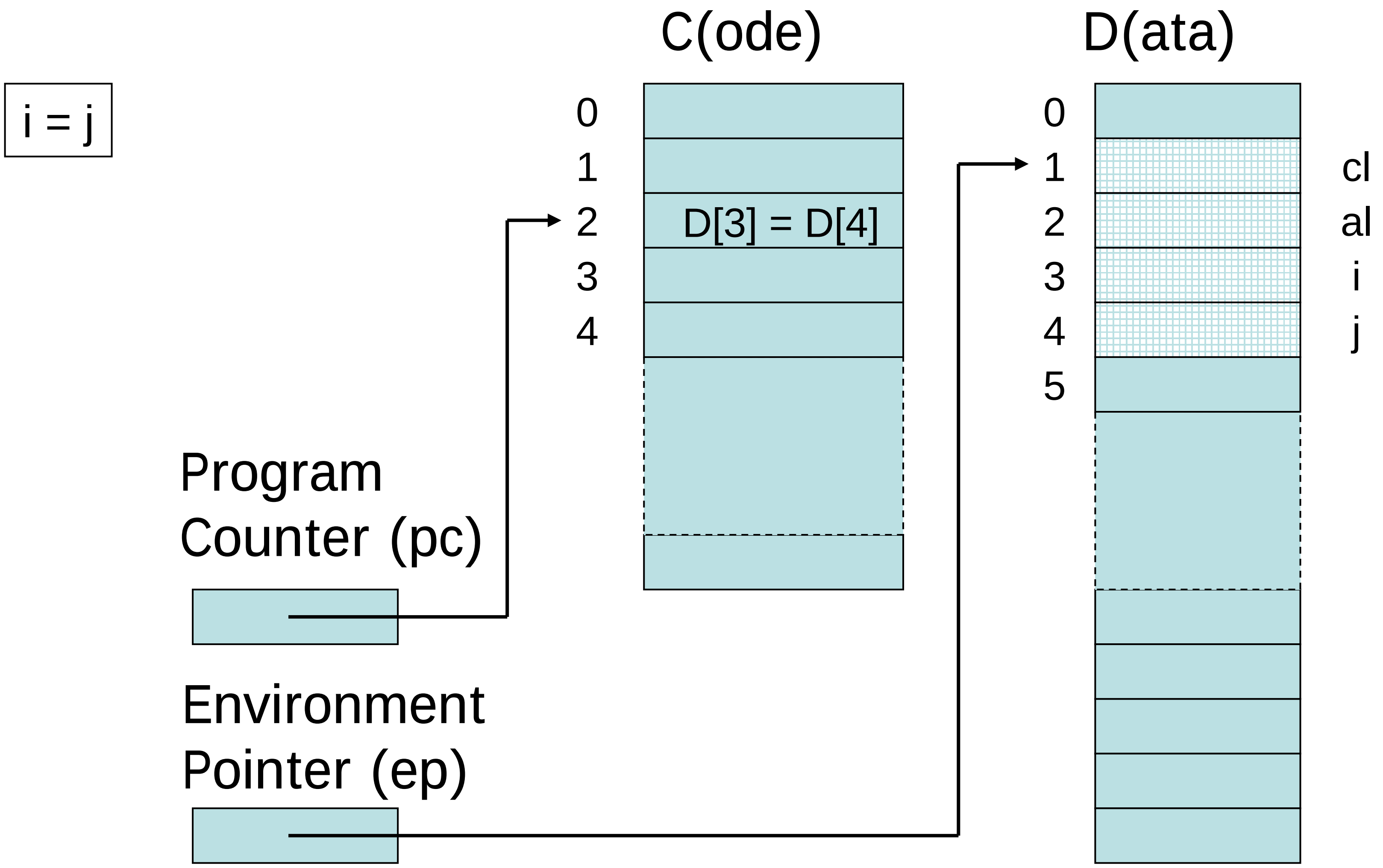
