Types

Chapters 7, 8

Data Types

- Types provide implicit context for operations
- C: `a + b`
  - integer/floating point addition
- Pascal: `new p`
  - allocate right size
- C: `new my_type()`
  - allocate right size
  - call right constructor

Data Types

- Boolean
  - true/false; one byte, sometimes one bit
  - C: integers, true = non-0, false = 0
- Character
  - one byte – ASCII
  - two bytes - Unicode
- Numeric
  - integers, reals
  - complex: C, Fortran, Scheme (pair of floats)
  - rational: Scheme (pair of integers)
- Discrete (or ordinal)
  - integers, Booleans, characters
  - countable, well-define predecessor/successor
- Scalar (or simple): discrete, rational, real, complex

Data Types

- Enumeration
  - introduced in Pascal:

```
type weekday = (sun, mon, tue, wed, thu, fri, sat);
```

  - ordered: `mon < tue`; can index an array
- Subrange: `type test_score = 0..100`
- Composite (non-scalar)
  - Records (struct) – collection of fields
  - Arrays – most common; map from index to elements
    - strings = arrays of characters
  - Sets – powerset of base type
  - Pointers –references to objects; recursive data types
  - Lists – sequence; no map; recursive definition, fundamental in functional programming
  - Files – like arrays but with current position

Type checking

- *Type equivalence*: two types are the same
- *Type compatibility*: a type can be used in a context
- *Type inference*: deduce the type from components
- *Type clash*: violation of type rules

Type Systems

- *Strongly typed* language
  - prohibits any application of an operation to an object that is not intended to support that operation
- *Statically typed* language
  - strongly typed
  - at compile time – good performance
  - C, C++, Java
  - C: more strongly typed with each new version
- *Dynamically typed* language
  - at run time - ease of programming
  - Scheme, Lisp, Smalltalk – strongly typed
  - Scripting: Python, Ruby – strongly typed

Type Checking: Equivalence

- *Structural equivalence*
  - same components put together in the same way
  - C, Algol-68, Modula-3, ML
- *Name equivalence*
  - lexical occurrence
  - each definition is a new type
  - Java, C#, Pascal

Type Checking: Equivalence

- Structural equivalence:
  - format should not matter

```
type R1 = record
  a, b : integer
end;
```

```
type R1 = record
  a : integer;
  b : integer;
end;
```

  - What about order? (most languages consider it equivalent)

```
type R3 = record
 b : integer;
 a : integer
end;
```

Type Checking: Equivalence

- Structural equivalence: problem

```
type student = record
   name, address : string
   age : integer
type school = record
   name, address : string
   age : integer
x : student;
y : school;
…
x := y; -- is this an error?
```

- compiler says it's okay
- programmer most likely says it's an error

Type Checking: Equivalence

- Name equivalence
  - Distinct definitions mean distinct types
  - If the programmer takes the time to write two type definitions, then they are different types
  - Aliases

```
type new_type = old_type (* Algol syntax *)
typedef old_type new_type /* C syntax */
```

  - Are aliases the same or different types?
  - Different: *strict name equivalence*
  - Same: *loose name equivalence*

Type Checking: Equivalence

- Strict name equiv.:
  - `blink` different from `alink`
  - `p,q` – same type; `r,u` – same type
- Loose name equiv.:
  - `blink, alink` – same type
  - `p,q` – same type; `r,s,u` – same type
- Structural equiv.:
  - `p,q,r,s,t,u` – same type

```
type cell = ...              -- whatever
type alink = pointer to cell
type blink = alink           -- alias
p, q : pointer to cell
r : alink
s : blink
t : pointer to cell
u : alink
```

Type Checking: Conversion

- *Type conversion* (*cast*): **explicit** conversion

```
r = (float) n;
```

- *Type coercion:* **implicit** conversion
  - very useful
  - weakens type security
  - dynamically typed languages: very important
  - statically typed languages: wide variety
    - C: arrays and pointers intermixed
    - C++: programmer-defined coercion to and from existing types to a new type (class)

Type Checking: Compatibility

- *Type compatibility*
  - more important than equivalence
  - most of the time we need compatibility
  - assignment: RHS compatible with LHS
  - operation: operands types compatible with a common type that supports the operation
  - subroutine call: arguments types compatible with formal parameters types

Type Checking: Inference

- *Type inference*
  - infer expression type from components
  - int + int => int
  - float + float => float
  - subranges cause complications

```
type Atype = 0..20; Btype = 10..20;
var a : Atype; b : Btype;
```

  - What is the type of `a + b` ?

Type Checking: Inference

- Type inference
  - declarations: type inferred from the context

  - C#: `var`

```
var i = 123;
// equiv. to:
int i = 123;

var map = new Dictionary<string, int>();
// equiv. to:
Dictionary<string, int> map = new
Dictionary<string, int>();
```

Type Checking: Inference

- C++: `auto`

```
auto reduce = [](list<int> L, int f(int, int), int s) {
             for (auto e : L) { s = f(e, s); }
             return s;
             };
...
int sum = reduce(my_list, [](int a,int b){return a+b;}, 0);
int prod = reduce(my_list, [](int a,int b){return a+b;}, 1);
```

- the `auto` keyword allows to omit the type:

```
int (*reduce) (list<int>, int (*)(int, int), int)
      = [](list<int> L, int f(int, int), int s) {
             for (auto e : L) { s = f(e, s); }
             return s;
             };
```

Type Checking: Inference

- C++: `decltype`
  - match the type of an existing expression
  - the type of `sum` depends on the types of `A` and `B` under the coercion rules of C++
  - both `int` gives `int`
  - one is `double` gives `double`

```
template <typename A, typename B>
...
   A a;
   B b;
   decltype(a + b) sum;
```

