Names, Scopes and Bindings

Chapter 3

Name, Scope, and Binding

- *Ease of programming* – main driving force behind the design of modern languages
- Core issues in language design:
  - names – abstraction
  - control flow
  - types, composite types
  - subroutines – control abstraction
  - classes – data abstraction
- High level programming – more abstract
  - Farther from hardware
- *Abstraction* – complexity becomes manageable
  - This is true in general

Name, Scope, and Binding

- *Name*: a character string representing something else
  - Abstraction
  - Easy for humans to understand
  - Much better than addresses
- *Binding*: association of two things
  - Example: between a name and the thing it names
- *Scope* of a binding: the part of the program (textually) in which the binding is active
- *Binding Time*: the point at which a binding is created

Binding

- Static vs. Dynamic
  - *Static*: bound before run time
  - *Dynamic*: bound at run time
- Trade-off:
  - *Early* binding times: greater *efficiency*
  - *Late* binding times: greater *flexibility*
- Compiled vs. Interpreted languages
  - *Compiled* languages tend to have *early* binding times
  - *Interpreted* languages tend to have *late* binding times

Language	Binding Time	Advantage
Compiled	Early (static)	Efficiency
Interpreted	Late (dynamic)	Flexibility

Lifetime and Storage Management

- *Lifetime* of name-to-binding:
  - from creation to destruction
  - Object's lifetime ≥ binding's lifetime
    - Example: C++ variable passed by reference (`&`)
  - Object's lifetime < binding's lifetime – *dangling reference*
    - Example: C++ object
      - created with `new`
      - passed by reference to subroutine with `&`
      - deallocated with `delete`

- *Scope of a binding*:
  - the textual region of the program in which the binding is *active*

Lifetime and Storage Management

- *Storage Allocation* mechanisms:

- Static
  - absolute address, retained throughout the program
- Stack
  - last-in, first-out order; for subroutines calls and returns
- Heap
  - allocated and deallocated at arbitrary times

Lifetime and Storage Management

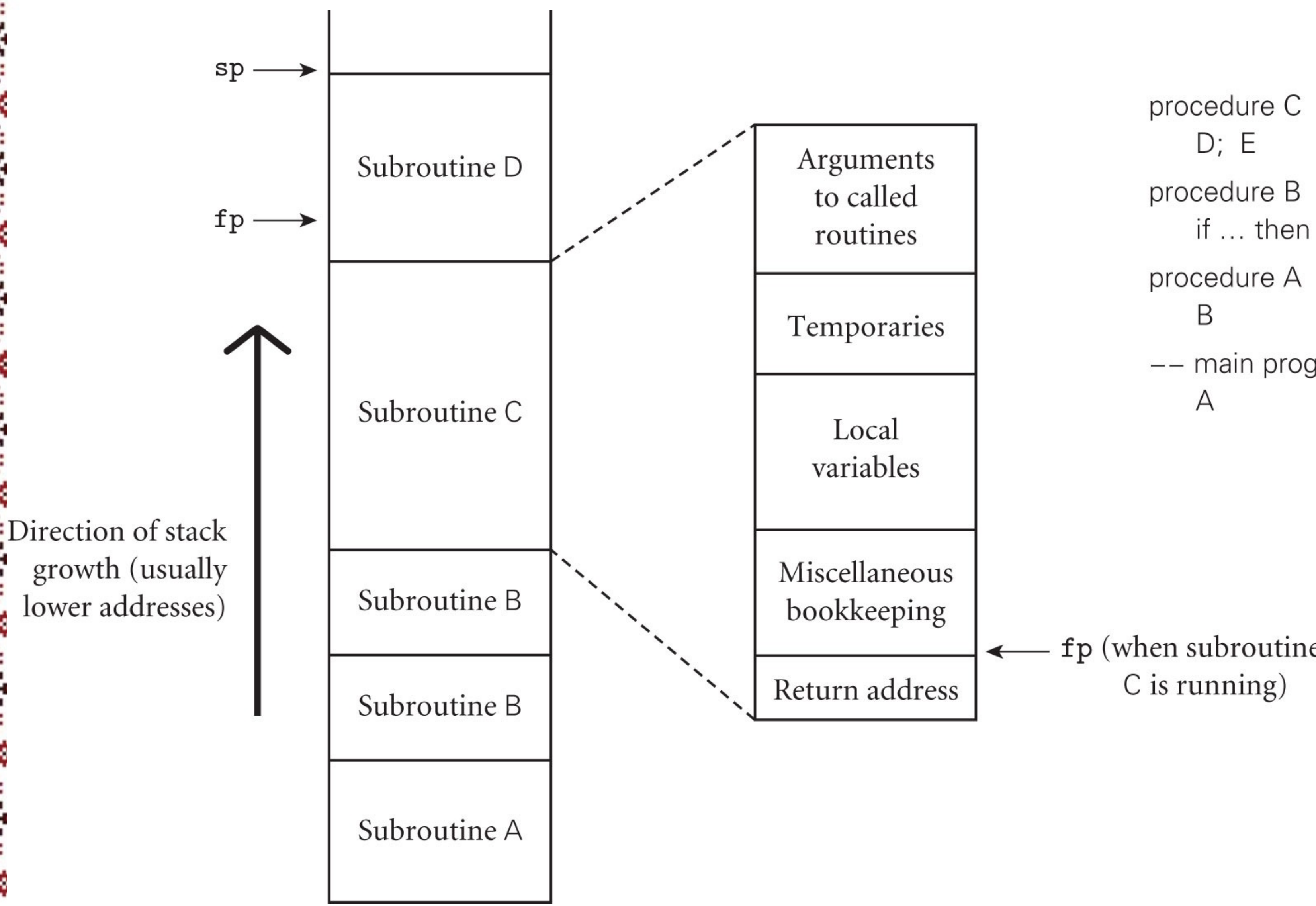
- *Static allocation*:
  - global variables
  - code instructions
  - explicit constants (including strings, sets, etc.)
    - `A = B / 14.7`
    - `printf(“hello, world\n”)`
    - small constants may be stored in the instructions
  - C++ `static` variables (or Algol `own`)

