CSC 533: Programming Languages

Spring 2014

Data types

- primitive types (integer, float, boolean, char, pointer)
- heap management, garbage collection
- complex data types (string, enum, subrange, array, record, …)
- misc: expressions and assignments, conditional control & branching

We will focus on C, C++, and Java as example languages

Primitive types: integer

languages often provide several sizes/ranges

in C/C++/Java

`short`	(2 bytes in Java)
`int`	(4 bytes in Java)
`long`	(8 bytes in Java)

absolute sizes are implementation dependent in C/C++

TRADEOFFS?

- Java has a `byte` type (1 byte)
- in C/C++, `char` is considered an integer type
- most languages use 2's complement notation for negatives

```
1 = 00…000001        -1 = 11…111111
2 = 00…000010        -2 = 11…111110
3 = 00…000011        -3 = 11…111101
```

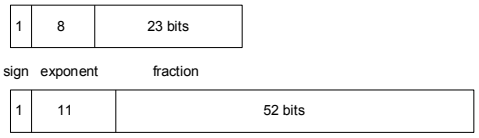
Primitive types: floating-point

again, languages often provide several sizes/ranges

in C/C++/Java `float` (4 bytes in Java)
`double` (8 bytes in Java)

C/C++ also have a `long double` type

- historically, floating-points have been stored in a variety of formats
  same basic components: sign, fraction, exponent
- in 1985, IEEE floating-point formats were standardized



(sign)fraction x $2^{exponent}$

special bit patterns represent:

- `infinity`
- `NaN`

other number types: decimal, fixed-point, rational, …

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Primitive types: boolean

introduced in ALGOL 60

C does not have a boolean type, conditionals use zero (false) and nonzero (true)

C++ has `bool` type
- really just syntactic sugar, automatic conversion between `int` and `bool`

Java has `boolean` type
- no conversions between `int` and `bool`

implementing booleans

- could use a single bit, but not usually accessible
- use smallest easily-addressable unit (e.g., byte)

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Primitive types: character

stored as numeric codes, e.g., ASCII (C/C++) or UNICODE (Java)

in C/C++, `char` is an integer type

- can apply integer operations, mix with integer values

```
char ch = 'A';
ch = ch + 1;
cout << ch << endl
```

```
char ch = '8';
int d = ch - '0';
cout << d << endl;
```

in Java, `char` to `int` conversion is automatic

- but must explicitly cast `int` to `char`

```
char next = (char)(ch + 1);
```

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Primitive types: pointer

a pointer is nothing more than an address (i.e., an integer)

useful for:

- dynamic memory management (allocate, dereference, deallocate)
- indirect addressing (point to an address, dereference)

PL/I was the first language to provide pointers

- pointers were not typed, could point to any object
  - ➔ no static type checking for pointers

ALGOL 68 refined pointers to a specific type

in many languages, pointers are limited to dynamic memory management
e.g., Pascal, Ada, Java, …

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Primitive types: pointer (cont.)

C/C++ allows for low-level memory access using pointers

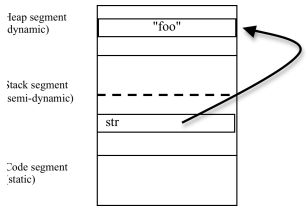
`*` dereferencing operator `&` address-of operator

```
int x = 6;
int * ptr1 = &x;
int * ptr2 = ptr1;
*ptr2 = 3;
```

in C/C++, the 0 (NULL) address is reserved, attempted access → ERROR

Java does not provide explicit pointers, but every object is really a pointer

```
String str = "foo";
```



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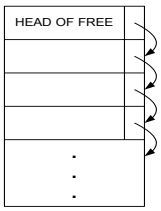
Heap management

pointers access memory locations from the heap (a dynamically allocated storage area)

the heap is divided into equal-size cells, each with a pointer

- the pointer fields are used initially to organize the heap as a linked list



- keep pointer to head of free list
- to allocate space, take from front of free list
- to deallocate, put back at front