Polymorphism

- *Polymorphism* (polymorphous = multiform)
- code works with multiple types
  - must have common characteristics
- *parametric polymorphism*: take a type as parameter
  - explicit parametric polymorphism (*generics,* C++: *templates*) appears in statically typed languages
  - implemented at compile time
- *subtype polymorphism*: code works with subtypes
  - object-oriented languages
- combination (subtype + parametric polymorphism)
  - container classes
  - `List<T>`, `Stack<T>`; `T` instantiated later

Polymorphism

- *Implicit*:
  - Scheme:
    `(define min (lambda (a b) (if (< a b) a b)))`
  - applied to arguments of any type to which it can be applied
  - disadvantage: checked dynamically
- *Explicit*: *generics*
  - C++: *templates*
  - checked statically
- Generics in object-oriented programming
  - parametrize entire class
  - *container*

Polymorphism

- Ada example: overloading (left) vs generics (right)

```
function min(x, y : integer)
    return integer is
begin
    if x < y then return x;
    else return y;
    end if;
end min;

function min(x, y : long_float)
    return long_float is
begin
    if x < y then return x;
    else return y;
    end if;
end min;
```

```
generic
    type T is private;
    with function "<"(x, y : T) return Boolean;
function min(x, y : T) return T;

function min(x, y : T) return T is
begin
    if x < y then return x;
    else return y;
    end if;
end min;

function int_min is new min(integer, "<");
function real_min is new min(long_float, "<");
function string_min is new min(string, "<");
function date_min is new min(date, date_precedes);
```

- C++ example

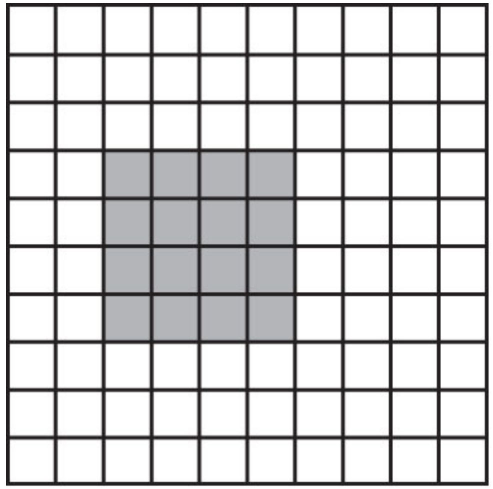
```
template<class item, int max_items = 100>
class queue {
    item items[max_items];
    int next_free, next_full, num_items;
public:
    queue() : next_free(0), next_full(0), num_items(0) { }
    bool enqueue(const item& it) {
        if (num_items == max_items) return false;
        ++num_items;  items[next_free] = it;
        next_free = (next_free + 1) % max_items;
        return true;
    }
    bool dequeue(item* it) {
        if (num_items == 0) return false;
        --num_items;  *it = items[next_full];
        next_full = (next_full + 1) % max_items;
        return true;
    }
};
...
queue<process> ready_list;
queue<int, 50> int_queue;
```

Arrays

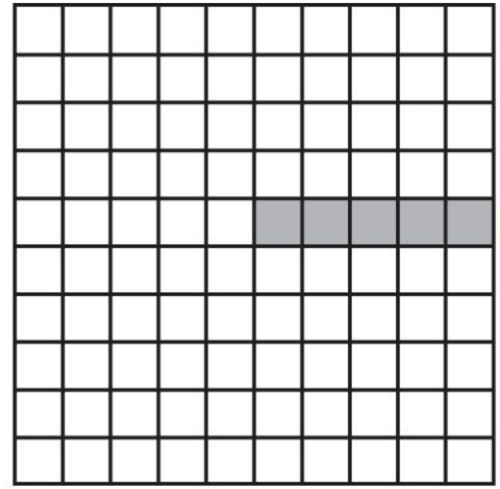
- Arrays
  - the most important composite data type
  - semantically, map: index type → element type
- Homogenous data
- Index type
  - usually discrete type: int, char, enum, subranges of those
  - non-discrete type: *associative array*, *dictionary*, *map*
    - implemented using hash tables or search trees
- Dense – most positions non-zero
  - sparse arrays – stored using linked structures

Arrays

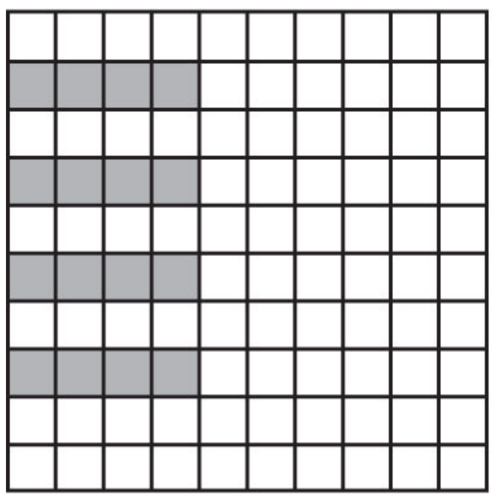
- Slices



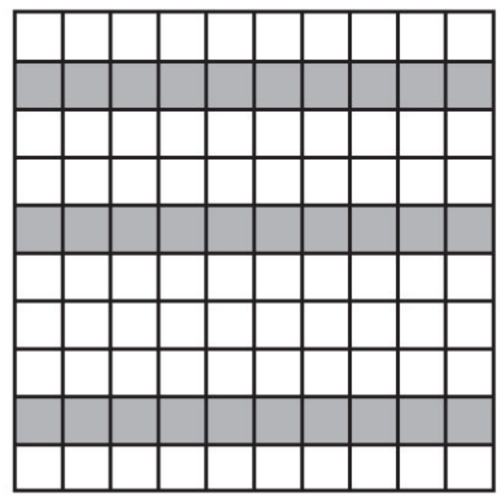
`matrix(3:6, 4:7)`



`matrix(6:, 5)`



`matrix(:4, 2:8:2)`



`matrix(:, (/2, 5, 9/))`

Arrays: Dimensions, Bounds, Allocation

- Static allocation:
  - array with lifetime the entire program
  - shape known at compile time
- Stack allocation:
  - array with lifetime inside subroutine
  - shape known at compile time
- Heap / stack allocation
  - dynamically allocated arrays
  - *dope vector*: holds shape information at run time
  - compiled languages need the number of dimensions
  - shape known at elaboration time – can allocate on stack
  - shape changes during execution: allocated on heap