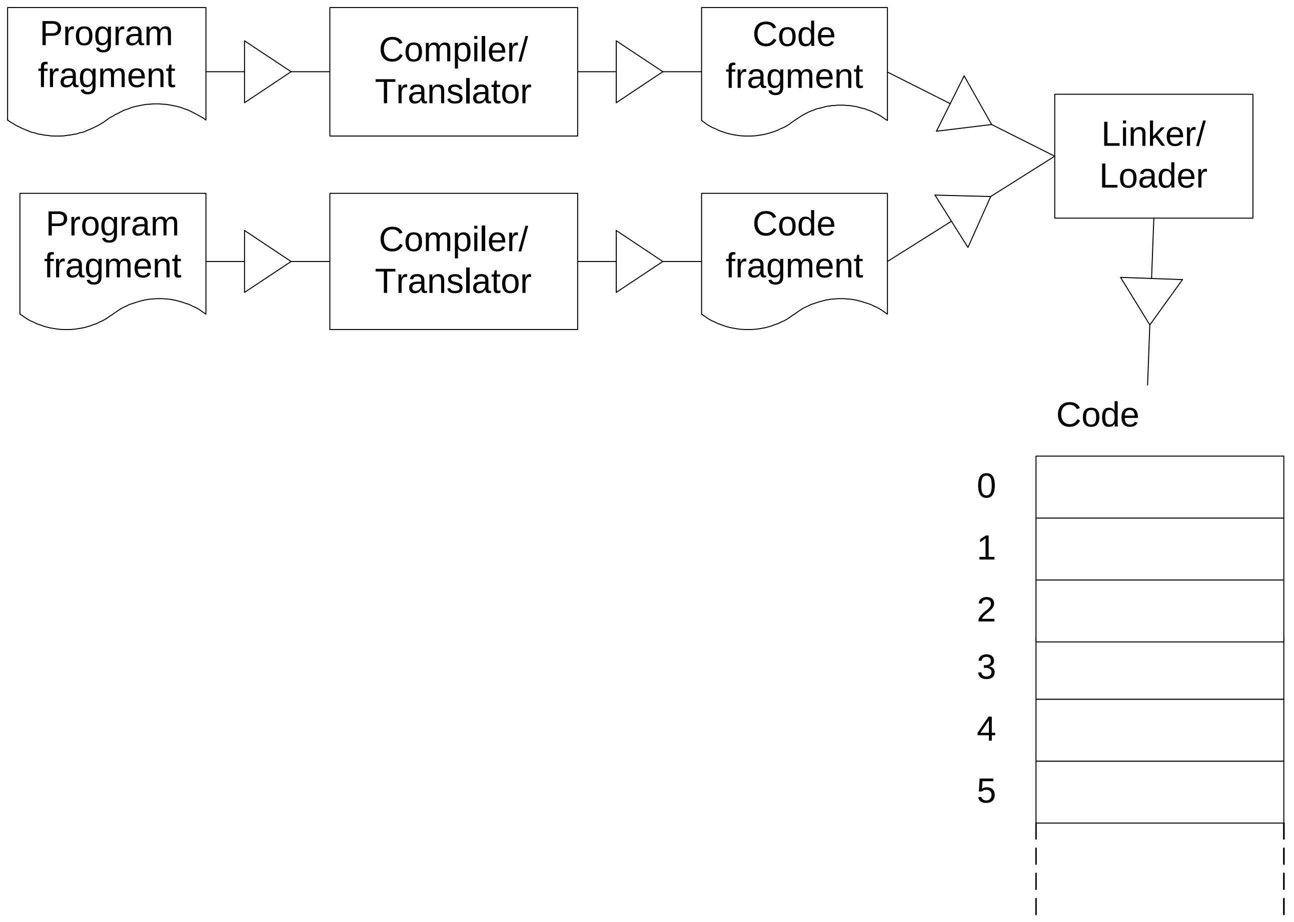
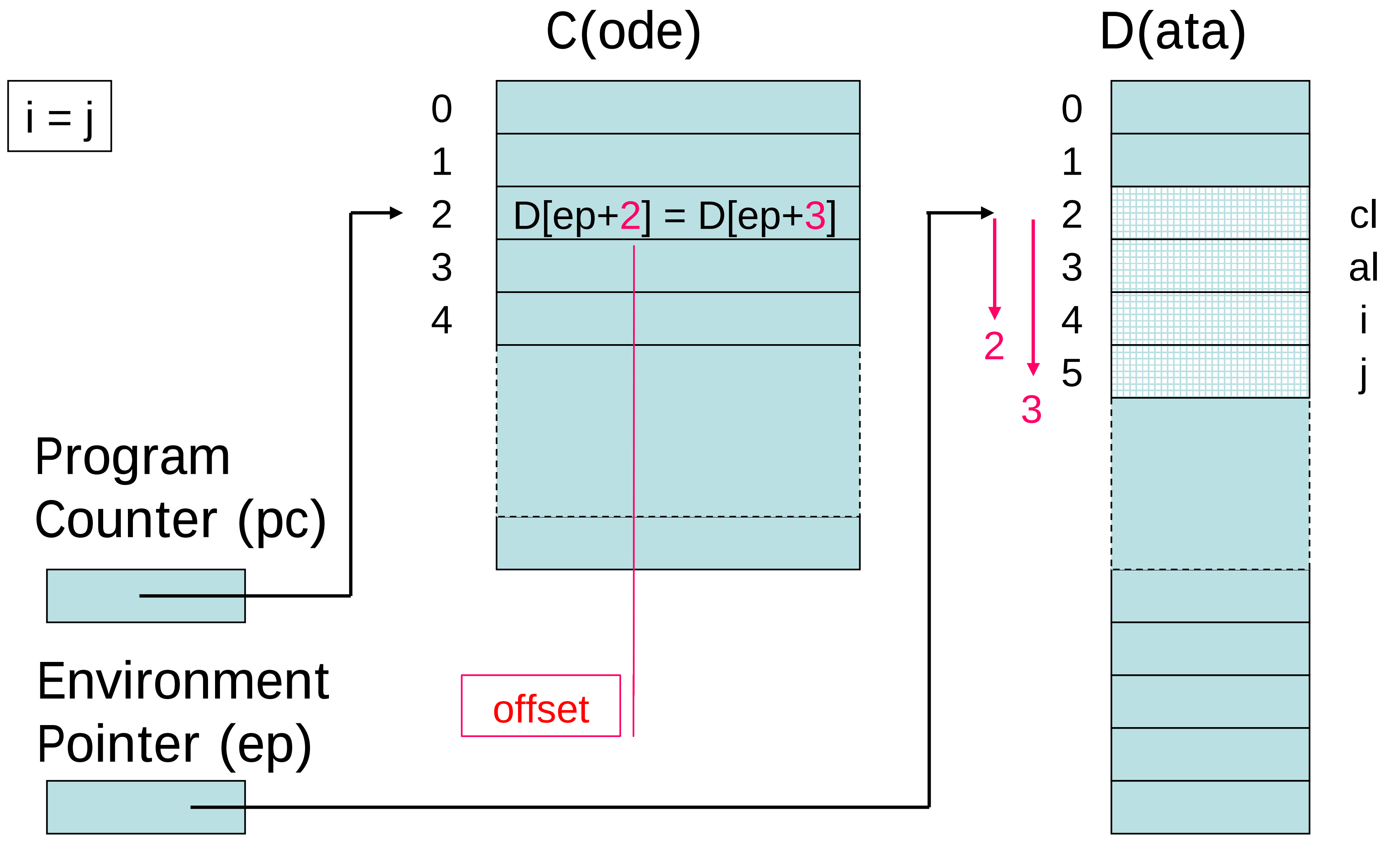
Details of virtual machine operation



