Principles of Programming Languages

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Prof. Andrea Corradini
Department of Computer Science, Pisa

Lesson 24

- Composite data types (cont'd)

Summary

- Data Types in programming languages
- Type system, Type safety, Type checking
  - Equivalence, compatibility and coercion
- Primitive and composite types
  - Discrete and scalar types
  - Tuples and records
  - *Arrays*
  - *Unions*
  - *Pointers*
  - *Recursive types*

A brief overview of composite types

- We review type constructors in several languages corresponding to the following mathematical concepts:
  - Cartesian products (records and tuples)
  - mappings (arrays)
  - disjoint unions (algebraic data types, unions)
  - recursive types (lists, trees, etc.)

Mappings

- We write $m : S \rightarrow T$ to state that m is a **mapping** from set S to set T. In other words, m maps every value in S to some value in T.
- If m maps value x to value y, we write $y = m(x)$. The value y is called the **image** of x under m.
- Some of the mappings in $\{u, v\} \rightarrow \{a, b, c\}$:

$$m_1 = \{u \rightarrow a, v \rightarrow c\}$$

$$m_2 = \{u \rightarrow c, v \rightarrow c\}$$

$$m_3 = \{u \rightarrow c, v \rightarrow b\}$$

image of u is c,
image of v is b

Arrays (1)

- **Arrays** (found in all imperative and OO PLs) can be understood as mappings.
- If the array's elements are of type *T* (*base type*) and its index values are of type *S,* the array's type is $S \rightarrow T$.
- An array's **length** is the number of components, #*S*.
- Basic operations on arrays:
  - **construction** of an array from its components
  - **indexing** – using a *computed* index value to select a component.

so we *can* select the *i*th component

Arrays (2)

- An array of type $S \rightarrow T$ is a *finite* mapping.
- Here S is nearly always a finite range of consecutive values $\{l, l+1, \ldots, u\}$. This is called the array's **index range**.

lower bound upper bound

- In C and Java, the index range must be $\{0, 1, \ldots, n-1\}$. In Pascal and Ada, the index range may be any scalar (sub)type other than real/float.
- We can generalise to n-dimensional arrays. If an array has index ranges of types $S_1, \ldots, S_n$, the array's type is $S_1 \times \ldots \times S_n \rightarrow T$.

When is the index range known?

- A **static array** is an array variable whose index range is fixed by the program code.
- A **dynamic array** is an array variable whose index range is fixed at the time when the array variable is created.
  - In Ada, the definition of an array type must fix the index *type*, but need not fix the index *range*. Only when an array variable is created must its index range be fixed.
  - Arrays as formal parameters of subroutines are often dynamic (eg. *conformant arrays* in Pascal)
- A **flexible** (or **fully dynamic**) **array** is an array variable whose index range is not fixed at all, but may change whenever a new array value is assigned.

Example: C static arrays

- Array variable declarations:

```
float v1[] = {2.0, 3.0, 5.0, 7.0};
float v2[10];
```

index range is {0, …, 3}

index range is {0, …, 9}

- Function:

```
void print_vector (float v[], int n) {
// Print the array v[0], …, v[n-1] in the form "[…  …]".
   int i;
   printf("[%f", v[0]);
   for (i = 1; i < n; i++)
      printf(" %f", v[i]);
   printf("]");
}
…
print_vector(v1, 4);  print_vector(v2, 10);
```

A C array doesn't know its own length!

