# CS 280
# Programming Language Concepts

## 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
- Design issue for all data types: What operations are defined and how are they specified?

## Primitive Data Types

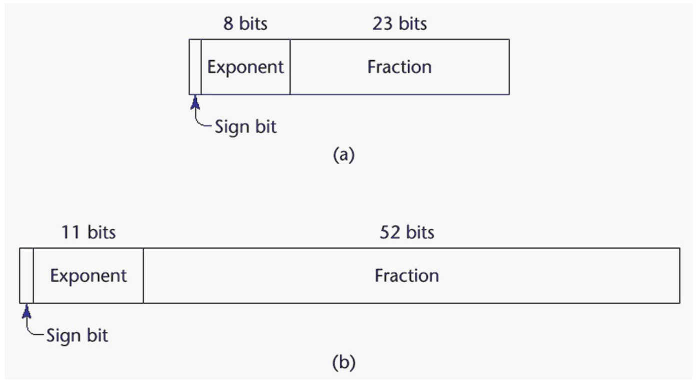
- Almost all programming languages provide a set of *primitive data types*
- Primitive data types: Those not defined in terms of other data types
- Some primitive data types are merely reflections of the hardware
- Others require only a little non-hardware support for their implementation

## 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



## Primitive Data Types: Complex

- Some languages support a complex type, e.g., C99, 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 encodings
- Most commonly used coding: ASCII
- An alternative, 16-bit coding: Unicode (UCS-2)
  - Includes characters from most natural languages
  - Originally used in Java
  - C# and JavaScript also support Unicode
- 32-bit Unicode (UCS-4)
  - Supported by Fortran, starting with 2003

## 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
  - A `string` class is provided in C++
- 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, AWK and PHP

  - Provide built-in pattern matching, using regular expressions

## 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 different support for enumeration than C++: 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 a homogeneous aggregate of 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?
- Are ragged or rectangular multidimensional arrays allowed, or both?
- 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 and Ada use parentheses
    - Ada explicitly uses parentheses to show uniformity between array references and function calls because both are *mappings*
  - Most other languages use square 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 (continued)

- *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 (continued)

- 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 (continued)

- 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

## 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″};
```

## Array Initialization

- C-based languages
  - `int list [] = {1, 3, 5, 7};`
  - `char *names [] = {"Mike", "Fred", "Mary Lou"};`
- Ada
  - `List : array (1..5) of Integer :=`
    `(1 => 17, 3 => 34, others => 0);`
- Python
  - List comprehensions

```
list = [x ** 2 for x in range(12) if x % 3 == 0]
```

puts `[0, 9, 36, 81]` in `list`

## 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

## 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 has 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

- Python

```
vector = [2, 4, 6, 8, 10, 12, 14, 16]

