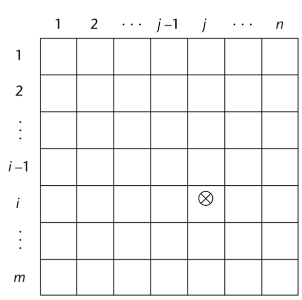


Accessing Multi-dimensioned Arrays

- Two common ways:
  - Row major order (by rows) – used in most languages
  - column major order (by columns) – used in Fortran

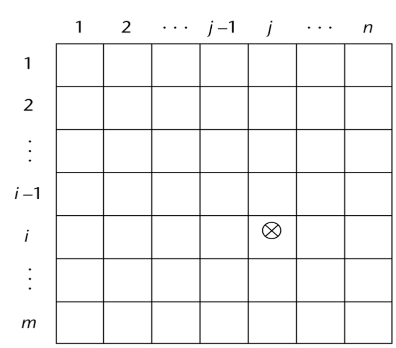
Locating an Element in a Multi-dimensioned Array

location (a[i,j]) = address of a [1,1] +
((((number of rows above the ith row) *
(size of a row)) +
(number of elements left of the jth column)) *
element_size)



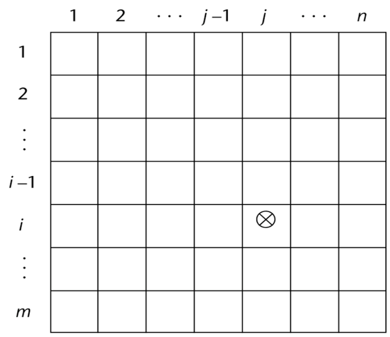
Locating an Element in a Multi-dimensioned Array (2)

location (a[i,j]) = address of a [1,1] +
((((i−1) * n) + (j−1)) * element_size)



Locating an Element in a Multi-dimensioned Array (3)

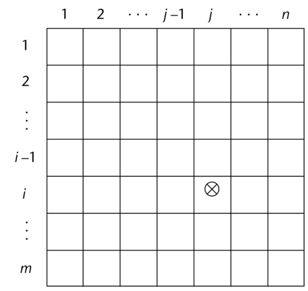
location (a[i,j]) = address of a [1,1] –((n+1) * element_size) + (i*n+j)) * element_size)



Locating an Element in a Multi-dimensioned Array

- General format

  Location (a[i,j]) = address of a [row_lb,col_lb] + (((I – row_lb) * n) + (j – col_lb)) * element_size



Compile-Time Descriptors

Array
Element type
Index type
Index lower bound
Index upper bound
Address

Single-dimensioned array

Multidimensioned array
Element type
Index type
Number of dimensions
Index range 1
⋮
Index range *n*
Address

Multi-dimensional array

Associative Arrays

- An associative array is an unordered collection of data elements that are indexed by an equal number of values called keys
  - User-defined keys must be stored
- Design issues:
  - What is the form of references to elements?
  - Is the size static or dynamic?

Associative Arrays in Perl

- Names (hash variable) begin with `%`; literals are delimited by parentheses

```
%hi_temps = ("Mon" => 77, "Tue" => 79, “Wed”
  => 65, …);
```

- Subscripting is done using braces and keys

```
$hi_temps{"Wed"} = 83;
```

  - Elements can be removed with `delete`

```
delete $hi_temps{"Tue"};
```


Record Types

- A record is a possibly heterogeneous aggregate of data elements in which the individual elements are identified by names
- Design issues:
  - What is the syntactic form of references to the field?
  - Are elliptical references allowed

Definition of Records in COBOL

- COBOL uses level numbers to show nested records; others use recursive definition

```
01 EMP-REC.
   02 EMP-NAME.
      05 FIRST PIC X(20).
      05 MID   PIC X(10).
      05 LAST  PIC X(20).
   02 HOURLY-RATE PIC 99V99.
```


Definition of Records in Ada

- Record structures are indicated in an orthogonal way

```
type Emp_Name_Type is record
    First: String (1..20);
    Mid: String (1..10);
    Last: String (1..20);
end record;
type Emp_Rec_Type is record
    Emp_Name: Emp_Name_Type;
    Hourly_Rate: Float;
end record;
Emp_Rec: Emp_Rec_Type;
```


References to Records

- Record field references
  1. COBOL
  field_name OF record_name_1 OF ... OF record_name_n
  2. Others (dot notation)
  record_name_1.record_name_2. ... record_name_n.field_name

- Fully qualified references must include all record names

- Elliptical references allow leaving out record names as long as the reference is unambiguous, for example in COBOL
  `FIRST`, `FIRST OF EMP-NAME`, and `FIRST` of EMP-REC are elliptical references to the employee's first name