Example: Ada dynamic arrays

- Array type and variable declarations:

```
type Vector is
     array (Integer range <>) of Float;
v1: Vector(1 .. 4) := (1.0, 0.5, 5.0, 3.5);
v2: Vector(0 .. m) := (0 .. m => 0.0);
```

- Procedure:

```
procedure print_vector (v: in Vector) is
-- Print the array v in the form “[… … …]”.
begin
  put('[');  put(v(v'first));
  for i in v'first + 1 .. v'last loop
    put(' ');  put(v(i));
  end loop;
  put(']');
end;
…
print_vector(v1);  print_vector(v2);
```

Example: Java flexible arrays

- Array variable declarations:

```
float[] v1 = {1.0, 0.5, 5.0, 3.5};
float[] v2 = {0.0, 0.0, 0.0};
…
v1 = v2;
```

index range is {0, …, 3}

index range is {0, …, 2}

v1's index range is now {0, …, 2}

- Method:

```
static void printVector (float[] v) {
// Print the array v in the form "[… … …]".
     System.out.print("[" + v[0]);
     for (int i = 1; i < v.length; i++)
       System.out.print(" " + v[i]);
     System.out.print("]");
}
…
printVector(v1);  printVector(v2);
```

Enhanced for:

```
for  (float f : v)
System.out.print(" " + f)
```

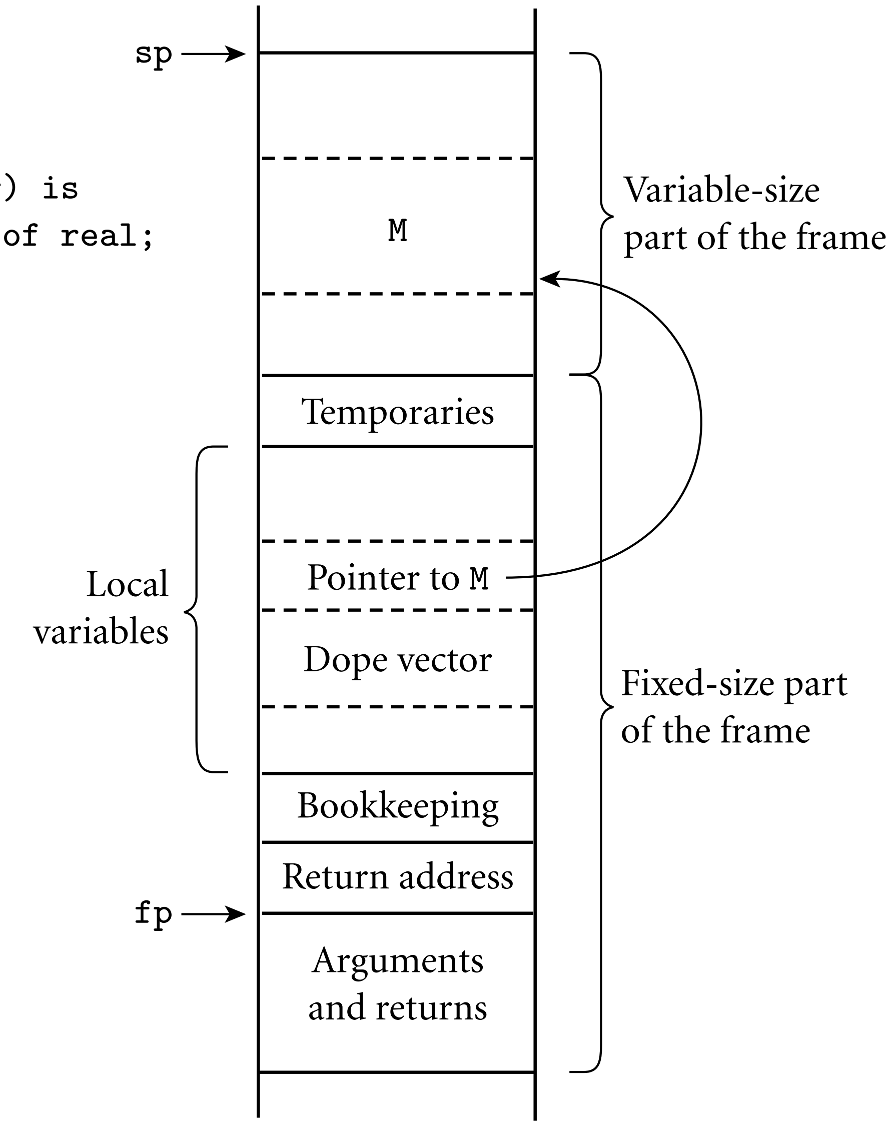
Array allocation

- ***static array, global lifetime*** **—** If a static array can exist throughout the execution of the program, then the compiler can allocate space for it in *static global memory*
- ***static array, local lifetime*** **—** If a static array should not exist throughout the execution of the program, then space can be allocated *in the subroutine's stack frame* at run time.
- ***dynamic array, local lifetime*** **—** If the index range is known at runtime, the array can still be allocated *in the stack*, but in a variable size area
- ***fully dynamic*** **—** If the index range can be modified at runtime it has to be allocated *in the heap*