mat = [[1, 2, 3], [4, 5, 6], [7, 8, 9]]
```

`vector (3:6)` is a three-element array

`mat[0][0:2]` is the first and second element of the first row of `mat`

- Ruby supports slices with the `slice` method

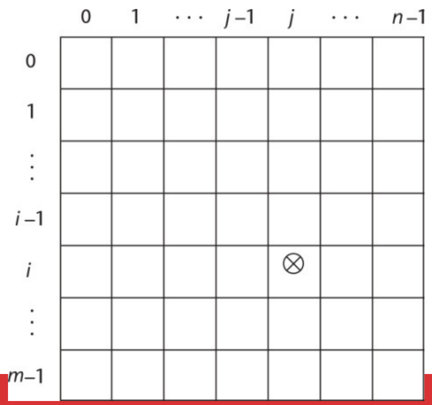
`list.slice(2, 2)` returns the third and fourth elements of `list`

## 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)

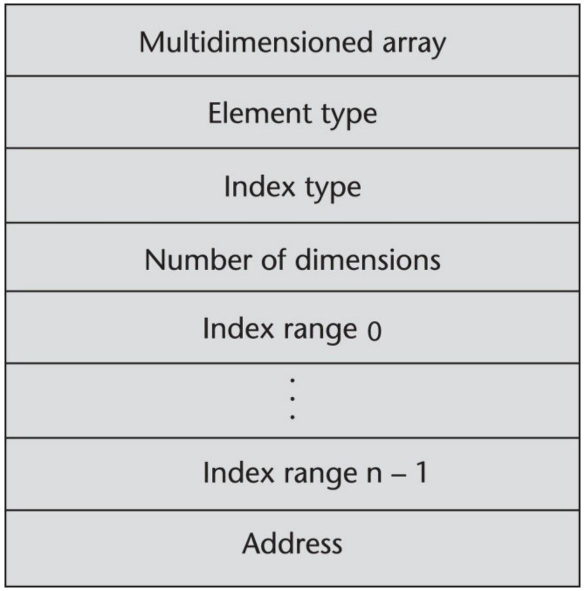


## Accessing Multi-dimensioned Arrays

- Two common ways:
  - Row major order (by rows) – used in most languages
  - Column major order (by columns) – used in Fortran
  - A compile-time descriptor

for a multidimensional

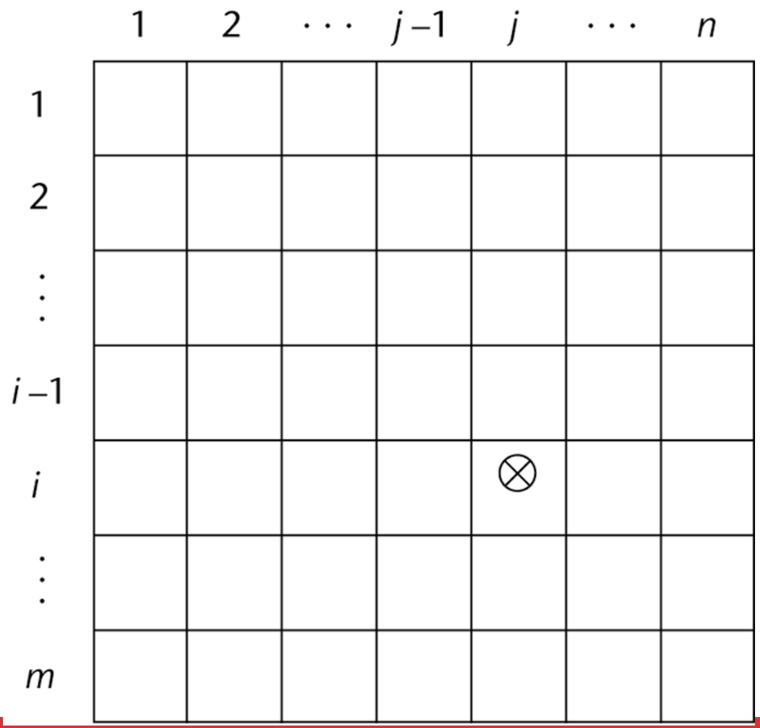
array



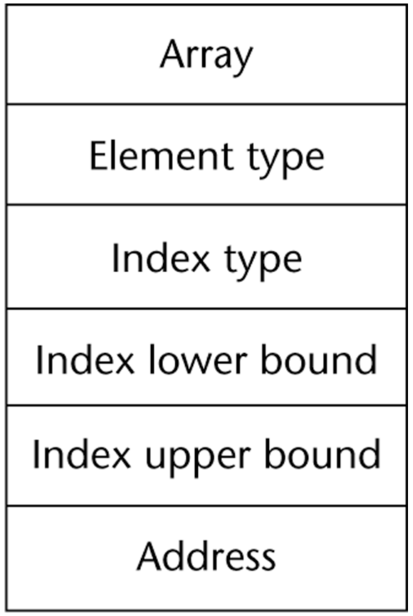
# Locating an Element in a Multi-dimensioned Array

- General format

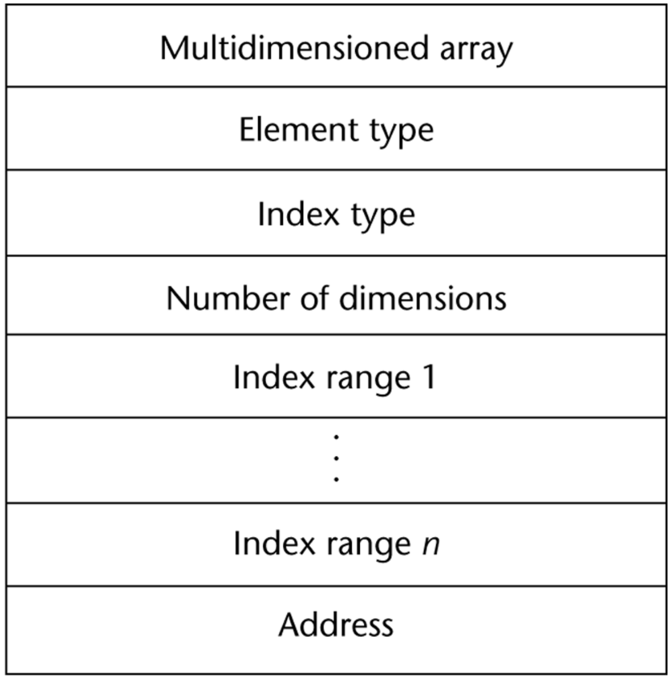
  Location (a[I,j]) = address of a [row_lb,col_lb] + (((I - row_lb) * n) + (j - col_lb)) * element_size



# Compile-Time Descriptors



Single-dimensioned array



Multidimensional 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-def ned keys must be stored
- Design issues:

  - What is the form of references to elements?

  - Is the size static or dynamic?
- Built-in type in Perl, Python, Ruby, …

## Associative Arrays in Perl

- Names 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"};
```

