Data Types

- Two components:
  - → range of allowable values
  - → available 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?)

Type Compatibility

- **name**
  - → **efficient but restrictive**
- **structural**
  - → **flexible, harder to implement**
  - → **Issues:**

    hard to make types incompatible

    what is considered the same structure?

      array [0..10] of int

      array [1..11] of int

Strings

- Array of char or primitive string type
- Length
  → fixed
  → limited dynamic
  → 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
semistatic:	compile time	decl. elaboration time
semidyn:	runtime, but fixed for lifetime	
dynamic:	runtime	runtime

- Semidynamic & 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

$$\text{addr}(a[i]) = b + e * (i - 1)$$
$$= b + ei - e$$
$$= b - e + ei$$

may know statically

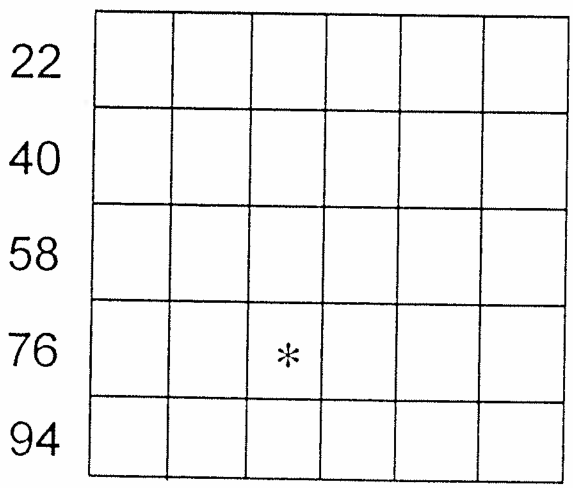
compute dynamically

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

$$addr(a[i,j]) = b + \underbrace{((i - 1) * m}_{\text{beginning of ith row}} + \underbrace{(j - 1)) * e}_{\text{offset in ith row}}$$



b = 22

n = 5   m = 6

e = 3

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

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
ex.flag := false
```

Type-checking Issues with Union Types

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

```
ex.flag := true;
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

- **Delcaration**

```
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.**

Algol 68 Union Types

- **Declaration**

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

→ **Can assign either type . . .**

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

. . . but need conformity clause to access 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

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 ();
```

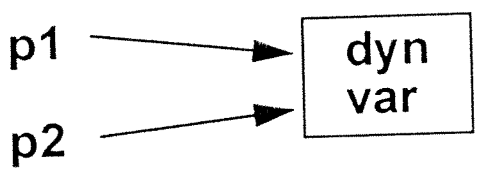
-- *p is a dangling ref.

Preventing Dangling References

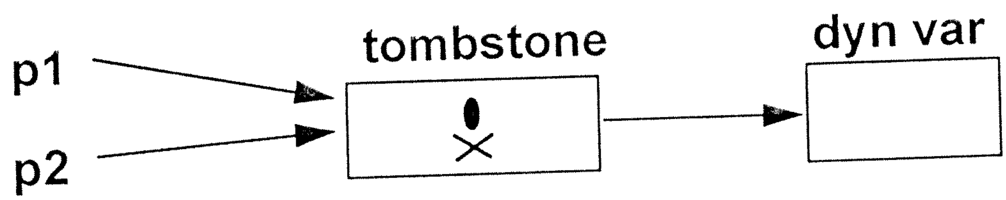
- **Tombstones**
  - → **Pointers can't point directly to a dynamic variable**

    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 ina 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

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)**

    Know where pointers are within cells

    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 <u>compaction</u>