Allocation of dynamic arrays on stack

```
-- Ada:
procedure foo (size : integer) is
M : array (1..size, 1..size) of real;
...
begin
    ...
end foo;
```

```
// C99:
void foo(int size) {
    double M[size][size];
    ...
}
```



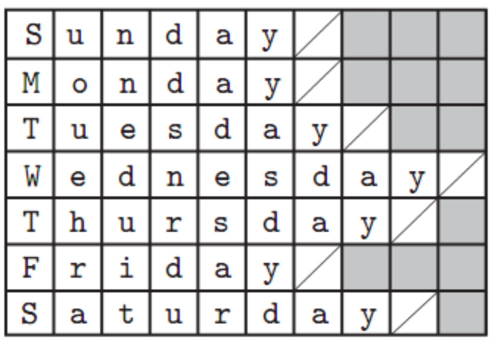
Arrays: memory layout

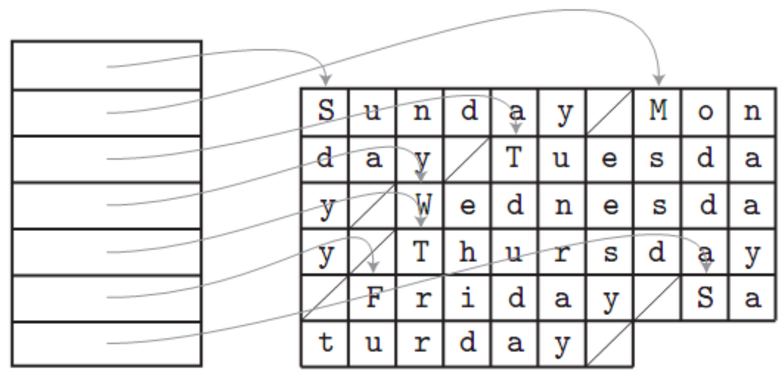
- Contiguous elements
  - column major - only in Fortran
  - row major
    - used by everybody else
- Row pointers
  - an option in C, the rule in Java
  - allows rows to be put anywhere - nice for big arrays on machines with segmentation problems
  - avoids multiplication
  - nice for matrices whose rows are of different lengths
    - e.g. an array of strings
  - requires extra space for the pointers

Arrays' memory layout in C

```
char days[][10] = {
    "Sunday", "Monday", "Tuesday",
    "Wednesday", "Thursday",
    "Friday", "Saturday"
};
...
days[2][3] == 's';   /* in Tuesday */
```

```
char *days[] = {
    "Sunday", "Monday", "Tuesday",
    "Wednesday", "Thursday",
    "Friday", "Saturday"
};
...
days[2][3] == 's';   /* in Tuesday */
```





- Address computation varies a lot
- With contiguous allocation part of the computation can be done statically

Strings

- A **string** is a sequence of 0 or more characters.
- Usually ad-hoc syntax is supported
- Some PLs (ML, Python) treat strings as *primitive*.
- Haskell treats strings as *lists* of characters. Strings are thus equipped with general list operations (length, head selection, tail selection, concatenation, …).
- Ada treats strings as *arrays* of characters. Strings are thus equipped with general array operations (length, indexing, slicing, concatenation, …).
- Java treats strings as *objects*, of class `String`.