Separate compilation



Relocation/offsets

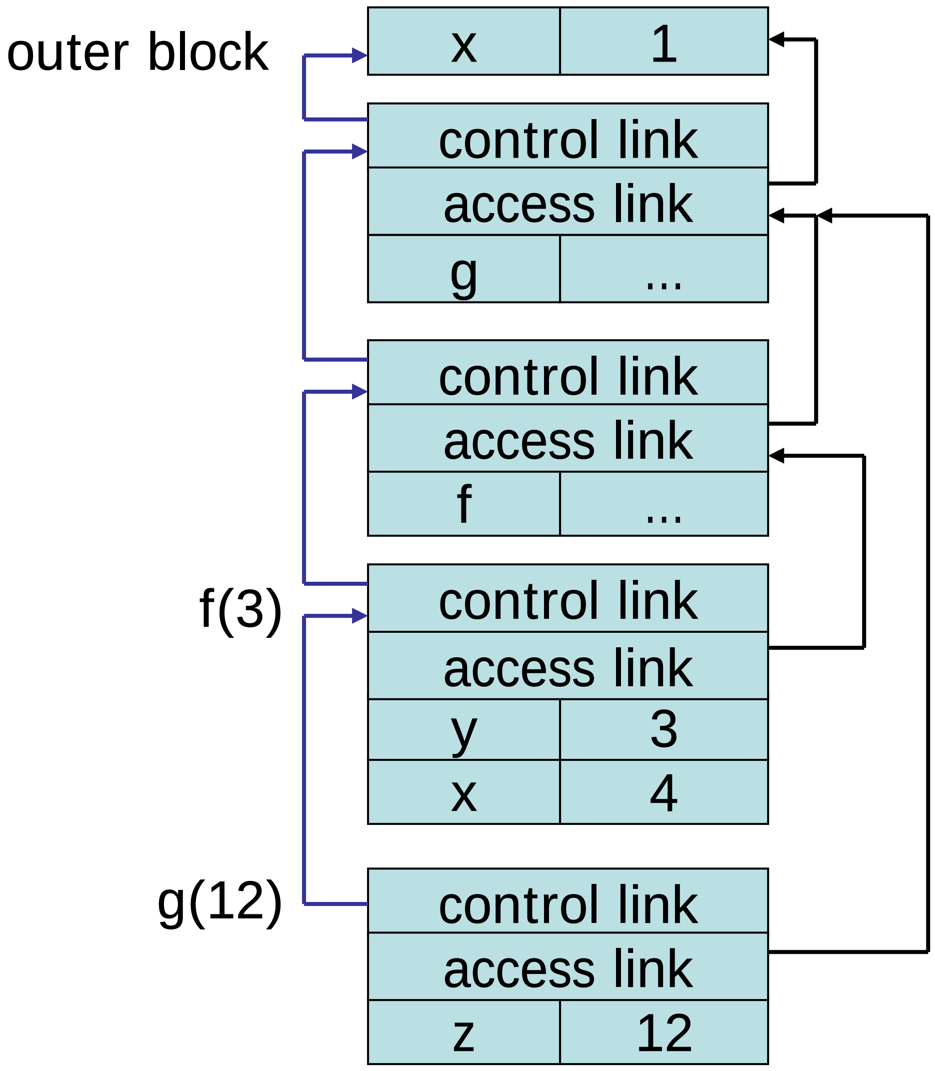


Static scope with access links

```
int x=1;
function g(z) = x+z;
function f(y) =
   { int x = y+1;
     return g(y*x) };
f(3);
```

Use access link to find global variable:

- Access link is always set to frame of closest enclosing lexical block
- For function body, this is block that contains function declaration



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Access link (static link)

- A variable will always be reached in a certain distance from the actual block
  - A local variable has distance = 0.
  - A local variable declared in immediate enclosing block has distance = 1.
  - ...
- How to find variables
  - Each application of a variable is turned into a pair <distance, offset >
  - Follow access link distance times, and then add offset.
  - The value of a variable is Data[fp(distance) + offset], where the fp-function (frame pointer) gives index for the activation record distance times outwards

Static Block Level (BL) and Context Vector (CV)

```
Blocks              BL

{ int x=1 …         1
    { …             2
        { ...;      3
          x; ...
        }
    }
    { …             2
       { ...;       3
         x;
       }

    }
}
```