Operations on Records

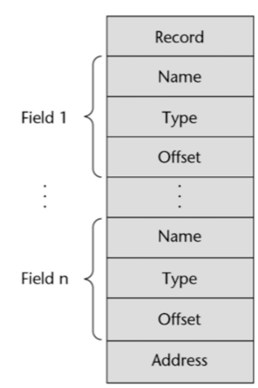
- Assignment is very common if the types are identical
- Ada allows record comparison
- Ada records can be initialized with aggregate literals
- COBOL provides `MOVE CORRESPONDING`
  - Copies a field of the source record to the corresponding field in the target record

Evaluation and Comparison to Arrays

- Records are used when collection of data values is heterogeneous
- Access to array elements is much slower than access to record fields, because subscripts are dynamic (field names are static)
- Dynamic subscripts could be used with record field access, but it would disallow type checking and it would be much slower

Implementation of Record Type

Offset address relative to the beginning of the records is associated with each field



Unions Types

- A union is a type whose variables are allowed to store different type values at different times during execution
- Design issues
  - Should type checking be required?
  - Should unions be embedded in records?

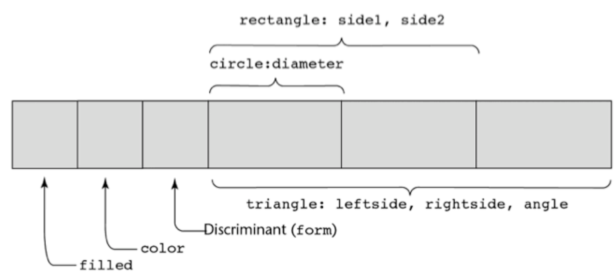
Discriminated vs. Free Unions

- Fortran, C, and C++ provide union constructs in which there is no language support for type checking; the union in these languages is called free union
- Type checking of unions require that each union include a type indicator called a discriminant
  - Supported by Ada

Ada Union Types

```
type Shape is (Circle, Triangle, Rectangle);
type Colors is (Red, Green, Blue);
type Figure (Form: Shape) is record
  Filled: Boolean;
  Color: Colors;
  case Form is
      when Circle => Diameter: Float;
      when Triangle =>
            Leftside, Rightside: Integer;
            Angle: Float;
      when Rectangle => Side1, Side2: Integer;
  end case;
end record;
```

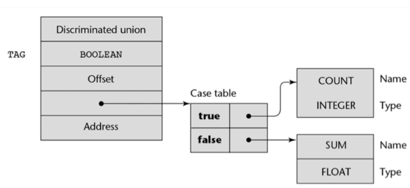

Ada Union Type Illustrated



A discriminated union of three shape variables

Implementation of Union Types

```
type Node (Tag : Boolean) is
  record
  case Tag is
    when True => Count : Integer;
    when False => Sum : Float;
  end case;
end record
```



Evaluation of Unions

- Free unions are unsafe
  - Do not allow type checking
- Java and C# do not support unions
  - Reflective of growing concerns for safety in programming language
- Ada's discriminated unions are safe

Pointer and Reference Types

- A pointer type variable has a range of values that consists of memory addresses and a special value, nil
- Provide the power of indirect addressing
- Provide a way to manage dynamic memory
- A pointer can be used to access a location in the area where storage is dynamically created (usually called a heap)

Design Issues of Pointers

- What are the scope of and lifetime of a pointer variable?
- What is the lifetime of a heap-dynamic variable?
- Are pointers restricted as to the type of value to which they can point?
- Are pointers used for dynamic storage management, indirect addressing, or both?
- Should the language support pointer types, reference types, or both?

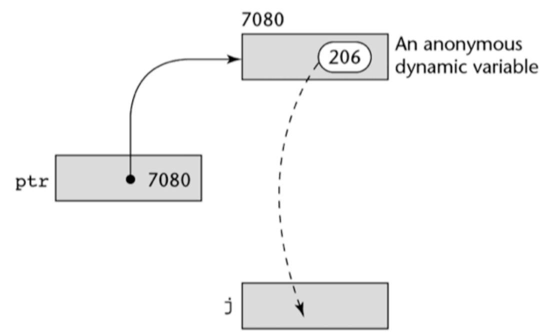
Pointer Operations

- Two fundamental operations: assignment and dereferencing
- Assignment is used to set a pointer variable's value to some useful address
- Dereferencing yields the value stored at the location represented by the pointer's value
  - Dereferencing can be explicit or implicit
  - C++ uses an explicit operation via *