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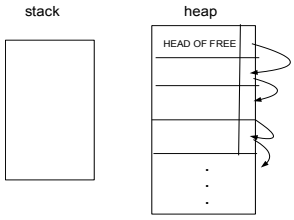
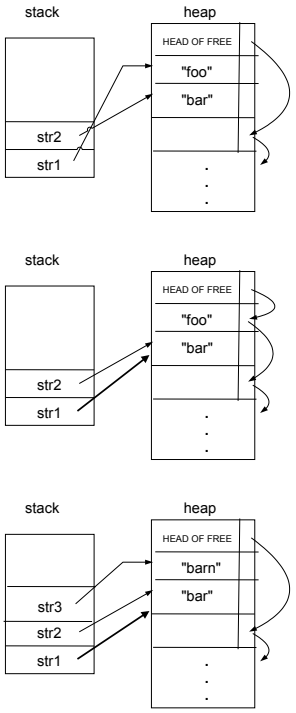
Heap example




```
String str1 = "foo";
String str2 = "bar";

/* CHECKPOINT 1 */

str1 = str2;

/* CHECKPOINT 2 */

String str3 = str1+"n";

/* CHECKPOINT 3 */
```



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Pointer problems

returning memory to the free list is easy, but when do you do it?

dangling reference: memory is deallocated, but still have a pointer to it

```
int * Foo() {
   int x = 5;
   return &x;
}
```

a problem in C/C++, since the & operator allows access to stack memory that has already been reclaimed

not a problem in Java since no equivalent to the & operator

garbage reference: pointer is destroyed, but memory has not been deallocated

```
void Bar() {
   Date today = new Date();
    …
}
```

a problem in both C/C++ and Java
when `today`'s lifetime ends, its dynamic memory is inaccessible
(in C/C++, must explicitly deallocate dynamic memory w/ `delete`)

would like to automatically and safely reclaim heap memory

2 common techniques: reference counts, garbage collection

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Reference counts

along with each heap element, store a reference count

- indicates the number of pointers to the heap element

- when space is allocated, its reference count is set to 1
- each time a new pointer is set to it, increment the reference count
- each time a pointer is lost, decrement the reference count

provides a simple method for avoiding garbage & dangling references

- if result of an operation leaves reference count at 0, reclaim memory
- can even double check explicit deallocations

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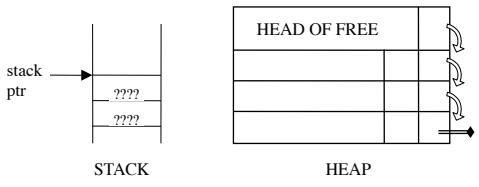
Reference counts example

```
String str1 = "foo";
String str2 = "bar";

/* CHECKPOINT 1 */

str1 = str2;

/* CHECKPOINT 2 */

if (str1.equals(str2)) {
  String temp = "biz";
  str2= temp;

  /* CHECKPOINT 3 */
}

String str3 = "baz";

/* CHECKPOINT 4 */
```



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Reference counts (cont.)

unfortunately, reference counts are very costly

- must update & check reference counts for each assignment, end of lifetime

```
String str1;
String str2;
…
str1 = str2;
```

➔

1) dereference `str1`, decrement count
2) if count = 0, deallocate
3) copy `str1` reference to `str2`
4) dereference `str1`, increment count

reference counts are popular in parallel programming

- work is spread evenly

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Garbage collection

approach: allow garbage to accumulate, only collect if out of space

as program executes, no reclamation of memory (thus, no cost)
when out of memory, take the time to collect garbage (costly but rare)

e.g., toothpaste tube analogy

2 common approaches to garbage collection

1. Partition & Copy
2. Mark & Sweep

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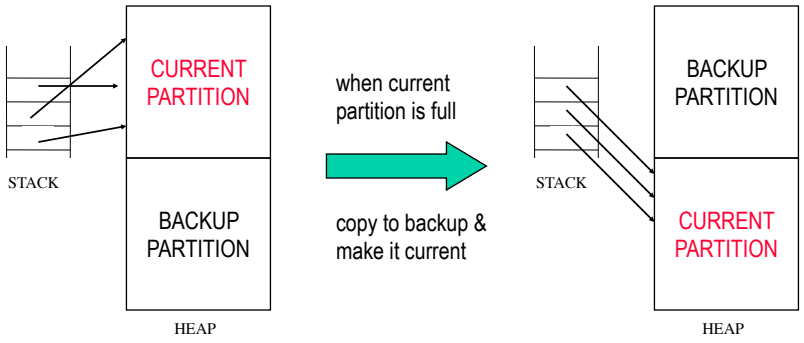
Partition & Copy approach