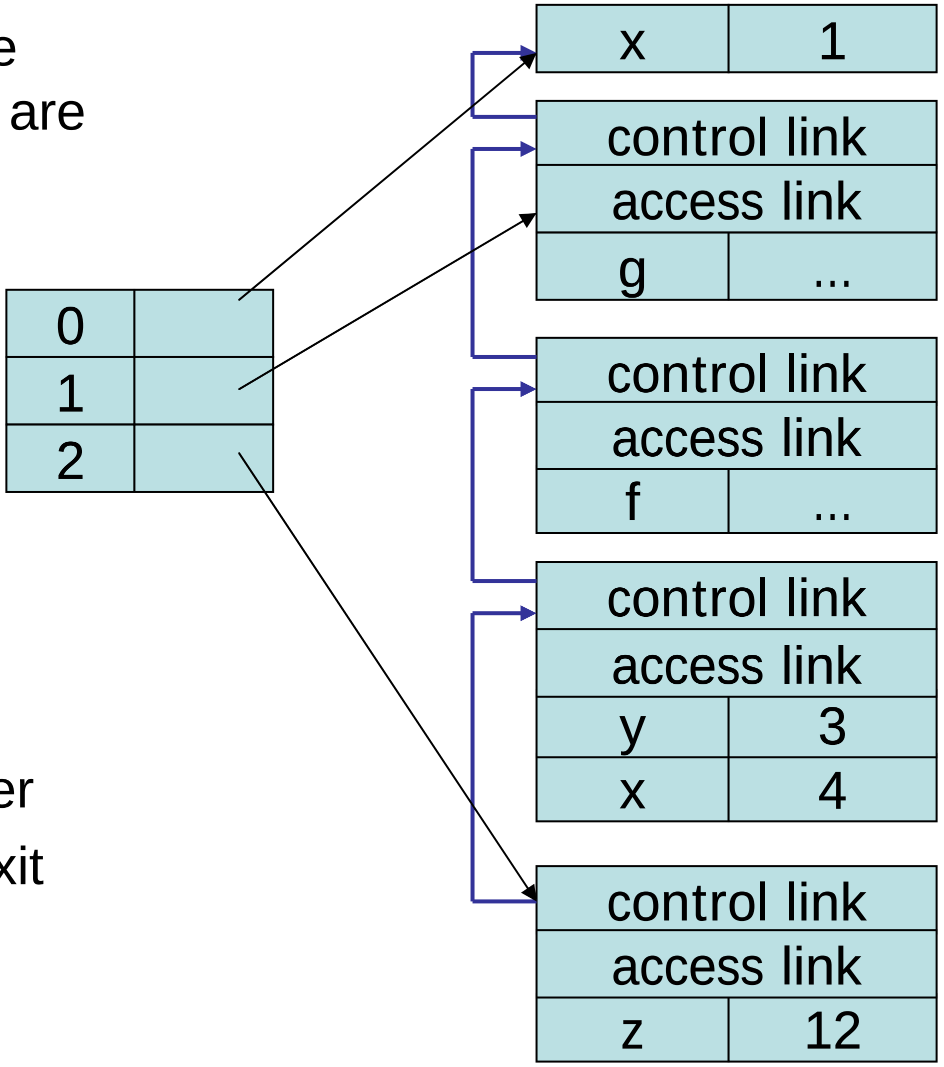
```
void makeContextVector() {
    int i;
    CV[ep.BL] = ep;
    for (i = ep.BL; i >= 2; i--) {
        CV[i-1] = CV[i].AL;
    }
}
```

where AL is the Access Link (Static Link).

CV[0] always denotes the main program block, and is thereby constant.

Context vector

- A vector pointing to the activation records that are currently visible



- + variable access faster
- - More work at entry/exit

By name

```
begin integer i;
     integer procedure sum(i,j);
              integer i,j;
     begin
              integer sm; sm:= 0;
              for i = 1 step 1 until 100 do
                             sm := sm + j;
              sum:= sm
     end;
     print(sum(i,i*10)
end;
```

```
swap(int a, b) {
  int temp;
  temp = a;
  a = b;
  b = temp;
};
```

```
i=3;
a[3]=6;
swap(i, a[i]);

-- i = 6


-- a[3] = 6
-- a[6] = 3
```

```
x := x    ???

integer procedure p;  begin p := p end;
```

```
temp = i;
i = a[i];
a[i] = temp;
```

by name

“4.7.3.2. Name replacement (call by name). Any formal parameter not quoted in the value list is replaced, throughout the procedure body, by the corresponding actual parameter, after enclosing this latter in parentheses wherever syntactically possible. Possible conflicts between identifiers inserted through this process and other identifiers already present within the procedure body will be avoided by suitable systematic changes of the formal or local identifiers involved. “

What is the difference between this and macro expansion?

```
int i; int a[];
swap(int a, b) {
  int i;
  i = a;
  a = b;
  b = i;
};

swap(i, a[i]);
```

```
i=3;
a[3]=6;
swap(i, a[i]);
```

By name

```
-- i = 6
-- a[3] = 6
-- a[6] = 3
```

By macro expansion

```
i = i;        -- local i=0
i = a[i];     -- local i=a[0]
a[i] = i;     -- a[0]=0
```

