Introduction to Algorithms and Data Structures

Lecture 6: Representation of program data in memory

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Representations of data

Having seen a few algorithms, we now turn to data structures: i.e. ways of representing/structuring data in memory.

In due course, we'll see how to implement our own data structures. But we start at the bottom, with the 'primitive' data structures that programming languages typically provide as built-in.

Actually, we'll begin one step further back:

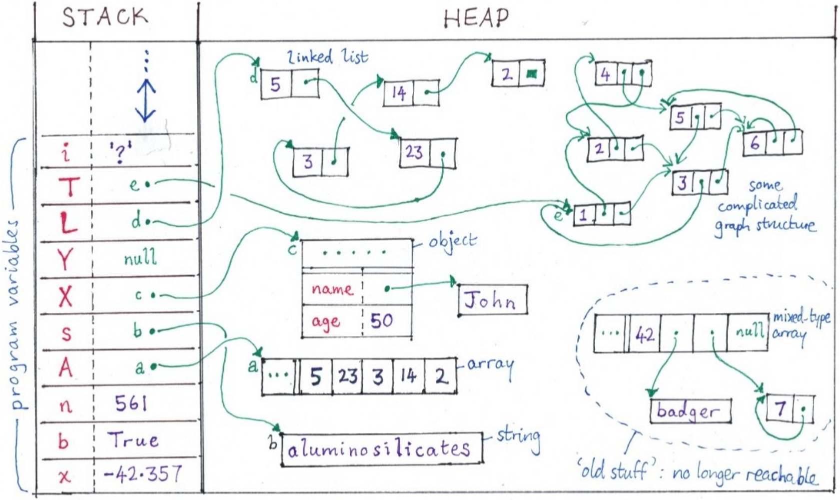
How, in general, is program data organized in memory?

Picture is broadly similar for most modern programming languages (Java, Python, Haskell, . . .): **Stack** and **Heap**.

Remember: simplifying a bit, we think of memory as consisting of words each with an address (i.e. location).

Any address can be itself be stored in a single word — though there may be fewer addresses than word values.

Typical organization of program data in memory



Program memory: summary

- Contents of program variables are stored on a stack, which grows and shrinks as variables come in and out of scope.
- Stack items are contiguously arranged in memory, so must have fixed size (e.g. 1 or 2 words).
- Typically, a stack item contains either a basic value (e.g. 561, True) or a reference to something on the heap.
- Heap objects can live anywhere in memory, be of any size, and may contain references to other heap objects.
- When heap objects are created (allocated), the memory manager will decide where to put them. But references to other objects can be changed later – so we can end up with a real mess!
- As execution proceeds, some heap objects may become unreachable. In many languages (e.g. Java, Python, Haskell), a garbage collector (i.e. memory recycler) detects this and reclaims the space.

Details may vary . . .

Our picture is mostly ‘Java-like’ (except for the mixed-type array).

- In Java, anything of reference type (including ‘objects’ and ‘arrays’) lives on the heap.
  In C, built-in ‘arrays’ live on the stack, and their size is static: an array variable A has an associated size fixed throughout its lifetime.
  In Python, pretty much everything lives on the heap.
- Python also offers ‘lists’ and ‘arrays’, both implemented much like the heap array in our picture. (Difference: ‘lists’ allow mixed types.)
  In functional programming languages (Haskell, ML, Lisp), ‘lists’ are more typically implemented as linked lists.
  Java offers many classes for ‘lists’, e.g. ArrayList, LinkedList.
- In Java, all reference types have special value `null` (‘pointer to nowhere’). Default initial value for any variable/field of ref type.
  Closest Python equivalent is `None` – this is actually a reference to a specific object, with no fields or methods.

Idea: Once we have the basic picture, we have a framework for understanding such differences.

Assignment by reference

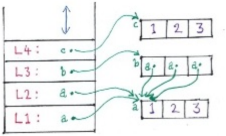
In Python or Java, assignment statements have the form

variable = *expression*

E.g. `s = "smiles"[1:5]   # assigns ref to s`

What does an expression actually evaluate to? Either a basic value or a reference to a heap object. (Or null in Java.)   List example:

```
L1 = [1,2,3]
L2 = L1
L3 = [L1,L1,L1]
L4 = L1[:]
```



This matters! Think what happens when we do `L1[2] = 5`.