  - Statically allocated objects that do not change value are allocated in read-only memory
    - constants, instructions

Lifetime and Storage Management

- *Stack-based allocation*:
  - parameters, local variables, temporaries
  - allocate space for recursive routines
  - reuse space
- *Frame* (*activation record*) for each subroutine call:
  - position in stack: *frame pointer*
  - arguments and returns
  - local variables, temporaries:
    - *fixed offset* from the frame pointer at compile time
  - return address
  - *dynamic link*: reference to (stack frame of) caller
  - *static link:* reference to (stack frame of) routine inside which it was declared

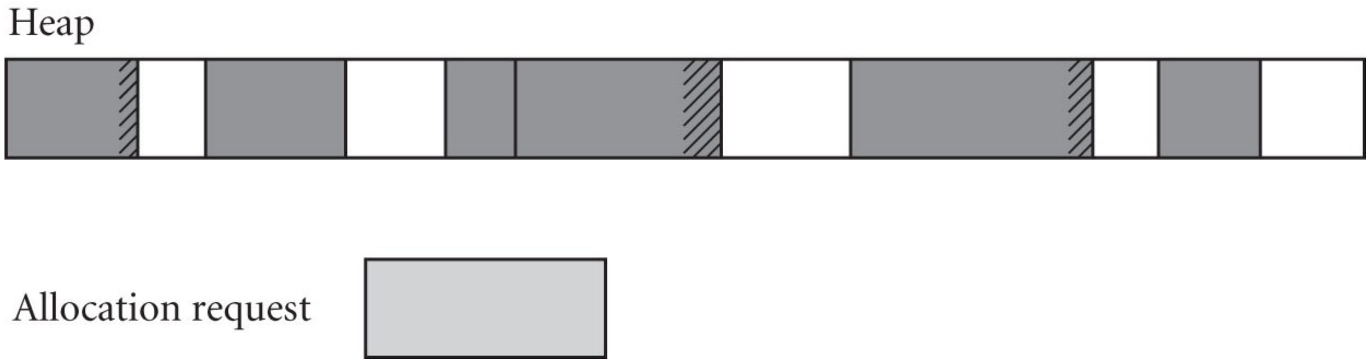
Lifetime and Storage Management




```
procedure C
    D;  E
procedure B
    if … then B else C
procedure A
    B
–– main program
    A
```