Disjoint Union (1)

- In a **disjoint union**, a value is chosen from one of several different types.
- Let ***S + T*** stand for a set of disjoint-union values, each of which consists of a **tag** together with a **variant** chosen from either type *S* or type *T*. The tag indicates the type of the variant:

  $$S + T \;=\; \{\, \mathit{left}\ x \mid x \in S \,\} \cup \{\, \mathit{right}\ y \mid y \in T \,\}$$

  - *left x* is a value with tag *left* and variant *x* chosen from *S*
  - *right x* is a value with tag *right* and variant *y* chosen from *T*.
- We write ***left S + right T*** (instead of *S* + *T*) when we want to make the tags explicit.

Disjoint Union (2)

- Basic operations on disjoint-union values in $S + T$:
  - **construction** of a disjoint-union value from its tag and variant
  - **tag test**, to determine whether the variant was chosen from S or T
  - **projection**, to recover either the variant in S or the variant in T.
- **Algebraic data types** (Haskell), **discriminated records** (Ada), **unions** (C) and **objects** (Java) can all be understood in terms of disjoint unions.
- We can generalise to multiple variants: $S_1 + S_2 + \ldots + S_n$.

Example: Haskell/ML algebraic data types

- Type declaration:

```
data Number = Exact Int | Inexact Float
```

Each Number value consists of a tag, together with either an Integer variant (if the tag is *Exact*) or a Float variant (if the tag is *Inexact*).

- Application code:

```
pi = Inexact 3.1416

rounded :: Number -> Integer
rounded num =
   case num of
    Exact i   -> i
    Inexact r -> round r
```

projection (by pattern matching)

Variant records (unions)

- Origin: Fortran I *equivalence statement:* variables should share the same memory location
- C's *union* types
- Motivations:
  - Saving space
  - Need of different access to the same memory locations for system programming
  - Alternative configurations of a data type

Fortran I -- equivalence statement

```
integer i
real r
logical b
equivalence (i, r, b)
```

C -- union

```
union {
    int i;
    double d;
    _Bool b;
};
```

Variant records (unions) (2)

- In Ada, Pascal, unions are *discriminated* by a tag, called *discriminant*
- Integrated with records in Pascal/Ada, not in C

ADA – discriminated variant

tag

```
type Form is
     (pointy, circular, rectangular);
type Figure (f: Form := pointy) is record
       x, y: Float;
       case f is
          when pointy      => null;
          when circular    => r: Float;
          when rectangular => w, h: Float;
       end case;
     end record;
```

Using discriminated records in Ada

- Application code:

```
box: Figure :=
    (rectangular, 1.5, 2.0, 3.0, 4.0);
function area (fig: Figure) return Float
is
begin
   case fig.f is
      when pointy =>
         return 0.0;
      when circular =>
         return 3.1416 * fig.r**2;
      when rectangular =>
         return fig.w * fig.h;
   end case;
end;
```

discriminated-record construction

tag test

projection

(Lack of) Safety in variant records

- Only Ada has strict rules for assignment: tag and variant have to be changed *together*
- For *nondiscriminated unions* (Fortran, C) no runtime check: responsibility of the programmer
- In Pascal the tag field can be modified independently of the variant. Even worse: the tag field is optional.
- Unions not included in Modula 3, Java, and recent OO laguages: replaced by classes + inheritance

Example: Java objects (1)

- Type declarations:

```
class Point {
  private float x, y;
  …   // methods
}
class Circle extends Point {
  private float r;
  …   // methods
}
class Rectangle extends Point {
  private float w, h;
  …   // methods
}
```

inherits x and y from Point

inherits x and y from Point

Example: Java objects (2)

- Methods:

```
class Point {
  …
  public float area()
  { return 0.0; }
}
class Circle extends Point {
  …
  public float area()
  { return 3.1416 * r * r; }
}
class Rectangle extends Point {
  …
  public float area()
  { return w * h; }
}
```

overrides Point's area() method (Circle's area())

overrides Point's area() method (Rectangle's area())

Example: Java objects (3)

- Application code:

```
Rectangle box =
    new Rectangle(1.5, 2.0, 3.0,4.0);

float a1 = box.area();
Point it = …;
float a2 = it.area();
```

it can refer to a Point, Circle, or Rectangle object

calls the appropriate area() method

Value model vs. reference model

- What happens when a composite value is assigned to a variable of the same type?
- **Value model** (aka **copy semantics**): all components of the composite value are copied into the corresponding components of the composite variable.
- **Reference model**: the composite variable is made to contain a reference to the composite value.
- **Note:** this makes no difference for basic or immutable types.