Arrays

- Example: C dynamic local array

```
void square(int n, double M[n][n]) {
   double T[n][n];
   for (int i = 0; i < n; i++) { // copy product to T
      for (int j = 0; j < n; j++) {
         double s = 0;
         for (int k = 0; k < n; k++)
            s += M[i][k] * M[k][j];
         T[i][j] = s;
      }
   }
   for (int i = 0; i < n; i++) {// copy T back to M
      for (int j = 0; j < n; j++)
         M[i][j] = T[i][j];
   }
}
```

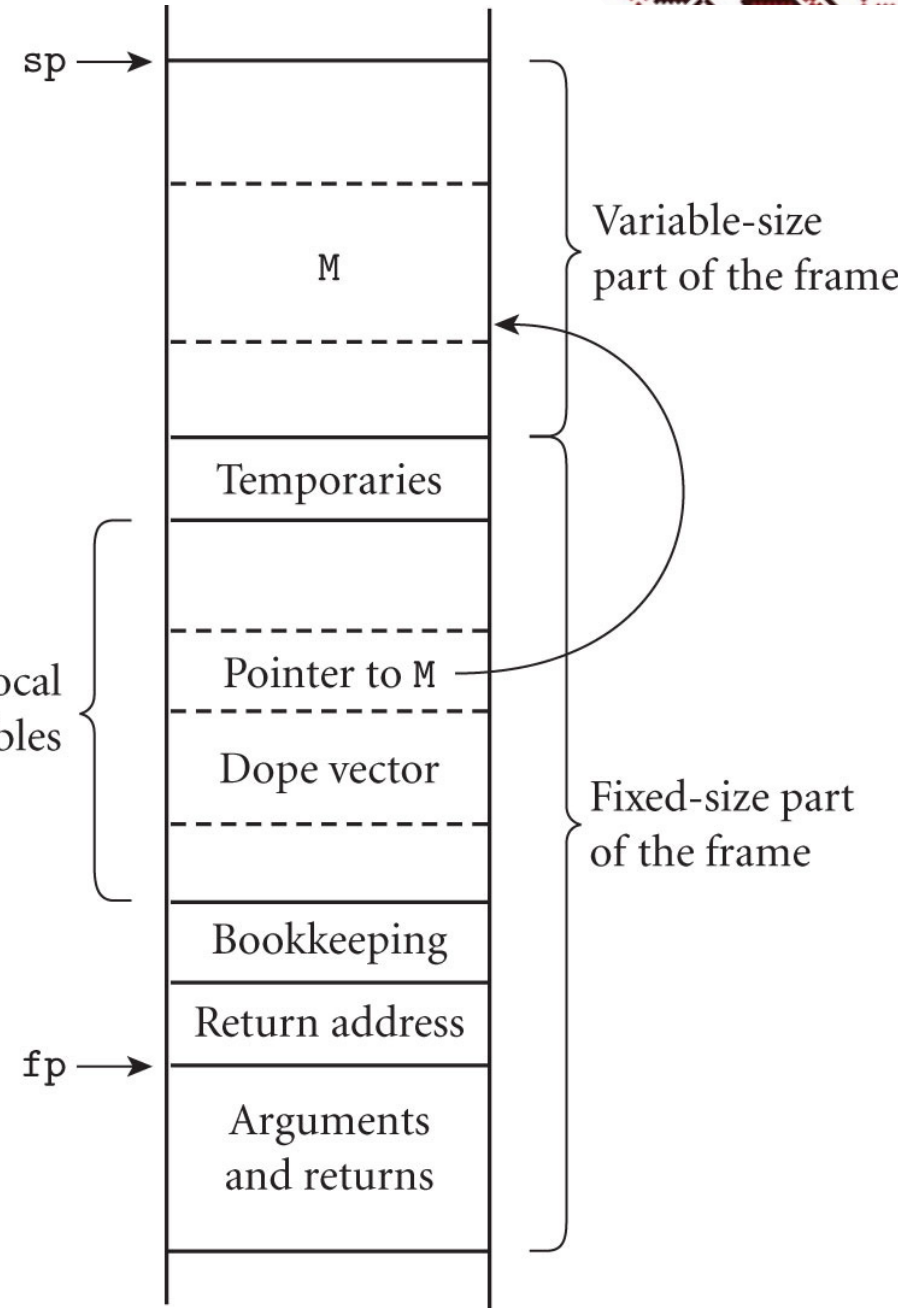
Arrays

- Shape known at elaboration time
  - can be allocated on stack
  - in the variable-size part

- Example:

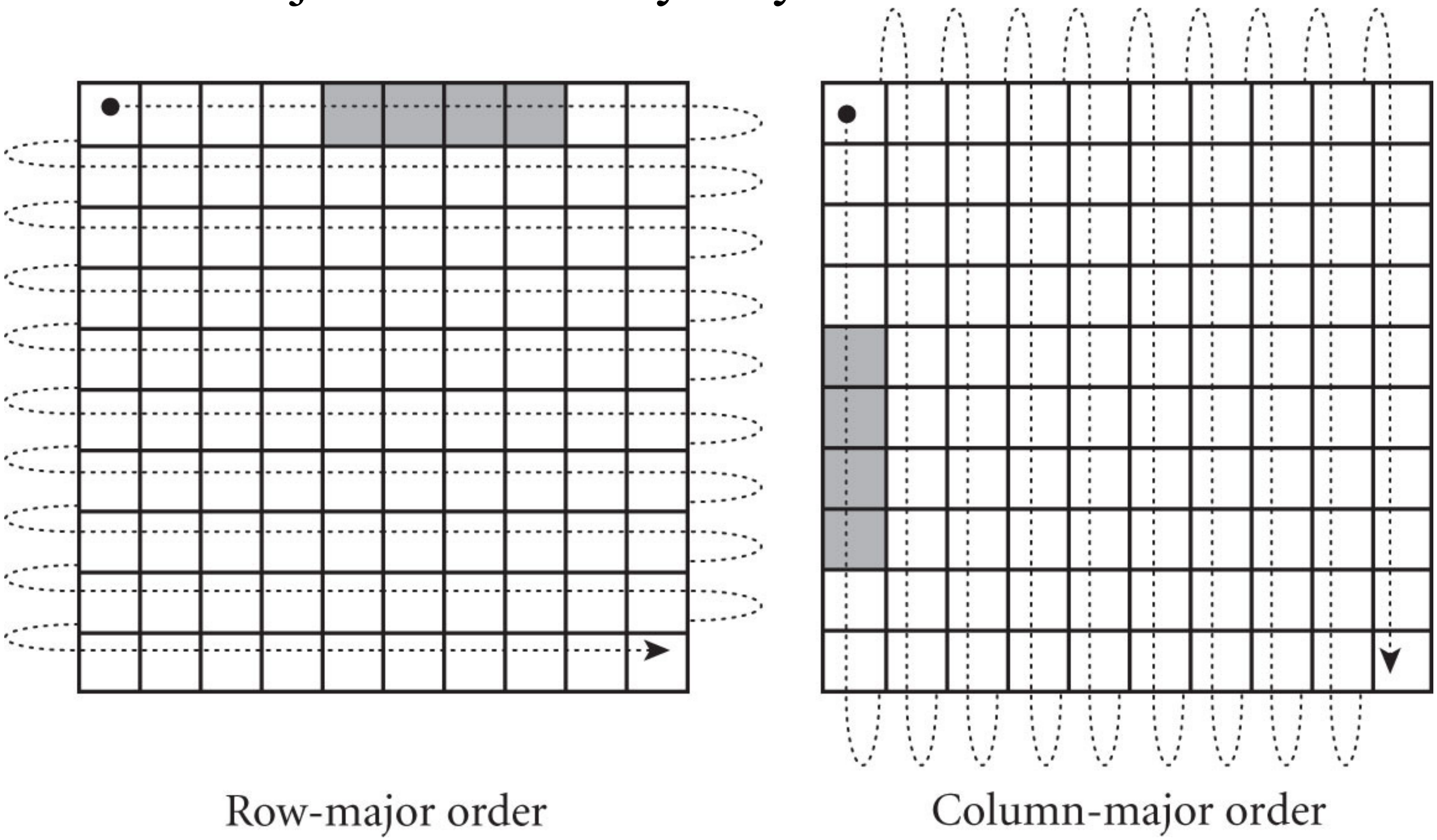
```
// C99:
void foo (int size) {
   double M[size][size];
   ...
}
```

is



Arrays

- Memory layout
  - column major order – Fortran
  - row major order – everybody else



Arrays

- Memory layout
- Contiguous allocation
  - consecutive locations in memory: `A[2,4], A[2,5]`
  - consecutive rows adjacent in memory
- Row pointers
  - consecutive rows anywhere in memory
  - extra memory for pointers
  - rows can have different lengths (ragged array)
  - can construct an array from existing rows without copying
- C, C++, C# - allow both
- Java – only row-pointer for all arrays

Arrays

- Example: C – array of strings
  - true two-dimensional array

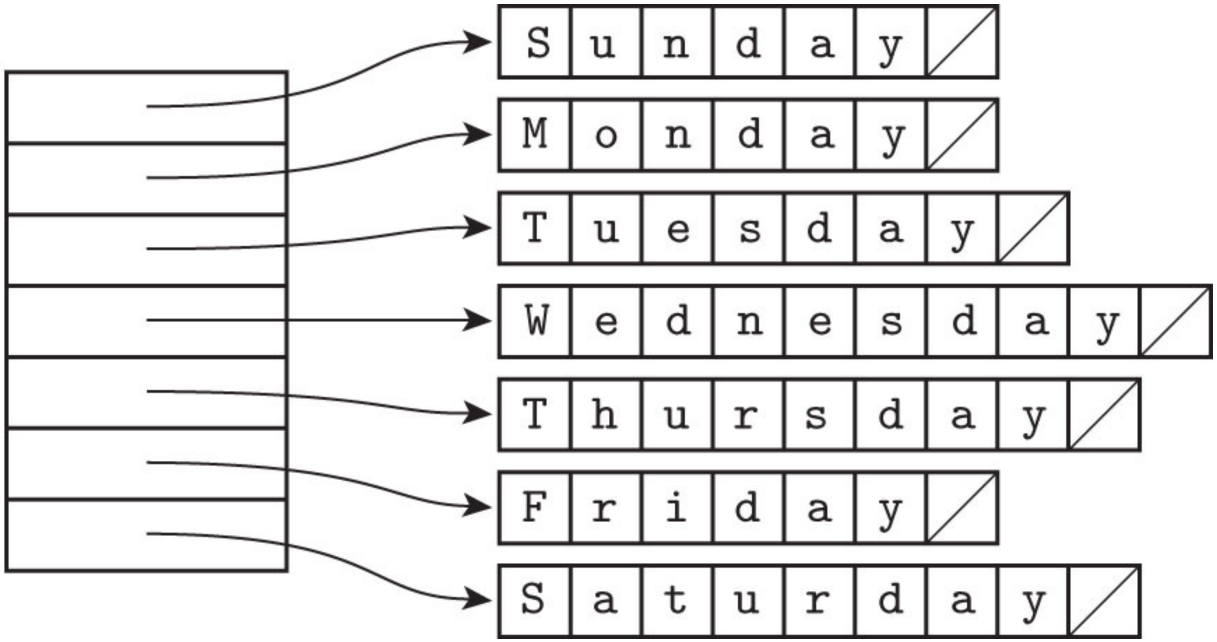
```
char days[][10] = {
      "Sunday", "Monday", "Tuesday",
      "Wednesday", "Thursday",
      "Friday", "Saturday"
};
...
days[2][3] == ’s’;  /* in Tuesday */
```