Higher-Order Functions

- Language features
  - Functions passed as arguments
  - Functions that return functions from nested blocks
  - Need to maintain environment of function
- Simpler case
  - Function passed as argument
  - Need pointer to activation record "higher up" in stack
- More complicated second case
  - Function returned as result of function call
  - Need to keep activation record of returning function

Why functions as parameters?

```
integer procedure fsum(f, a, l, u);
    value l, u; integer array a;
    integer procedure f;
begin
  integer sum:= 0;
  for i:= l step 1 until u do sum:= sum + f(a[i]);
  fsum:= sum
end
```

```
integer array aa[5:100];
integer procedure ip1(i); value i; integer i; begin ... end;
integer procedure ip2(i); value i; integer i; begin ... end;

fsum(ip1, aa, 5, 100)
fsum(ip2, aa, 5, 100)
```

Pass function as argument

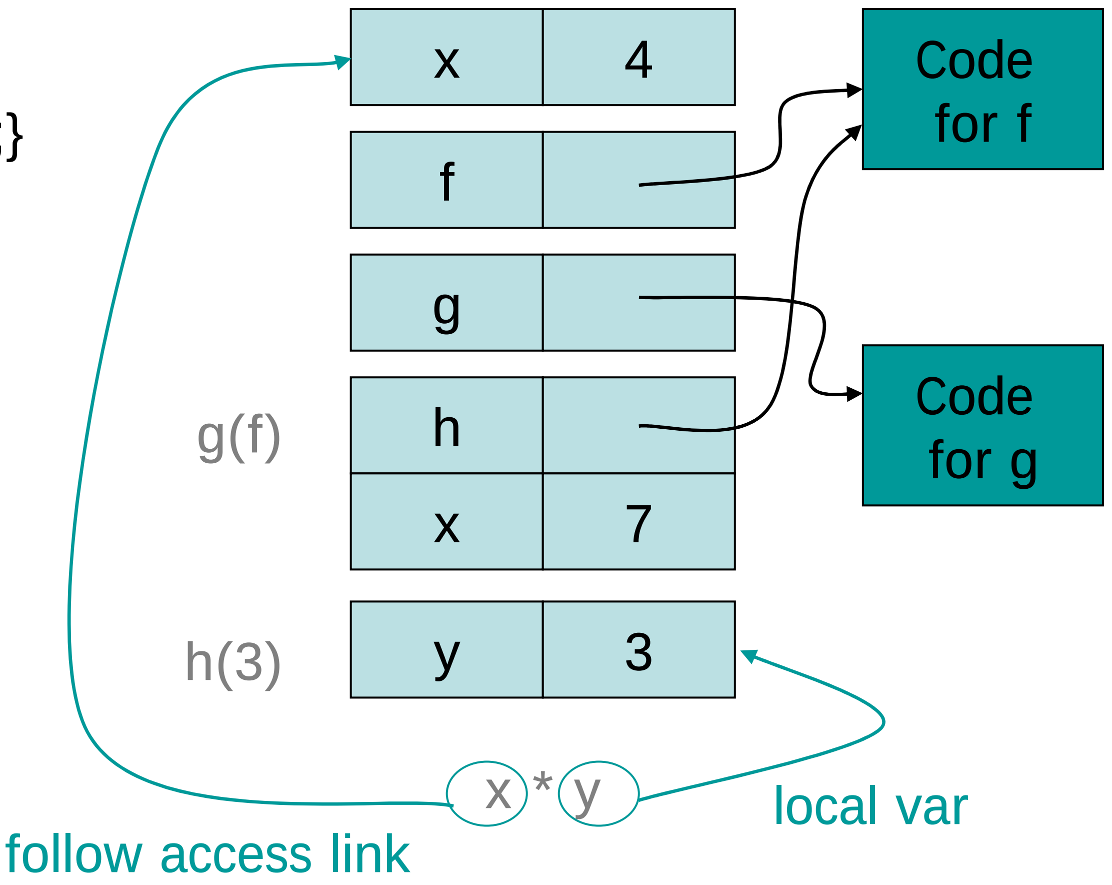
```
{ int x = 4;
   { int f(int y) {return x*y;}
       { int g(int→int h) {
                 int x=7;
                 return h(3) + x;
              }
           g(f);
       }
   }
}
```

There are two declarations of x

Which one is used for each occurrence of x?

