Data Types

- **Two components:**
  - **set of objects in the type**
  - **applicable operations**
- **May be determined:**
  - **statically (at compile time)**
  - **dynamically (at run time)**
- **A language's data types may be:**
  - **built-in**
  - **programmer-defined**
- **Languages may be:**
  - **strongly typed**
  - **weakly typed (untyped?)**

Primitive Types

- **Scalars:**
  - **arithmetic types**
  - **logical types**
  - **boolean types (T,F)**
  - **strings (may be a structure in some cases)**
  - **characters**
- **Structures:**
  - **arrays**
  - **lists**
  - **records**
  - **associative arrays (see PERL)**
- **Program elements:**
  - **program units**

Strings

- **Array of char or primitive string type**
- **Length**
  - **fixed (static)**
  - **limited dynamic (dynamic up to the point of first allocation, static thereafter)**
  - **dynamic**
- **Operations**
  - **substring reference**
  - **(con)catenation**
  - **relational operations**
  - **pattern matching**

Implementing Strings

- **Static**
  - **Need length descriptor only at compile-time**
- **Limited dynamic**
  - **Need max length and current length descriptors at runtime**
- **Dynamic**
  - **Need current length descriptor at runtime**
  - **Dynamic storage allocation:**

    linked list

    continuous memory

Ordinal Types

- **Each element can be associated with an integer**
  - ➸ **character**
  - ➸ **boolean**
  - ➸ **user-defined**

    enumeration

    Can a literal appear in more than one type? If so, how to distinguish?

    ```
    alphabet = [a..z]
    vowles = [a,e,i,o,u]
    ```

    subrange

    How to typecheck?

    ```
    i: integer;
    j: 1..10;
    ...
    j := i;        -- prohibit, or check dynamically?
    ```


Arrays (finite mappings)

- **homogeneous**
- **index computed dynamically**
- **binding of**

	subscript range	**storage**
***static*:**	**compile time**	**compile time**
fixed stack-dynamic	**compile time**	**declaration elaboration time**
***stack-dynamic*:**	**runtime, but fixed for lifetime**	
***heap-dynamic*:**	**runtime**	**runtime**

- **Fixed stack-dynamic and Stack-dynamic**
  - ➸ **a'first, a'last, a'length**
- **Type compatibility of arrays?**

Implementing Arrays

- **Stored contiguously**
- **Access ith element of a, where**
  - **b = address of a[1]**
  - **e = size of one element**

addr(a[i]) = b + e * (i - 1)

= b + ei - e

= b - e + ei

may know statically

compute dynamically

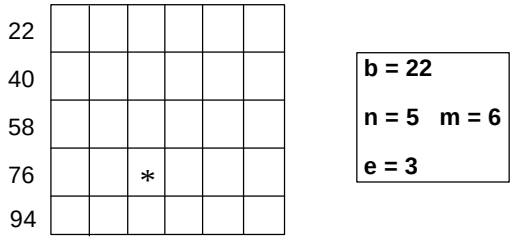
Multidimensional Arrays

- **Storage layout**
  - **row major**
  - **column major**
- **Row-major access a[i,j], where**
  - **b = address of a[1,1]**
  - **n x m = dimensions of a**
  - **e = size of one element**

addr(a[i,j]) = b + ((i - 1) * m + (j - 1)) * e

beginning of ith row

offset in ith row



a [4, 3] = 22 + (3 * 6 + 2) * 3 = 82

Records (Cartesian product)

- **heterogeneous**
- **selector determined statically (why?)**
- **implementation**
  - ➸ **fields stored contiguously**
  - ➸ **offset of each field known statically**
  - ➸ **no runtime info necessary**

Union Types

- **may store different types during execution**
- ***discriminated* union ==> tag stores type of current value**
- **e.g., Pascal variant record**

```
type rec =
    record
        case flag : bool of
            true : (x : integer;
                    y : char);
            false : (z : real)
    end

var ex : rec;
ex.flag := true;
ex.x := 5
```

Type-checking Issues with Union Types

- **system must check value of flag before each variable access**

```
ex.flag := true;
ex.x := 10;
:
:
print(ex.z);     -- error
```

- **still not good enough!**

```
ex.flag := true;
ex.x := 5;
ex.y := 'a';
ex.flag := false;
print (ex.z);    -- this should be an error, but how to check
```


Pascal Free Union

- **Declaration**

```
type rec = record
  case bool of
    true : . . .
    false : . . .
  end
```

- **No storage for tag, so union is inherently unsafe.**
- **So Pascal's union type is insecure in at least two ways.**

Ada Union Types

- **Similar to Pascal, except**
  - ➸ **no free union**
  - ➸ **when tag is changed, all fields must be set too.**

```
ex := (flag => false,
       z => 1.5)
```

- **So Ada union types are safe.**
  - ➸ **Ada systems <u>required</u> to check the tag of all references to variants**