    `j = *ptr`

    sets j to the value located at `ptr`

Pointer Assignment Illustrated



The assignment operation j = *ptr

Problems with Pointers

- Dangling pointers (dangerous)
  - A pointer points to a heap-dynamic variable that has been deallocated
- Lost heap-dynamic variable
  - An allocated heap-dynamic variable that is no longer accessible to the user program (often called garbage)
    - Pointer `p1` is set to point to a newly created heap-dynamic variable
    - Pointer `p1` is later set to point to another newly created heap-dynamic variable
    - The process of losing heap-dynamic variables is called memory leakage

Pointers in Ada

- Some dangling pointers are disallowed because dynamic objects can be automatically deallocated at the end of pointer's type scope
- The lost heap-dynamic variable problem is not eliminated by Ada (possible with `UNCHECKED_DEALLOCATION`)

Pointers in C and C++

- Extremely flexible but must be used with care
- Pointers can point at any variable regardless of when or where it was allocated
- Used for dynamic storage management and addressing
- Pointer arithmetic is possible
- Explicit dereferencing and address-of operators

Pointer Arithmetic in C and C++

```
float list[100];
float *p;
p = list;
```

`*(p+5)` is equivalent to `list[5]` and `p[5]`

`*(p+i)` is equivalent to `list[i]` and `p[i]`

- Domain type need not be fixed (**`void *`**)

  `void *` can point to any type and can be type checked (cannot be de-referenced)

Reference Types

- C++ includes a special kind of pointer type called a reference type that is used primarily for formal parameters
  - Advantages of both pass-by-reference and pass-by-value
- Java extends C++'s reference variables and allows them to replace pointers entirely
  - References are references to objects, rather than being addresses
- C# includes both the references of Java and the pointers of C++, must include 'unsafe' modifier

Evaluation of Pointers

- Dangling pointers and dangling objects are problems as is heap management
- Pointers are like `goto`'s--they widen the range of cells that can be accessed by a variable
- Pointers or references are necessary for dynamic data structures--so we can't design a language without them

Representations of Pointers

- Large computers use single values
- Intel microprocessors use segment and offset

Dangling Pointer Problem

- Tombstone: extra heap cell that is a pointer to the heap-dynamic variable
  - The actual pointer variable points only at tombstones
  - When heap-dynamic variable de-allocated, tombstone remains but set to nil
  - Costly in time and space
- Locks-and-keys: Pointer values are represented as (key, address) pairs
  - Heap-dynamic variables are represented as variable plus cell for integer lock value
  - When heap-dynamic variable allocated, lock value is created and placed in lock cell and key cell of pointer

Heap Management

- A very complex run-time process
- Single-size cells vs. variable-size cells
- Two approaches to reclaim garbage
  - Reference counters (eager approach): reclamation is gradual
  - Mark-sweep (lazy approach): reclamation occurs when the list of variable space becomes empty

Reference Counter

- Reference counters: maintain a counter in every cell that store the number of pointers currently pointing at the cell
  - Disadvantages: space required, execution time required, complications for cells connected circularly
  - Advantage: it is intrinsically incremental, so significant delays in the application execution are avoided

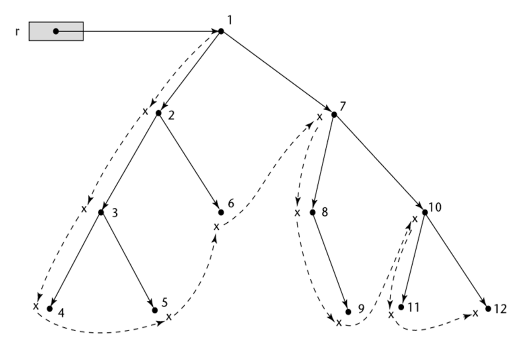
Mark-Sweep

- The run-time system allocates storage cells as requested and disconnects pointers from cells as necessary; mark-sweep then begins
  - Every heap cell has an extra bit used by collection algorithm
  - All cells initially set to garbage
  - All pointers traced into heap, and reachable cells marked as not garbage
  - All garbage cells returned to list of available cells
  - Disadvantages: in its original form, it was done too infrequently. When done, it caused significant delays in application execution. Contemporary mark-sweep algorithms avoid this by doing it more often—called incremental mark-sweep

Marking Algorithm

Figure 6.12

An example of the actions of the marking algorithm



Dashed lines show the order of node_marking

Variable-Size Cells

- All the difficulties of single-size cells plus more
- Required by most programming languages
- If mark-sweep is used, additional problems occur
  - The initial setting of the indicators of all cells in the heap is difficult
  - The marking process in nontrivial
  - Maintaining the list of available space is another source of overhead

Summary

- The data types of a language are a large part of what determines that language's style and usefulness
- The primitive data types of most imperative languages include numeric, character, and Boolean types
- The user-defined enumeration and subrange types are convenient and add to the readability and reliability of programs
- Arrays and records are included in most languages
- Pointers are used for addressing flexibility and to control dynamic storage management