S	u	n	d	a	y				
M	o	n	d	a	y				
T	u	e	s	d	a	y			
W	e	d	n	e	s	d	a	y	
T	h	u	r	s	d	a	y		
F	r	i	d	a	y				
S	a	t	u	r	d	a	y		

Arrays

- Example: C – array of strings
  - array of pointers

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



Arrays

- Address calculation

```
A : array [L₁..U₁] of array [L₂..U₂] of array
    [L₃..U₃] of elem_type;
```

S_3 = size of `elem_type`

$S_2 = (U_3 - L_3 + 1) \times S_3$

$S_1 = (U_2 - L_2 + 1) \times S_2$

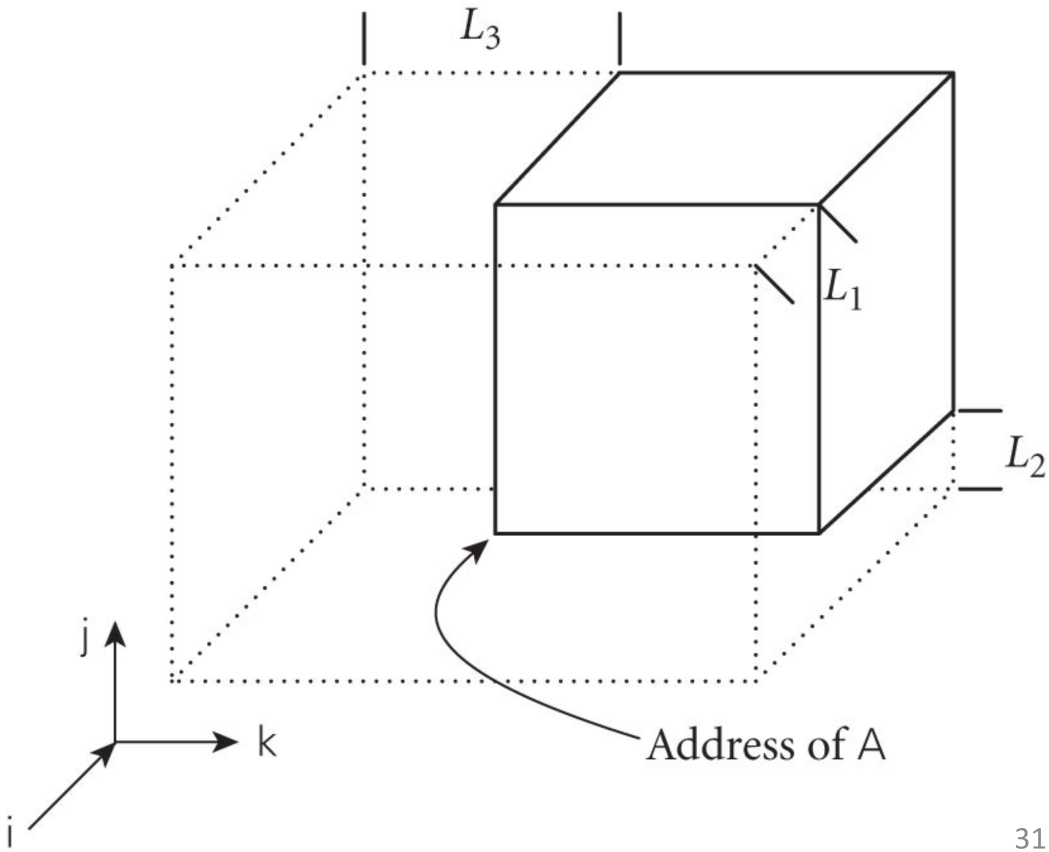
address of `A[i,j,k]`

$= $ address of `A`

$+ (i - L_1) \times S_1$

$+ (j - L_2) \times S_2$

$+ (k - L_3) \times S_3$



Arrays

- Faster address calculation

address of `A[i,j,k]`

$$= \text{address of } \mathtt{A} + (i - L_1) \times S_1 + (j - L_2) \times S_2 + (k - L_3) \times S_3$$

- Fewer operations
  - $C = [(L_1 \times S_1) + (L_2 \times S_2) + (L_3 \times S_3)]$
  - C – known at compile time

address of `A[i,j,k]`

$$= \text{address of A} + (i \times S_1) + (j \times S_2) + (k \times S_3) - C$$

Sets

- *Set*: unordered collection of an arbitrary number of distinct values of a common type
- Implementation
  - *characteristic array* – one bit for each value (small base type)
    - efficient operations – bitwise op
  - general implementation: hash tables, trees, etc.
  - Python, Swift – built-in sets
  - Others use dictionaries, hashes, maps

```
X = set(['a', 'b', 'c', 'd']) # set constructor
Y = {'c', 'd', 'e', ‘f’}      # set literal
U = X | Y                     # union
I = X & Y                     # intersection
D = X - Y                     # difference
O = X ^ Y                     # symmetric diff.
'c' in I                      # membership
```