Lifetime and Storage Management

- *Heap allocation*
- (different from “heap” data structure for priority queues)
- dynamic allocation: lists, sets, strings (size can change)
- single linked list of free blocks
- fragmentation: internal, external



Lifetime and Storage Management

- Heap allocation
- allocation algorithms
  - first fit, best fit– $O(n)$ time
  - pool allocation – $O(1)$ time
    - separate free list of blocks for different sizes
    - *buddy system*: blocks of size 2^k
    - *Fibonacci heap*: blocks of size Fibonacci numbers
- defragmentation

Lifetime and Storage Management

- Heap maintenance
- Explicit deallocation
  - C, C++
  - simple to implement
  - efficient
  - object deallocated too soon – *dangling reference*
  - object not deallocated at the end of lifetime – *memory leak*
  - deallocation errors are very difficult to find
- Implicit deallocation: *garbage collection*
  - functional, scripting languages
  - C#, Java, Python
  - avoid memory leaks (difficult to find otherwise)
  - recent algorithms more efficient
  - the trend is towards automatic collection

Scope Rules

- *Scope of a binding*:
  - textual region of the program in which binding is active
- Subroutine entry – usually creates a new scope:
  - create bindings for new local variables
  - deactivate bindings for redeclared global variables
  - make references to variables
- Subroutine exit:
  - destroy bindings for local variables
  - reactivate bindings for deactivated global variables
- *Scope*: maximal program section in which no bindings change
  - *block*: module, class, subroutine
  - C: { … }
  - *Elaboration time*: when control first enters a scope

Scope Rules

- *Referencing environment*
  - the set of active bindings; determined by:
  - *Scope rules* (static or dynamic)
  - *Binding rules* (deep or shallow)

- *Static Scoping* (*Lexical Scoping*)
  - almost all languages employ static scoping
  - determined by examining the text of the program
  - at compile time
  - *closest nested rule*
    - identifiers known in the scope where they are declared and in each enclosed scope, unless re-declared
    - examine local scope and statically enclosing scopes until a binding is found

Scope Rules

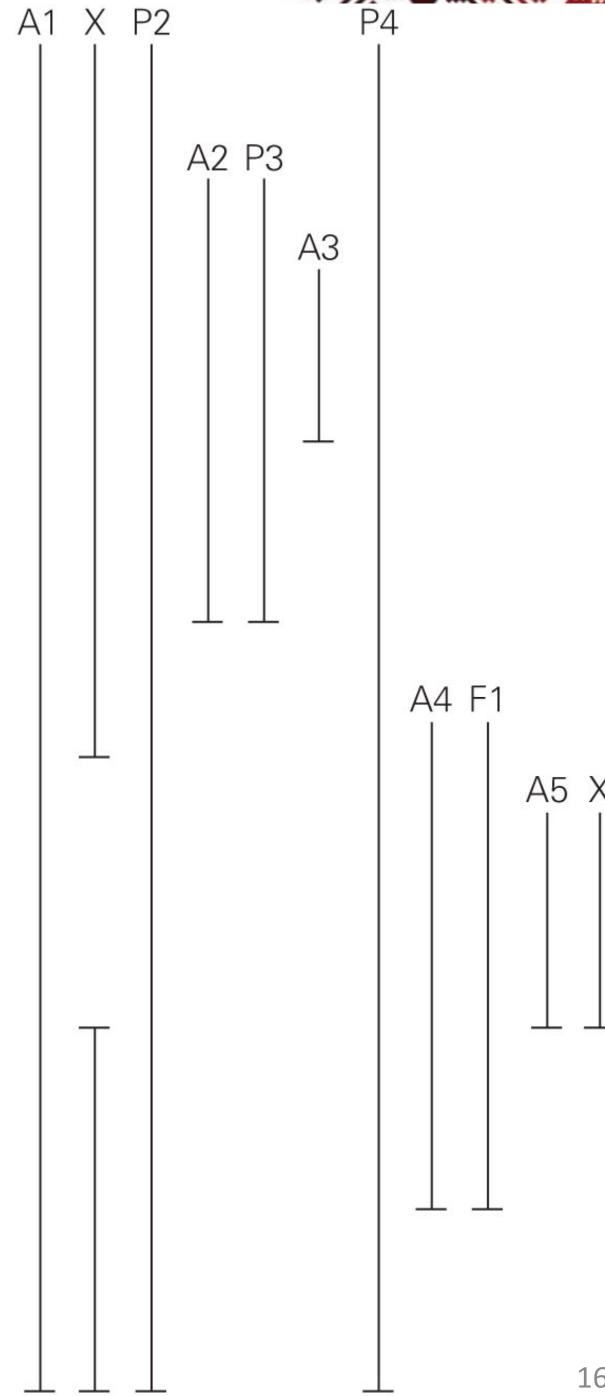
- Subroutines
  - bindings created are destroyed at subroutine exit
    - exception: `static` (C), `own` (Algol)
  - nested subroutines: *closest nested scope*
    - Python, Scheme, Ada, Common Lisp
    - not in: C, C++, Java
  - access to non-locals: *scope resolution operator*
    - C++ (global): `::X`
    - Ada: `MyProc.X`
  - built-in objects
    - outermost scope
    - outside global