- C and Ada adopt copy semantics.
- Java adopts value model for primitive values, reference model for objects.
- Functional languages usually adopt the reference model

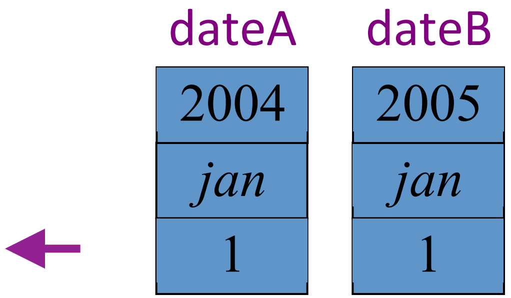
Example: Ada value model (1)

- Declarations:

```
type Date is
     record
        y: Year_Number;
        m: Month;
        d: Day_Number;
     end record;
dateA: Date := (2004, jan, 1);
dateB: Date;
```

- Effect of copy semantics:

```
dateB := dateA;
dateB.y := 2005;
```



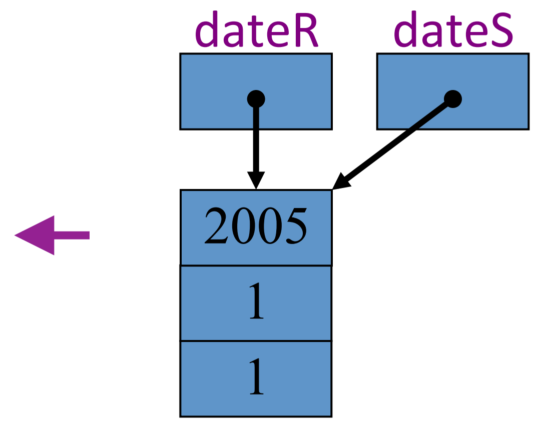
Example: Java reference model (1)

- Declarations:

```
class Date {
  int y, m, d;
  public Date (int y, int m, int d)
{ … }
}
Date dateR = new Date(2004, 1, 1);
Date dateS = new Date(2004, 12, 25);
```

- Effect of reference semantics:

```
dateS = dateR;
dateR.y = 2005;
```



Ada reference model with pointers (2)

- We can achieve the *effect* of reference model in Ada by using explicit ***pointers***:

```
type Date_Pointer is access Date;
Date_Pointer dateP = new Date;
Date_Pointer dateQ = new Date;
…
dateP.all := dateA;
dateQ := dateP;
```

Java value model with cloning (2)

- We can achieve the *effect* of copy semantics in Java by cloning:

```
Date dateR = new Date(2004, 4, 1);
dateT = dateR.clone();
```

Pointers

- Thus in a language adopting the *value model*, the *reference model* can be simulated with the use of pointers.
- A **pointer** (value) is a reference to a particular variable.
- A pointer's **referent** is the variable to which it refers.
- A **null pointer** is a special pointer value that has no referent.
- A pointer is essentially the address of its referent in the store, but it also has a *type*. The type of a pointer allows us to infer the type of its referent.
- Pointers mainly serve two purposes:
  – efficient (sometimes intuitive) access to elaborated objects (as in C)
  – dynamic creation of linked data structures, in conjunction with a heap storage manager

Dangling pointers

- A **dangling pointer** is a pointer to a variable that has been destroyed.
- Dangling pointers arise from the following situations:
  - where a pointer to a heap variable still exists after the heap variable is destroyed by a deallocator
  - where a pointer to a local variable still exists at exit from the block in which the local variable was declared.
- A deallocator immediately destroys a heap variable. All existing pointers to that heap variable become dangling pointers.
- Thus deallocators are inherently unsafe.