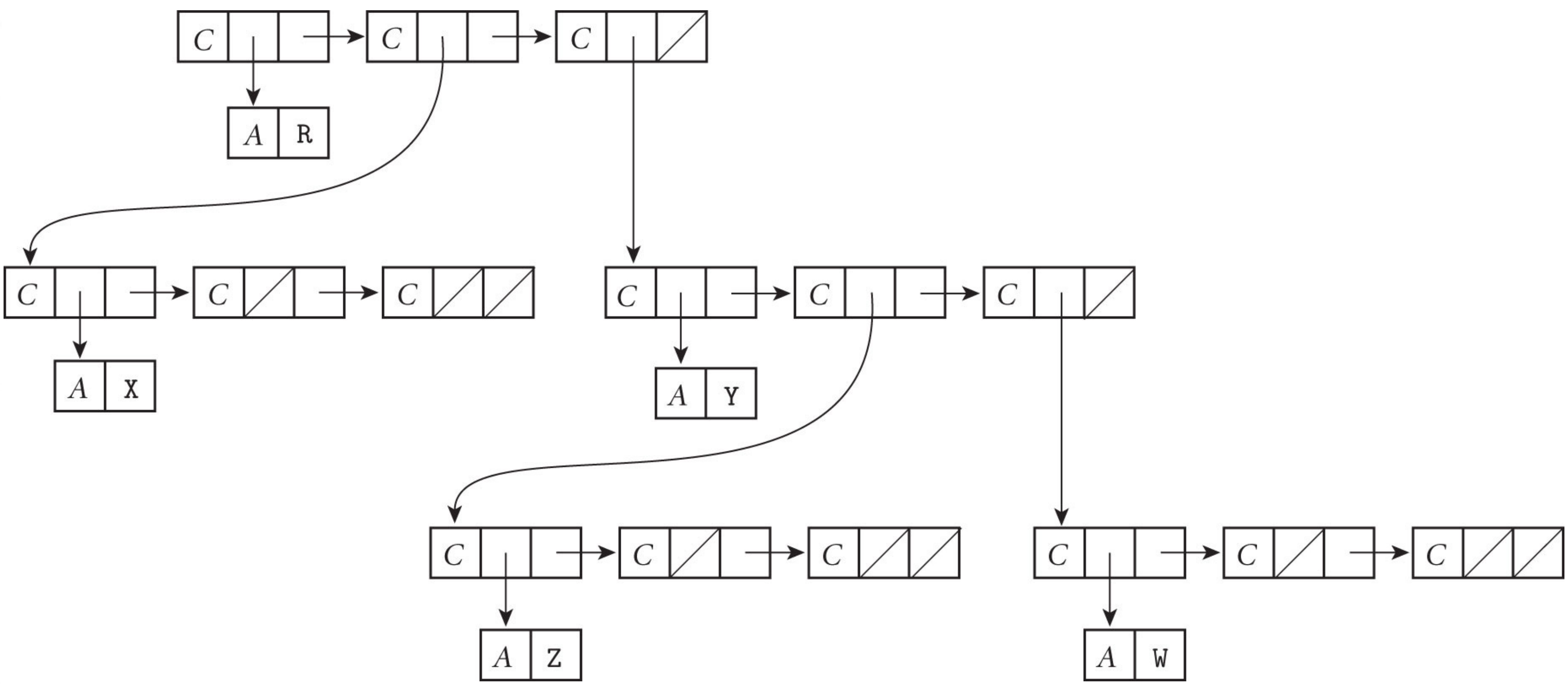
Pointers and Recursive Types

- *Pointer*
  - a variable whose value is a reference to some object
  - not needed with a reference model of variables
  - needed with a value model of variables
  - efficient access to complicated objects
- *Recursive type*
  - objects contain references to other objects
  - can create dynamic data structures
- Pointer ≠ address
  - pointer = high-level concept; reference to object
  - address = low-level concept; location in memory
  - pointers are implemented as addresses

Pointers and Recursive Types

- Reference model example: Tree in Scheme
- Two types of objects: (1) `cons` cells (2) atoms

```
'(#\R (#\X ()()) (#\Y (#\Z ()()) (#\W ()())))
```



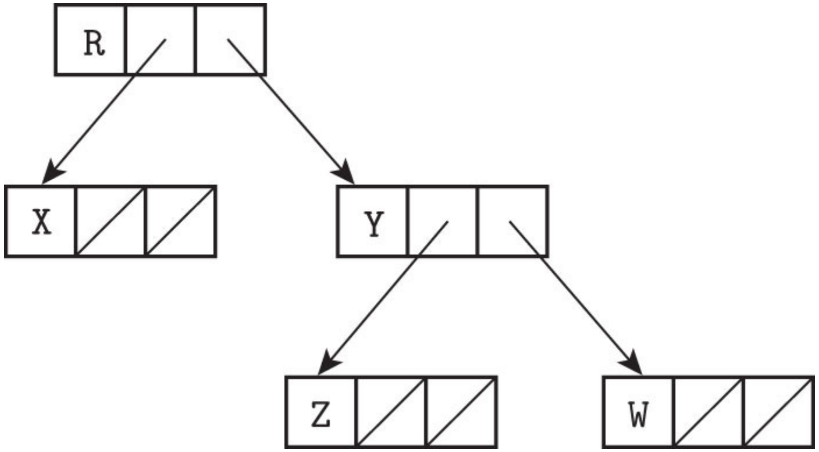
Pointers and Recursive Types

- Value model example: Tree in C

```
struct chr_tree {
   struct chr_tree *left, *right;
   char val;
};
my_ptr = malloc(sizeof(struct chr_tree));
```

- C++, Java, C# – type safe

```
     my_ptr = new chr_tree(arg_list);
(*my_ptr).val = 'X';
my_ptr->val = 'X';
```



Pointers and Recursive Types

- *Dangling reference*
  - live pointer that no longer points to a valid object
  - Example: caused by local variable after subroutine return:

```
int i = 3;
int *p = &i;
...
void foo(){ int n = 5; p = &n; }
...
cout << *p;        // prints 3
foo();
...
cout << *p; // undefined behavior: n is no
                        longer live
```