Scope Rules

- Example:

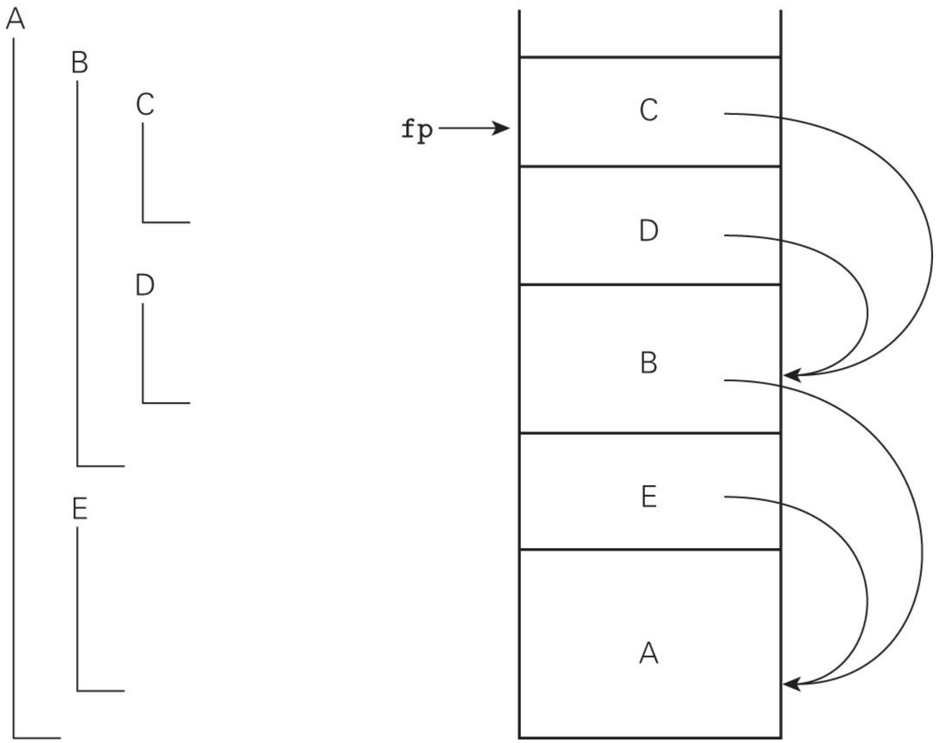
Nested subroutines

```
procedure P1(A1)
    var X              -- local to P1
    ...
    procedure P2(A2)
        ...
        procedure P3(A3)
            ...
        begin
            ...        -- body of P3
        end
        ...
    begin
        ...            -- body of P2
    end
    ...
    procedure P4(A4)
        ...
        function F1(A5)
            var X      -- local to F1
            ...
        begin
            ...        -- body of F1
        end
        ...
    begin
        ...            -- body of P4
    end
    ...
begin
    ...                -- body of P1
end
```



Scope Rules

- Access to non-locals: *static links*
  - each frame points to the frame of the routine inside which it was declared
  - access a variable in a scope *k* levels out by following *k* static links and then using the known offset within the frame



Scope Rules

- Declaration order
  - object *x* declared inside block *B*
  - the scope of *x* may be:
    - the entire block *B* or
    - only the part of *B* after *x*'s declaration

Scope Rules

- Declaration order

- Example: C++

```
int n = 1;
void f(void){
    int m = n;  // global n
    int n = 2;  // local n
}
```