## Related Implementations in Java/C++

- C++ map or Java HashMap
- These are parameterized using <> and type names, so the type of the key and value are fixed
- Advantage: compile time type checking

## 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.
```

## Related Implementations in C/C++

- struct: a collection of elements of different types

```
struct employeeType {
    int id;
    char name[25];
    int age;
    float salary;
    char dept;
};
struct employeeType employee;
...
employee.age = 45;
```

# 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
- 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

## Tuple Types

- A tuple is a data type that is similar to a record, except that the elements are not named
- Used in Python, ML, and F# to allow functions to return multiple values
  - Python
    - Closely related to its lists, but immutable
    - Create with a tuple literal

```
myTuple = (3, 5.8, 'apple')
```

Referenced with subscripts

Catenation with + and deleted with **`del`**

# List Types

- Lists in LISP and Scheme are delimited by parentheses and use no commas

  `(A B C D)` and `(A (B C) D)`
- Data and code have the same form

  As data, `(A B C)` is literally what it is

  As code, `(A B C)` is the function `A` applied to the parameters `B` and `C`
- The interpreter needs to know which a list is, so if it is data, we quote it with an apostrophe

  `'(A B C)` is data

## List Types (continued)

- List Operations in Scheme
  - `CAR` returns the first element of its list parameter

`(CAR '(A B C))` returns `A`

  - `CDR` returns the remainder of its list parameter after the first element has been removed

`(CDR '(A B C))` returns `(B C)`

- `CONS` puts its first parameter into its second parameter, a list, to make a new list

`(CONS 'A (B C))` returns `(A B C)`

  - `LIST` returns a new list of its parameters

`(LIST 'A 'B '(C D))` returns `(A B (C D))`

## List Types (continued)

- Python Lists
  - The list data type also serves as Python’s arrays
  - Unlike Scheme, Common LISP, ML, and F#, Python’s lists are mutable
  - Elements can be of any type
  - Create a list with an assignment

```
myList = [3, 5.8, "grape"]
```

## List Types (continued)

- Python Lists (continued)
  - List elements are referenced with subscripting, with indices beginning at zero

`x = myList[1]` Sets `x` to `5.8`

  - List elements can be deleted with `del`

```
del myList[1]
```

  - List Comprehensions – derived from set notation

```
[x * x for x in range(6) if x % 3 == 0]
```

`range(12)` creates `[0, 1, 2, 3, 4, 5, 6]`

Constructed list: `[0, 9, 36]`

## List Types (continued)

- C++ supports lists through standard templates like vector and list
- Both C# and Java supports lists through their generic heap-dynamic collection classes, `List` and `ArrayList`, respectively
- Types are fixed and are named in <> at declaration time

## Union 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

## C/C++ union