1. divide the memory space into 2 partitions: current + backup
2. when the current partition is full,
   a. sweep through all active objects (from the stack)
   b. copy each active object to the backup partition (contiguously)
   c. when done, make that the current partition



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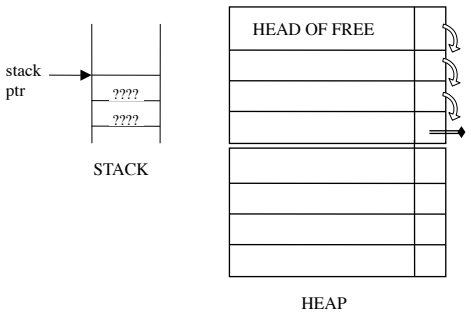
Partition & Copy example

```
String str1= "foo";
String str2= "bar";

/* CHECKPOINT 1 */

str1 = str2;

/* CHECKPOINT 2 */

if (str1.equals(str2)) {
  String temp = "biz";
  str2 = temp;

  /* CHECKPOINT 3 */
}

String str3 = "baz";

/* CHECKPOINT 4 */
```



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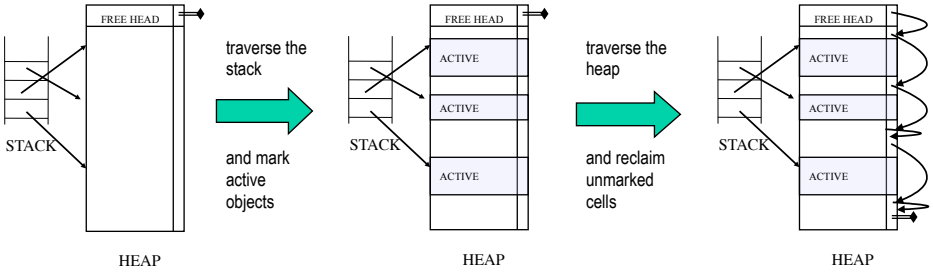
Mark & Sweep approach

1. mark all active objects
   a. sweep through all active objects (from the stack)
   b. mark each memory cell associated with an active object
2. sweep through the heap and reclaim unmarked cells
   a. traverse the heap sequentially
   b. add each unmarked cell to the FREE list



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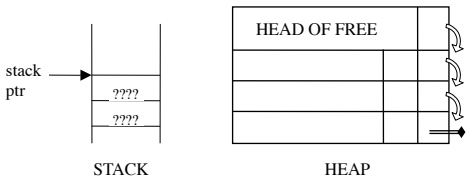
Mark & Sweep example

```
String str1= "foo";
String str2= "bar";

/* CHECKPOINT 1 */

str1 = str2;

/* CHECKPOINT 2 */

if (str1.equals(str2)) {
  String temp = "biz";
  str2 = temp;

  /* CHECKPOINT 3 */
}

String str3 = "baz";

/* CHECKPOINT 4 */
```



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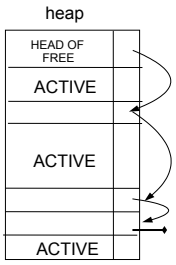
Mark & Sweep & Compactify

note: not all memory allocations are the same size

- C/C++/Java: double bigger than float, array elements must be contiguous, …



as memory is allocated & deallocated, fragmentation occurs

e.g., suppose wish to allocate a 3 element array
previous allocations/deallocations have left 3 free cells, but not contiguously
→ must garbage collect (even though free space exists)

using Partition & Copy, not a big problem

- simply copy active objects to other partition – this automatically coalesces gaps

using Mark & Sweep, must add another pass to defragment the space

- once active objects have been identified, must shift them in memory to remove gaps
- COSTLY!