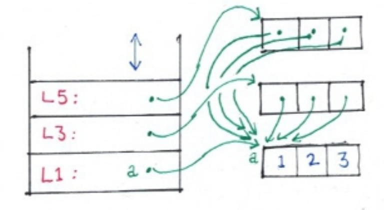
A heap object will be ‘copied’ only if we request it
(e.g. using ‘[:]’ for lists in Python).
Similarly in Java (copying often done by a clone() method).

Geek point: Technically, a small integer like 2 is itself a reference to a pre-allocated heap object. But harmless to write this ref just as ‘2’.

Shallow vs. deep cloning

In Python, '[:]' makes only a shallow clone: copies 'top level only'. E.g. think about lists of lists:

```
L1 = [1,2,3]
L3 = [L1,L1,L1]
L5 = L3[:]
```



Again, think what happens with `L1[2] = 5`.

For a deep clone (fresh copy of entire structure, with no sharing), we could in this case write `L6 = [L1[:],L1[:],L1[:]]`.

In general, may need to write a (possibly recursive) program to deep-clone the data structures in question.

Equality testing

Equality testing can be ...

- by reference ('are the addresses the same?'), or
- by value ('do we find identical things at those addresses?')

In Python, `is` means reference eq (a.k.a. identity),
`==` means (deep) value eq.

Exercise: After executing column 1, what does column 2 give?

```
L1 = [1,2,3]                    L2 is L1
L2 = L1                         L4 is L1
L3 = [L1,L1,L1]                 L2 == L1
L4 = L1[:]                      L4 == L1
L5 = L3[:]                      L6 is L3
L6 = [L1[:],L1[:],L1[:]]        L6 == L3
```

Warning: In Java, `==` means reference equality!
For value equality, typically use an `.equals` method.

For numbers and strings, always use value equality.
(Identity is unpredicatable!)

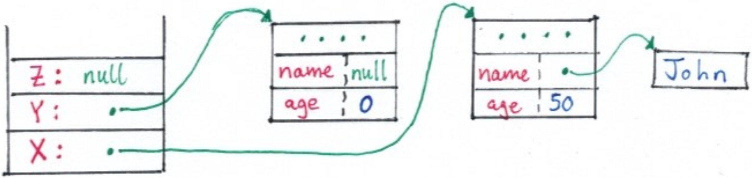
About those NullPointerExceptions

Consider a Java expression of form *expr*.*fieldname*. E.g. `X.age`.

The *expr* evaluates to a reference, or perhaps to null.

But when we pass the '.', we follow the reference to reach what it points to (dereferencing) . . . and so risk a NullPointerException if *expr* evaluates to null!

Same goes for the '.' in *expr*.*methodname*(arguments).
E.g. `X.name.length()`.



Understanding this (and drawing pictures) can go a long way towards rooting out those pesky NullPointerExceptions.

Basic operations

The following operations (among others) may all be assumed to work within constant time (i.e. $\Theta(1)$ time):

- Reading / writing contents of program variables (basic or ref type).

```
n        n = 341        X        Y = X
```

- Accessing / updating a field in a given object (involves deref).

```
X.age        X.age = 51        X.name = s
```

- Accessing / updating an entry in a given array (may involve deref).

```
A[42]        A[42] = 51
```

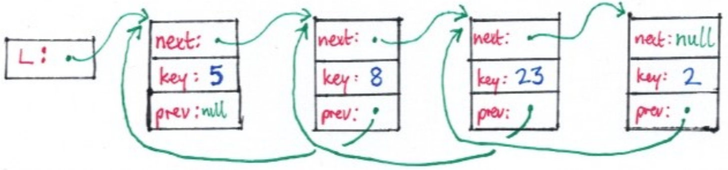
- Allocating a new object (e.g. of a given class) on the heap (not counting initialization of fields).

```
X = new Person()
```

- Allocating a new array on the heap, not counting initialization of all its entries.

Linked lists

In Java/Python, Linked list cells would typically be simple objects, e.g. of class Cell, with fields called `key`, `next` and maybe `prev`. E.g. a doubly linked list:



In functional languages, singly-linked lists are everywhere, but presentation may look more abstract. E.g.

`L.key`	written as	`head L`
`L.next`	written as	`tail L`
`new Cell(x,L)`	written as	`cons(x,L)` or `x:L`
`null`	written as	`nil` or `[]`

Anyway, find *n*th element of a linked list L takes time $\Theta(n)$.

Reading:
`https://docs.python.org/3/reference/datamodel.html`
(just 3.1);
CLRS chapter 10, especially 10.2 and 10.3.

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