Algol 68 Union Types

- **Declaration**

```
union (int, real) ir1, ir2
```

  - ➸ **Can <u>assign</u> either type . . .**

```
ir1 := 5;
...
ir1 := 3.4;
```

  - ➸ **. . . but need conformity clause to <u>access</u> value**

```
real x;
int count;
...
count := ir1;       -- illegal

case ir1 in
   (int i) : count := i;
   (real r) : x := r;
esac
```

Type-checked statically, chosen dynamically

Sets

- **E.g.,**

```
type day = (Sun, Mon, Tue, Wed, Thu, Fri, Sat);
work_days: set of day;
class_days: set of day;
church_days: set of day;
late_days, early_days, long_days, really_long_days: set of day;

late_days := work_days ∩ class_days;
early_days := work_days ∩ church_days;
long_days := late_days ∪ early_days;
really_long_days := late_days ∩ early_days;
```

- **Main issue: cardinality of base set.**
- **For efficiency,**
  - **max set size £ word length**
  - **then**

    union = *or*

    intersection = *and* etc...

- **But larger sets should be available, for a price. . .**

Pointers

- **Should be able to point to only one type of object**
- **Dereferencing**
  - **explicit**
  - **implicit**
- **Used for**
  - **dynamic vars only**
  - **any kind of variable**

Dangling References

- **Pointer to variable that has been deallocated.**

Pascal:

```
var p,q : ^cell;
begin
  new(p);
  q := p;
  dispose(p);
```

-- q is a dangling ref.

C:

```
int *p;
int fun1();
{ int x;
  p = &x;
  ...
}
main ();
fun1 ();
```

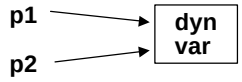
-- *p is a dangling ref.

Preventing Dangling References

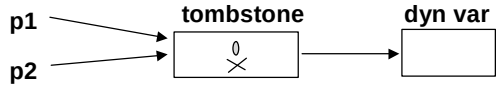
- **Tombstones**
  - ➡ **Pointers can't point directly to a dynamic variable**

    extra level of indirection called a *tombstone*.

without tombstone:



with tombstone:



Safe, but add space and time overhead

Preventing Dangling References (continued)

- **Locks and Keys**
  - **Additional information stored with pointers and dynamic variables:**

    pointer ≡ (key, address)

    dynamic variable ≡ (lock, var)
  - **A pointer can only access a dynamic variable if its key matches the lock.**
  - **When a dynamic variable is deallocated, its lock is changed.**
  - **Again, space and time overhead.**

Garbage ("dangling objects")

- **An object is garbage if it is stored in an inaccessible memory address.**
  - **Pascal:**

```
var p,q : ^cell;
begin
  new(p);
  new(q);
    ...          -- assuming no dispose or reassign
  p := q;
```

  - **original p^'s storage is now garbage**
  - **Wasteful, but not dangerous.**

Heap Management

- ***Allocation***
  - **Maintain a free list of available memory cells**
- ***Deallocation* (Reclamation)**
- **method 1: Reference Counting**
  - **Each cell has a tag with # of pointers to that cell.**
  - **When reference count = 0 => deallocate cell.**
  - **Advantage:**

    cost is distributed over time
  - **Disadvantages:**

    space/time overhead in maintaining reference counts

    won't collect circular structures

Heap Management (continued)

- **method 2a: Garbage Collection with mark-and-sweep**
  - **Each cell has a mark bit.**
  - **Mark and Sweep:**

    set all mark bits to "garbage"

    for each pointer into the heap, mark all reachable cells "not garbage"

    look at each cell in memory; if marked "garbage," reclaim.
  - **Advantages:**

    reclaims all garbage

    little space/no time overhead *during normal execution*
  - **Disadvantages:**

    must stop execution to garbage collect

    fragmentation

    time ~ memory size
  - **M&S initiated when system runs out of memory**

Heap Management (continued)

- **method 2b: Garbage Collection with copying**
  - **Start with two heaps of same size**

    working heap

    other heap
  - **Copying:**

    allocate new cells in *working heap*

    when *working heap* is full,

    for each pointer into *working heap*, copy all reachable cells into *other heap*.

    other heap is new *working heap*, *working heap* is new *other heap*
  - **Advantages:**

    both advantages of mark & sweep (reclaims all garbage, little space/no time overhead during normal execution)

    time ~ used cells, not total memory size

    automatic compaction (ameliorates fragmentation)
  - **Disadvantages**

    stopping to copy still a problem

    need twice as much memory for heap => only practical with virtual memory systems

Heap Management (continued)

- **This is all much easier for fixed-size allocate/deallocate than for variable-size:**
  - **Fixed size (& format)** **Lisp**

    Know where pointers are within cells — to reclaim linked list (avoid garbage)

    Fragmentation not a problem
  - **Variable size (& format)**

    Need header for each object in memory telling:

    its size

    where it may contain pointers to other objects

    Fragmentation is a problem--need compaction