Pointers and Recursive Types

- Dangling reference
  - Example: caused by manual deallocation:

```
int *p = new int;
*p = 3;
...
cout << *p;      // prints 3
delete p;
...
cout << *p; // undefined behavior: *p has been
                             reclaimed
```

- Problem: a dangling reference can write to memory that is part of a different object; it may even interfere with bookkeeping, corrupting the stack or heap

Garbage collection

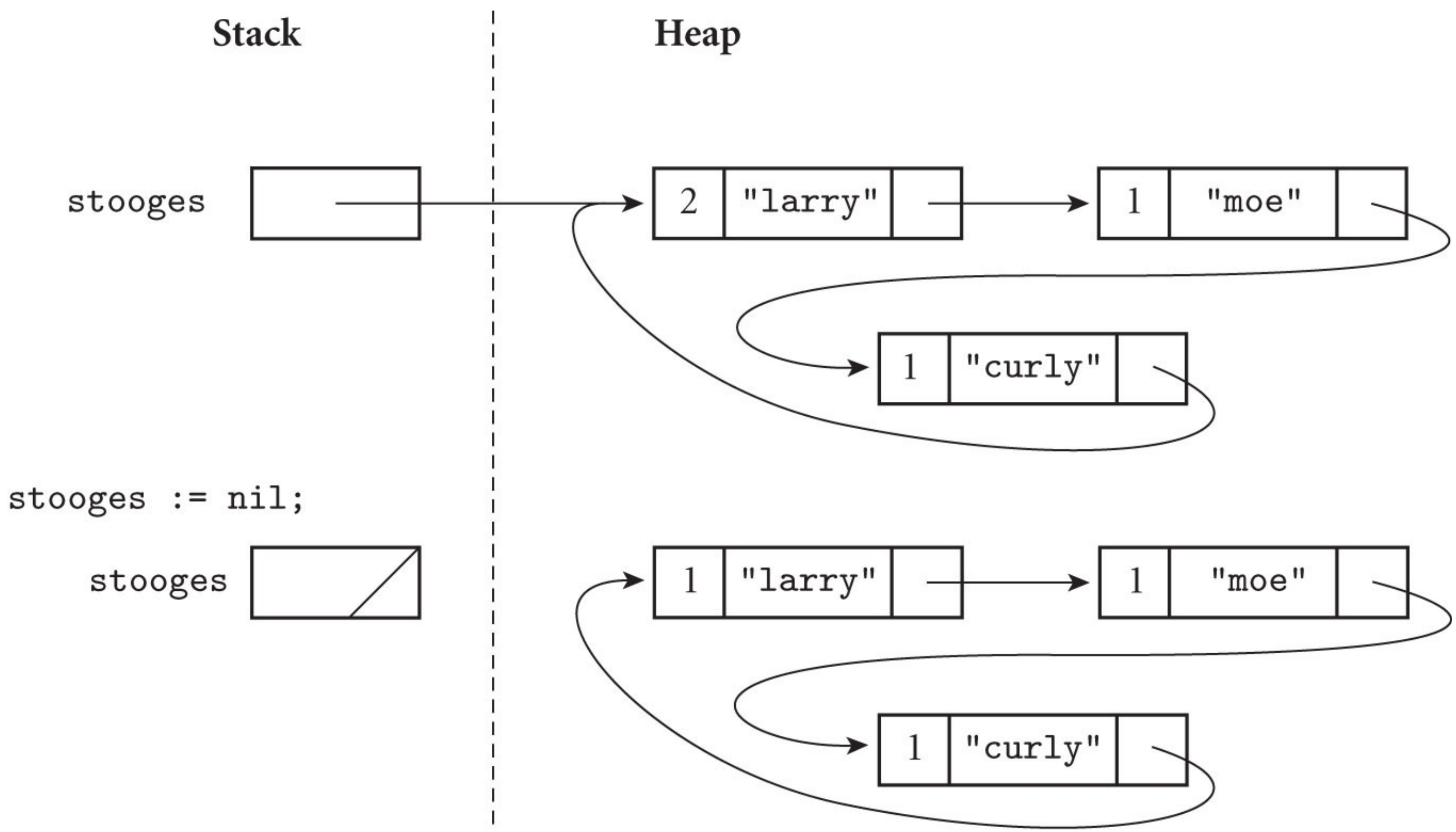
- *Garbage collection*
  - automatic reclamation of memory
  - slower than manual (`delete`)
  - difficult to implement
  - eliminates the need to check for dangling references
  - very convenient for programmers
  - essential for functional languages
  - increasingly popular in imperative languages
    - Java, C#

Garbage collection

- *Reference counts*
  - object no longer useful when no pointers to it exist
  - store *reference count* for each object
    - initially set to 1
    - update when assigning pointers
    - update on subroutine return
    - when 0, reclaim object

Garbage collection

- Reference counts
  - count ≠ 0 does not necessarily mean useful (circular lists)



Garbage collection

- Smart pointers in C++
- `unique_ptr`
  - one object only
- `shared_ptr`
  - implements a reference count
- `weak_ptr`
  - does not affect counts; for, e.g., circular structures

Garbage collection

- *Tracing collection*
  - object useful if reachable via chain of valid pointers from outside the heap
  - *Mark-and-sweep*