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Partition & Copy vs. Mark & Sweep & Compactify

Partition & Copy

- wastes memory by maintaining the backup partition
- but quick (especially if few active objects) and avoids fragmentation

Mark & Sweep & Compactify

- able to use the entire memory space for active objects
- but slow (2 complete passes through heap to reclaim and compactify)

Java takes a hybrid approach to provide automatic garbage collection

- memory is divided into two types: new objects and old objects
- the new objects partition is optimized for objects with short lifetimes
  garbage collection happens relatively frequently
  uses Partition & Copy, since it is expected that few active objects will remain
- eventually, persistent new objects are moved to the old objects partition
  garbage collections happens relatively infrequently
  uses Mark & Sweep & Compactify, since many active objects will persist

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Complex data types

early languages had limited data types

- FORTRAN elementary types + arrays
- COBOL introduced structured data type for record
- PL/I included many data types, with the intent of supporting a wide range of applications

better approach:

ALGOL 68 provided a few basic types & a few flexible combination methods that allow the programmer to structure data

common types/structures:

string	enumeration	subrange
array	record	union
set	list	. . .

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Strings

- can be a primitive type (e.g., Scheme, SNOBOL)
- can be a special kind of character array (e.g., Pascal, Ada, C)

In C++ & Java, OOP can make the string type appear primitive

- C++ string type is part of the Standard Template Library `#include <string>`
- Java String type is part of the `java.lang` package (automatically loaded)
- both are classes built on top of '\0'-terminated, C-style strings

```
String str = "Dave";
```

str → | 'D' | 'a' | 'v' | 'e' | '\0' |

- Java strings are immutable – can't change individual characters, but can reassign an entire new value

```
str = str.substring(0, 1) + "el" + str.substring(2, 5);
```

reason: structure sharing is used to save memory

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Enumerations & subranges

an *enumeration* is a user-defined ordinal type

- all possible values (symbolic constants) are enumerated

in C++ & Java: `enum Day {Mon, Tue, Wed, Thu, Fri, Sat, Sun};`

- C++: enum values are mapped to ints by the preprocessor (*kludgy*)

```
Day today = Wed;              // same as  today = 2;
cout << today << endl;        // prints 2
today = 12;                   // illegal
```

- Java: enum values are treated as new, unique values

```
Day today = Day.Wed;
System.out.println(today);    // prints Wed
```

some languages allow new types that are *subranges* of other types

- subranges inherit operations from the parent type
- can lead to clearer code (since more specific), safer code (since range checked)

in Ada: `subtype Digits is INTEGER range 0..9;`

no subranges in C, C++ or Java

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Arrays

an *array* is a homogeneous aggregate of data elements that supports random access via indexing

design issues:

- index type (C/C++ & Java only allow int, others allow any ordinal type)
- index range (C/C++ & Java fix low bound to 0, others allow any range)
- bindings
  - static (index range fixed at compile time, memory static)
    - FORTRAN, C/C++ (for globals)
  - fixed stack-dynamic (range fixed at compile time, memory stack-dynamic)
    - Pascal, C/C++ (for locals)
  - stack-dynamic (range fixed when bound, memory stack-dynamic)
    - Ada
  - heap-dynamic (range can change, memory heap-dynamic)
    - C/C++ & Java (using new), JavaScript
- dimensionality (C/C++ & Java only allow 1-D, but can have array of arrays)

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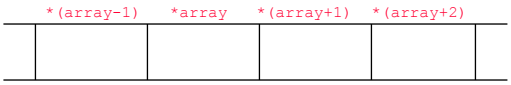
C/C++ arrays

C/C++ think of an array as a pointer to the first element

- when referred to, array name is converted to its starting address

```
int counts[NUM_LETTERS];              // counts ≡ &counts[0]
```

- array indexing is implemented via pointer arithmetic: `array[k] ≡ *(array+k)`



the pointer type determines the distance added to the pointer

since an array is a pointer, can dynamically allocate memory from heap

```
int * nums = new int[numNums];        // allocates array of ints
```