- Example: Python – no declarations

```
n = 1
def f():
   m = n # error
         # add “global n” to use the global n
   n = 2
```

Scope Rules

- Declaration order

- Example: Scheme

```
(let ((A 1))
  (let ((A 2)
        (B A))
    B))            ; return 1

(let ((A 1))
  (letrec ((A 2)
        (B A))
    B))            ; return 2
```

Scope Rules

- *Dynamic Scoping*
- binding depends on flow at run time
  - use the most recent, active binding made at run time
- Easy to implement – just a stack with names
- Harder to understand
  - not used any more
  - why learn? – history

Scope Rules

- Example: Dynamic Scoping

```
n: integer                – global
procedure first()
    n := 1
procedure second()
    n : integer           – local
    first()
n := 2
if read_integer() > 0
    second()
else
    first()
write_integer(n)
```

- Static scoping: prints 1
- Dynamic scoping: prints 2 for positive input, 1 for negative

Scope Rules

- Example: Dynamic scoping problem
  - `scaled_score` uses the wrong `max_score`

```
max_score : integer        –– maximum possible score
function scaled_score(raw_score : integer) : real
   return raw_score / max_score * 100
...
procedure foo( )
   max_score : real := 0 –– highest % seen so far
   ...
   foreach student in class
      student.percent := scaled_score(student.points)
      if student.percent > max_score
         max_score := student.percent
```

Binding of Referencing Environments

- Referencing environment: the set of active bindings
  - static: lexical nesting
  - dynamic: order of declarations at run time
- Reference to subroutine: when are the scope rules applied?
  - *Shallow binding*: when routine is called
    - default in dynamic scoping
  - *Deep binding*: when reference is created
    - default in static scoping
- Example (next slides)

Binding of Referencing Environments

- `print_routine`
  - shallow binding
  - to pick `line_length`
- `older_than_threshold`
  - deep binding
  - otherwise, if `print_selected_records` has a variable `threshold`, it will hide the one in the main program

```
type person = record
    ...
    age : integer
    ...
threshold : integer
people : database

function older_than_threshold(p : person) : boolean
    return p.age ≥ threshold

procedure print_person(p : person)
    –– Call appropriate I/O routines to print record on standard output.
    –– Make use of nonlocal variable line_length to format data in columns.
    ...
```

Binding of Referencing Environments

```
procedure print_selected_records(db : database;
        predicate, print_routine : procedure)
    line_length : integer

    if device_type(stdout) = terminal
        line_length := 80
    else      -- Standard output is a file or printer.
        line_length := 132
    foreach record r in db
        -- Iterating over these may actually be
        -- a lot more complicated than a 'for' loop.
        if predicate(r)
            print_routine(r)

-- main program
. . .
threshold := 35
print_selected_records(people, older_than_threshold, print_person)
```

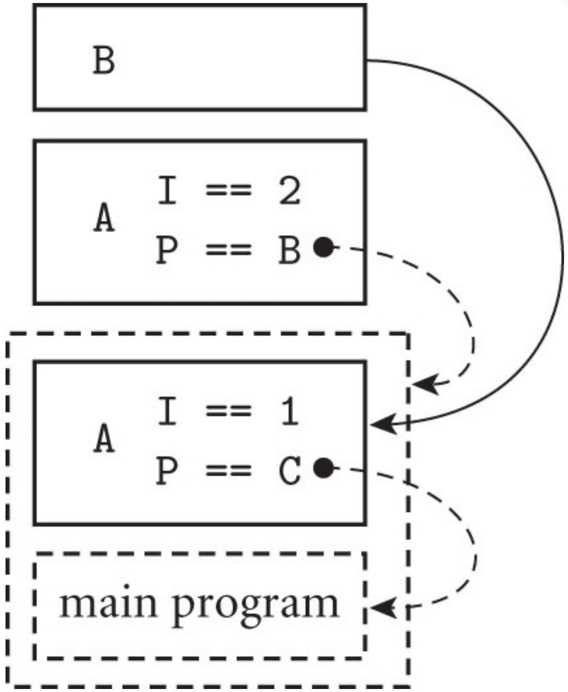
Binding of Referencing Environments

- Deep binding implementation: *subroutine closure*
  - explicit representation of a referencing environment
    (the one in which the subroutine would execute if called now)
  - reference to subroutine
- Why binding time matters with static scoping?
  - the running program may have two instances of an object
  - only for objects that are neither local nor global
  - Examples when it does not matter:
    - subroutines cannot be nested: C
    - only outermost subroutines can be passed as parameters: Modula-2
    - subroutines cannot be passed as parameters: PL/I, Ada 83