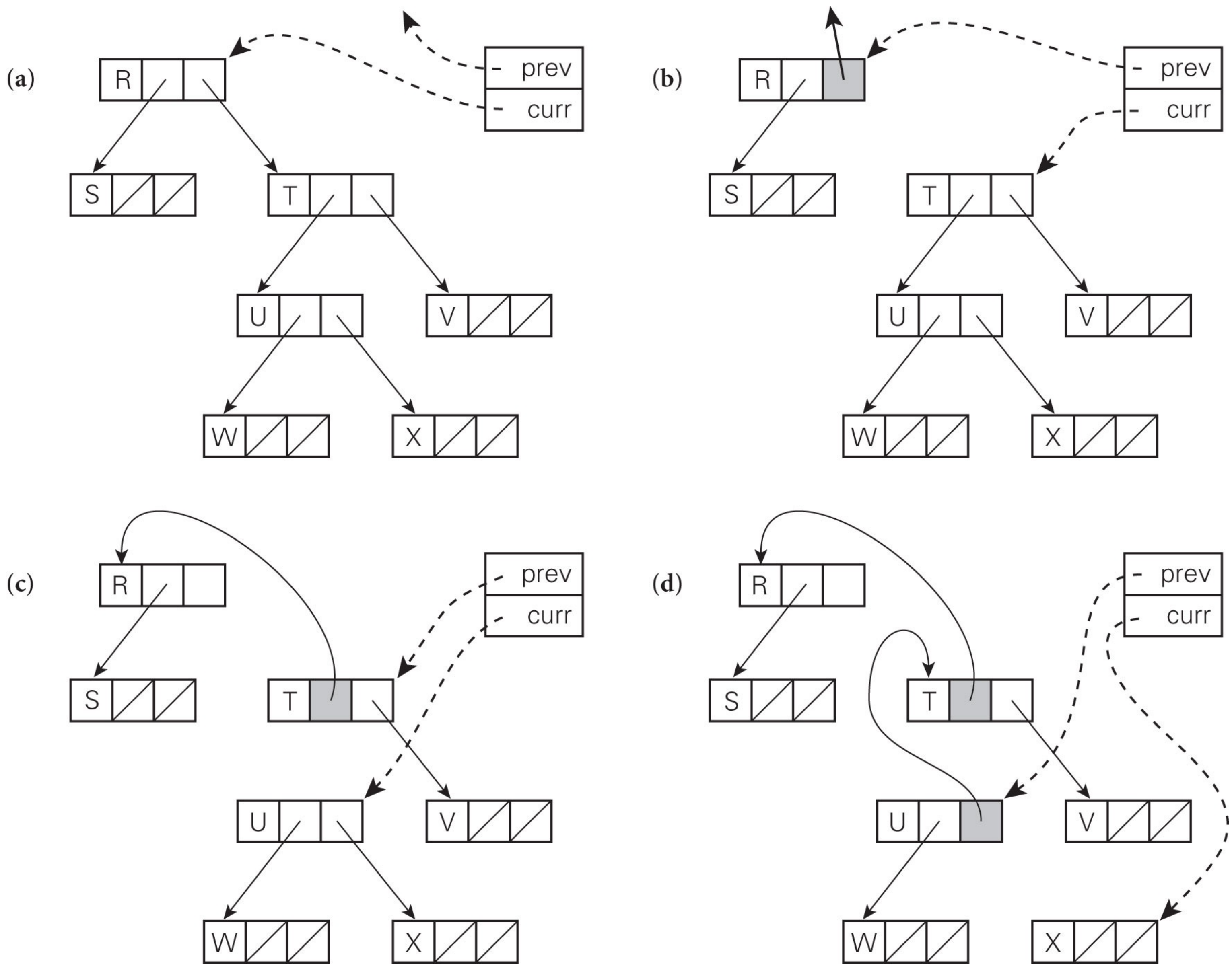
    (1) mark entire heap as "useless"

    (2) staring from outside heap, recursively mark as "useful"

    (3) move "useless" block from heap to free list

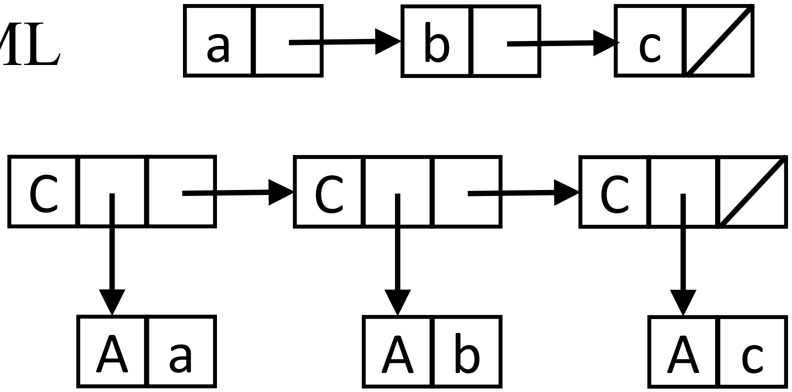
  - Step (2) requires a potentially very large stack
  - Without stack: *pointer reversal* (next slide)
- *Stop-and-copy*: defragmentation
  - use half of heap; copy useful data compactly to the other one

Pointer reversal



Lists

- *List*: empty or (head + tail)
- essential in functional and logic programming (recursive)
- used also in imperative languages
- *Homogeneous* (same type): ML
- *Heterogeneous*: Scheme



Lists

- Scheme:
  - `'(...)` prevents evaluation; also `(quote (...))`

```
 (+ 1 2) ⟹ 3
'(+ 1 2) ⟹ '(+ 1 2)
```

```
(cons 'a '(b))           ⟹ '(a b)
(car '(a b))             ⟹ a
(car '())                ⟹ error
(cdr '(a b c))           ⟹ '(b c)
(cdr '(a))               ⟹ '()
(cdr '())                ⟹ error
(append '(a b) '(c d)) ⟹ '(a b c d)
```

Lists

- *List comprehension*
  - adapted from traditional math set notation:
    $\{i \times i \mid i \in \{1, \ldots, 10\} \wedge i \bmod 2 = 1\}$
  - Example: Python

```
[i*i for i in range(1, 10) if i % 2 == 1]
      ⇒ [1, 9, 25, 49, 81]
```