Dangling pointers in languages

- C is highly unsafe:
  - After a heap variable is destroyed, pointers to it might still exist.
  - At exit from a block, pointers to its local variables might still exist (e.g., stored in global variables).
- Ada and Pascal are safer:
  - After a heap variable is destroyed, pointers to it might still exist.
  - But pointers to local variables may not be stored in global variables.
- Java is very safe:
  - It has no deallocator.
  - Pointers to local variables cannot be obtained.
- Functional languages are even safer:
  - they don't have pointers

Example: C dangling pointers

- Consider this C code:

```
struct Date {int y, m, d;};
struct Date* dateP, dateQ;
dateP = (struct Date*)malloc(sizeof (struct Date));
dateP->y = 2004; dateP->m = 1; dateP->d = 1;
dateQ = dateP;
free(dateQ);

printf("%d", dateP->y);
dateP->y = 2005;
```

allocates a new heap variable

makes dateQ point to the same heap variable as dateP

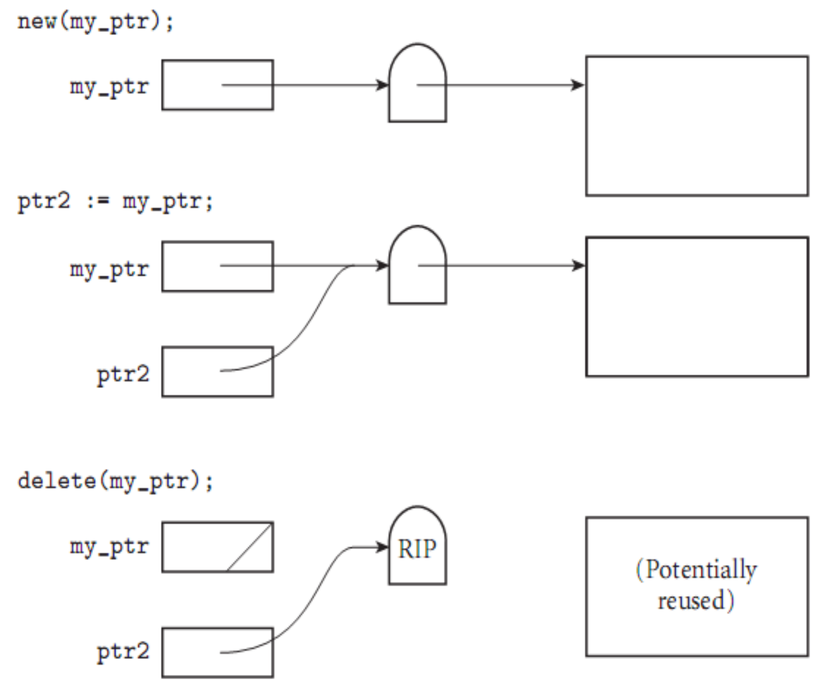
deallocates that heap variable (dateP and dateQ are now dangling pointers)