Binding of Referencing Environments

- Example: Deep binding in Python

```
def A(I, P):
    def B():
        print(I)
    # body of A:
    if I > 1:
        P()
    else:
        A(2, B)
def C():
    pass # do nothing
A(1, C)  # main program; output 1
```



- referencing environment captured in closures: dashed boxes, arrows
- when `B` is called via `P`, two instances of `I` exist
- the closure for `P` was created in the initial invocation of `A`
- `B`'s static link (solid arrow) points to the frame of the earlier invocation

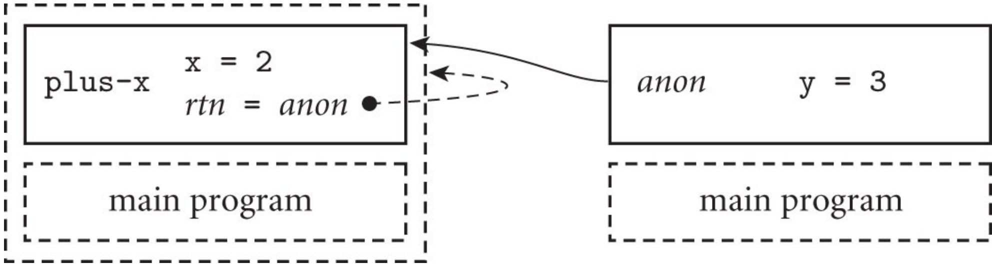
Binding of Referencing Environments

- *First-class* values
  - can be passed as a parameter
  - can be returned from subroutine
  - can be assigned into a variable
- *Second-class* values
  - can only be passed as a parameter
- *Third-class*: none
  - Other authors may have different definitions: no second-class; first-class may require anonymous function definition (lambda expressions)
- Subroutines:
  - first-class: functional and scripting languages, C#
    - C, C++: pointers to functions are first-class
  - second-class: most imperative languages
  - third class: Ada83

Binding of Referencing Environments

- First-class subroutines: additional complexity
  - a reference to a subroutine may outlive the execution of the scope in which that subroutine was declared
  - Example: Scheme

```
(define plus-x
  (lambda (x)
   (lambda (y)(+ x y))))
(let ((f (plus-x 2)))
  (f 3))        ; return 5
```



- `plus-x` returns an unnamed function (3rd line), which uses the parameter `x` of `plus-x`
- when `f` is called in 5th line, its referencing environment includes the `x` in `plus-x`, even though `plus-x` has already returned
- `x` must be still available – *unlimited extent* – allocate on heap (C#)

Binding of Referencing Environments

- *Lambda expressions*
  - come from lambda calculus: anonymous functions
  - Example: Scheme

```
((lambda (i j) (> i j) i j) 5 8)  ;return 8
```

  - Example: C#: `delegate` or `=>`

```
(int i, int j) => i > j ? i : j
```

Binding of Referencing Environments

- First-class subroutines
  - are increasingly popular; made their way into C++, Java
  - Problem: C++, Java do not support unlimited extent
- Example: C++

```
for_each(V.begin(), V.end(),
    [](int e){ if (e < 50) cout << e << " "; }
);
```

Binding of Referencing Environments

- *Lambda functions* in Python
  - Example

```
ids = ['id1', 'id2', 'id30', 'id3', 'id22', 'id100']

# Lexicographic sort
print(sorted(ids))
  => ['id1', 'id100', 'id2', 'id22', 'id3', 'id30']

# Integer sort
sorted_ids = sorted(ids, key=lambda x: int(x[2:]))
print(sorted_ids)
  => ['id1', 'id2', 'id3', 'id22', 'id30', 'id100']
```

Binding of Referencing Environments

- Lambda functions in Python
  - Example

```
def myfunc(n):
  return lambda a : a * n

mydoubler = myfunc(2)
print(mydoubler(11))
  => 22

mytripler = myfunc(3)
print(mytripler(11))
  => 33
```