- can resize by allocating new space, copying values, and reassigning the pointer

the C++ `vector` class encapsulates a dynamic array, with useful methods

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Java arrays

in Java, arrays are reference types (dynamic objects)

must: 1) declare an array `int nums[];`

2) allocate space `nums = new int[20];`

can combine: `int nums[] = new int[20];`

- as in C/C++, array indices start at 0
- unlike C/C++, bounds checking performed, can access length field

```
for (int i = 0; i < nums.length; i++) {
    System.out.println(nums[i]);
}
```

- like C++, Java also provides a more flexible `ArrayList` class
  but can only store objects (no primitives)

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Records

a *record* is a (possibly) heterogeneous aggregate of data elements, each identified by a field name

heterogeneous → flexible access by field name → restrictive

in C, a `struct` can group data values into a new type of object

```
struct Person {
    string lastName, firstName;
    char middleInit;
    int age;
};
```

C++: has both `struct` and `class`

- only difference: default protection (`public` in struct, `private` in class)
- structs can have methods, but generally used for C-style structures

Java: simplifies so that only `class`

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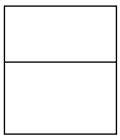
Unions (variant records)

a *union* is allowed to store different values at different times

```
struct Person {
    string name;
    union {
        string spouse;
        string relative;
    }
};
```



C/C++ do no type checking wrt unions

```
Person p;
p.relative = "Mom";
cout << p.spouse << endl;
```

in Ada, a tag value forces type checking (can only access one way)

no unions in Java

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Assignments and expressions

when an assignment is evaluated,

- expression on rhs is evaluated first, then assigned to variable on lhs

within an expression, the order of evaluation can make a difference

```
x = 2;
y = x + x++;
```

```
foo(x++, x);
```

in C/C++, if not covered by precedence/associativity rules, order is undefined (i.e., implementation dependent) – similarly, in Pascal, Ada, … WHY?

one exception: boolean expressions with and/or are evaluated left-to-right

```
for (int i = 0; i < size && nums[i] != 0; i++) {
    . . .
}
```

in Java, expressions are always evaluated left-to-right

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Conditionals & loops

early control structures were tied closely to machine architecture

e.g., FORTRAN arithmetic if: based on IBM 704 instruction

```
      IF (expression) 10, 20, 30
10    code to execute if expression < 0
      GO TO 40
20    code to execute if expression = 0
      GO TO 40
30    code to execute if expression > 0
40    . . .
```

later languages focused more on abstraction and machine independence

some languages provide counter-controlled loops

e.g., in Pascal:

```
for i := 1 to 100 do
begin
    . . .
end;
```

- counter-controlled loops tend to be more efficient than logic-controlled
- C/C++ and Java don't have counter-controlled loops (for is syntactic sugar for while)

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Branching

unconditional branching (i.e., GOTO statement) is very dangerous

- leads to *spaghetti code*, raises tricky questions w.r.t. scope and lifetime
  what happens when you jump out of a function/block?
  what happens when you jump into a function/block?
  what happens when you jump into the middle of a control structure?

most languages that allow GOTO's restrict their use

- in C/C++, can't jump into another function
  can jump into a block, but not past declarations

```
void foo() {
    . . .
    goto label2;      // illegal: skips declaration of str
    . . .
  label1:
    string str;
    . . .
  label2:
    goto label1;      // legal: str's lifetime ends before branch
}
```

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Branching (cont.)

why provide GOTO's at all? (Java doesn't)

- backward compatibility
- some argue for its use in specific cases (e.g., jump out of deeply nested loops)

C/C++ and Java provide statements for more controlled loop branching

- *break:* causes termination of a loop

```
while (true) {
    num = input.nextInt();
    if (num < 0) break;
    sum += num;
}
```

- *continue:* causes control to pass to the loop test

```
while (inputKey != 'Q') {
    if (keyPressed()) {
        inputKey = GetInput();
        continue;
    }
    . . .
}
```

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