fails

fails

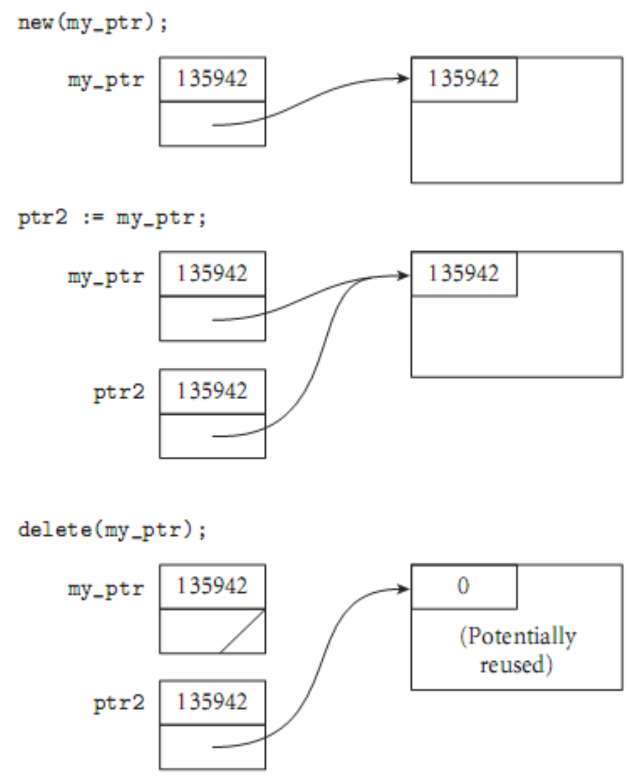
Techniques to avoid dangling pointers

- Tombstones
  - A pointer variable refers to a *tombstone* that in turn refers to an object
  - If the object is destroyed, the tombstone is marked as "expired"



Locks and Keys

- Heap objects are associated with an integer (lock) initialized when created.
- A valid pointer contains a key that matches the lock on the object in the heap.
- Every access checks that they match
- A dangling reference is unlikely to match.



Pointers and arrays in C

- In C, an array variable is a pointer to its first element

```
int *a == int a[]
int **a == int *a[]
```

- BUT equivalences don't always hold
  - Specifically, a declaration allocates an array if it specifies a size for the first dimension, otherwise it allocates a pointer

`int **a, int *a[]` pointer to pointer to `int`

`int *a[n],` n-element array of row pointers

`int a[n][m],` 2-d array

- Pointer arithmetics: operations on pointers are scaled by the base type size. All these expressions denote the third element of **a**:

`a[2]` **`(a+2)[0]`** **`(a+1)[1]`** **`2[a]`** **`0[a+2]`**

C pointers and recursive types

- C declaration rule: read right as far as you can (subject to parentheses), then left, then out a level and repeat

```
int *a[n], n-element array of pointers to integer
int (*a)[n], pointer to n-element array of
  integers
```

- Compiler has to be able to tell the size of the things to which you point
  - So the following aren't valid:

```
int a[][]       bad
int (*a)[]      bad
```

Recursive types: Lists

- A **recursive type** is one defined in terms of itself, like lists and trees
- A **list** is a sequence of 0 or more component values.
- The **length** of a list is its number of components. The **empty list** has no components.
- A non-empty list consists of a **head** (its first component) and a **tail** (all but its first component).
- A list is **homogeneous** if all its components are of the same type. Otherwise it is **heterogeneous**.

List operations

- Typical list operations:
  - length
  - emptiness test
  - head selection
  - tail selection
  - concatenation.

Example: Haskell lists

- Type declaration for integer-lists:

```
data IntList = Nil | Cons Int IntList
```

recursive

- Some IntList constructions:

    Nil

    Cons 2 (Cons 3 (Cons 5 (Cons 7 Nil)))

- Actually, Haskell has built-in list types:

    [Int]   [String]   [[Int]]

- Some list constructions:

    []   [2,3,5,7]   ["cat","dog"]   [[1],[2,3]]

- Built-in operator for cons

    [2,3,5,7] = 2:[3,5,7] = 2:3:5:[7] = 2:3:5:7:[]

Example: Ada lists

- Type declarations for integer-lists:

```
type IntNode;
type IntList is access IntNode;
type IntNode is record
     head: Integer;
     tail: IntList;
   end record;
```

mutually recursive

- An IntList construction:

```
new IntNode'(2,
    new IntNode'(3,
        new IntNode'(5,
            new IntNode'(7, null)))
```

Example: Java lists

- Class declarations for generic lists:

```
class List<E> {
  public E head;
  public List<E> tail;
  public List<E> (E el, List<E> t) {
     head = h;  tail = t;
  }
}
```

recursive

- A list construction:

```
List<Integer> list =
    new List<Integer>(2,
        new List<Integer>(3,
             new List<integer>(5, null))));
```