```
union u {
  char   addr[4];
  short  pieces[2];
  long   full;
} ipaddr;

union spacesave {
  char  c;
  int       i;
  float  f;
} ss;
```

## 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

## User Defined Types

- A class in Java or C++
- Extensions of classes using generics/templates
- Java Interfaces

## 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 (the *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?

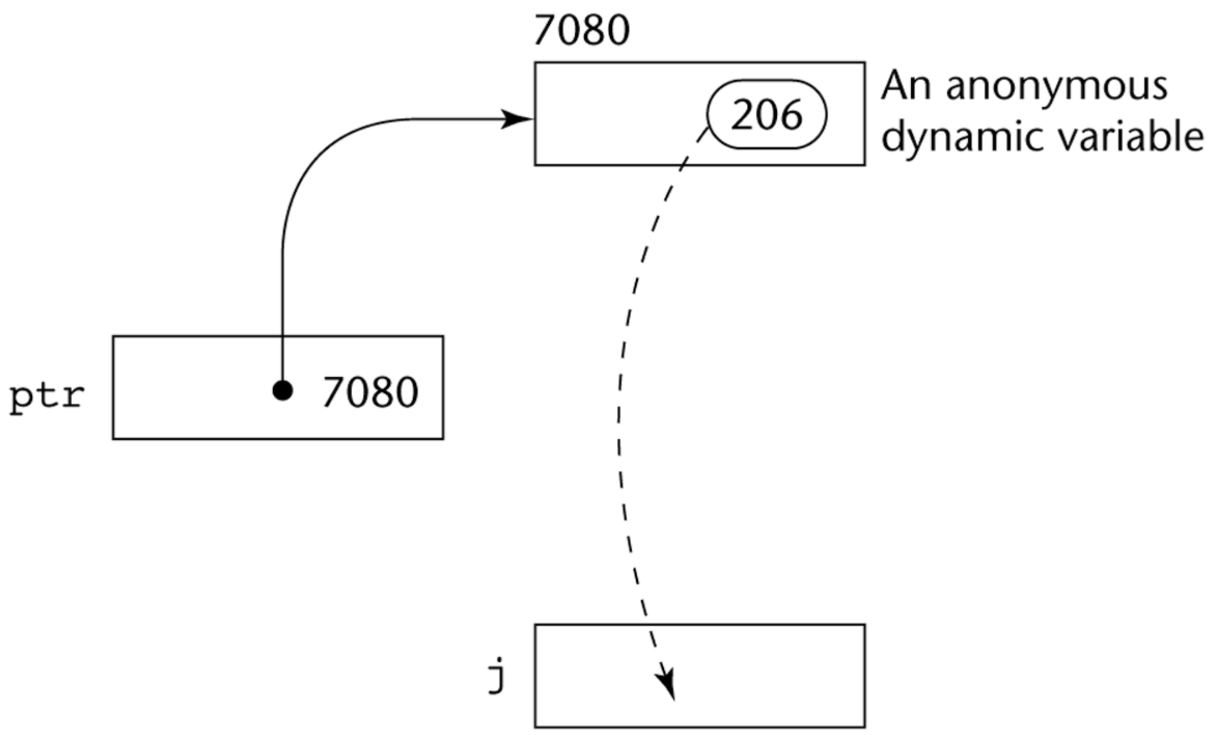
## Pointer Operations

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

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

## Pointer Arithmetic in C and C++

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

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

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

## 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++

## 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

## 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

## 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

## Type Checking

- Generalize the concept of operands and operators to include subprograms and assignments

- *Type checking* is the activity of ensuring that the operands of an operator are of compatible types

- A *compatible type* is one that is either legal for the operator, or is allowed under language rules to be implicitly converted, by compiler- generated code, to a legal type
  - This automatic conversion is called a *coercion*.

- A *type error* is the application of an operator to an operand of an inappropriate type

## Type Checking (continued)

- If all type bindings are static, nearly all type checking can be static
- If type bindings are dynamic, type checking must be dynamic
- A programming language is *strongly typed* if type errors are always detected
- Advantage of strong typing: allows the detection of the misuses of variables that result in type errors

NJIT

THE EDGE IN KNOWLEDGE