Static Scope for Function Argument

```
{ int x = 4;
  { int f(int y) {return x*y;}
    { int g(int→int h) {
          int x=7;
          return h(3) + x;
          }
      g(f);
    }
  }
}
```



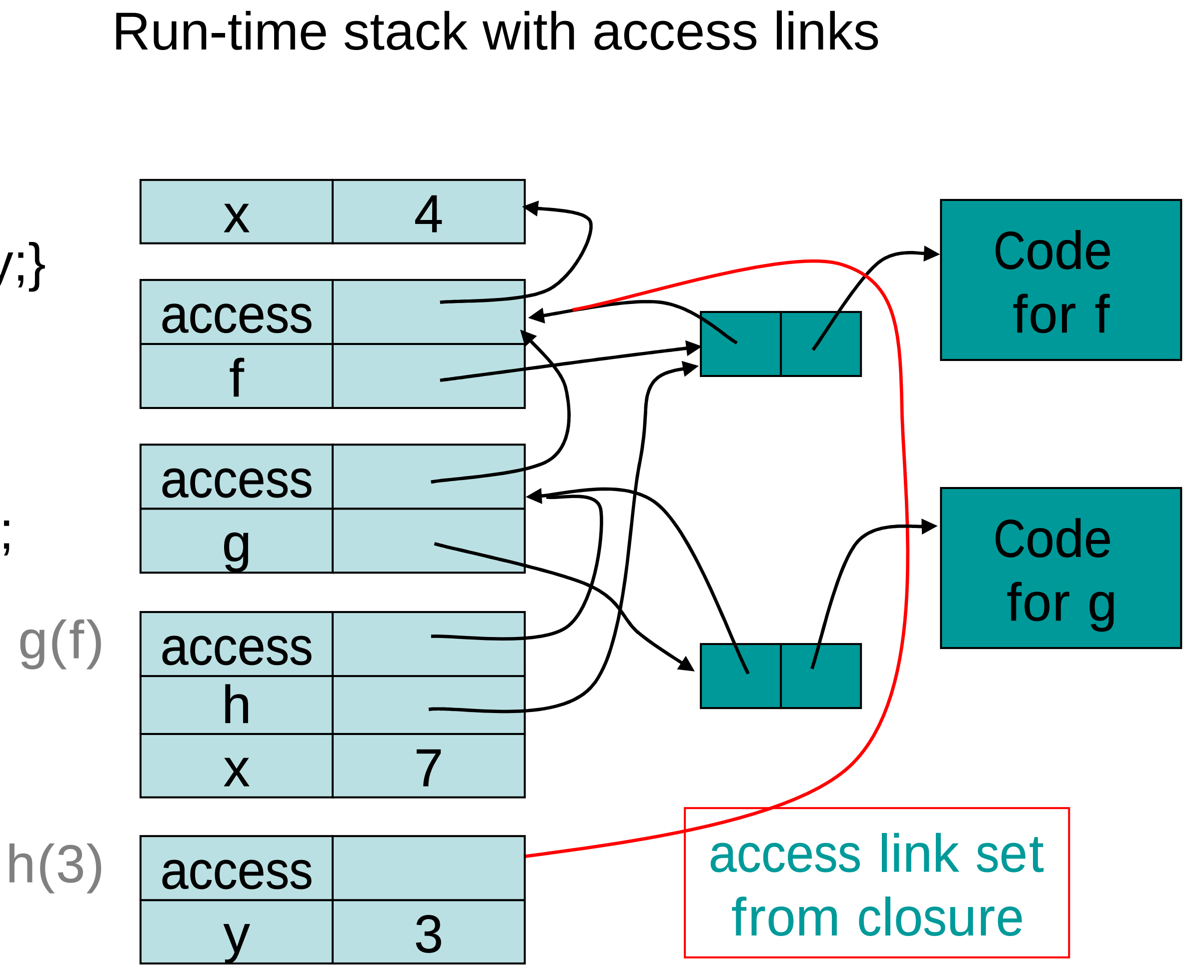
How is access link for h(3) set?

Closures

- Function value is pair *closure* = ⟨*env*, *code* ⟩
- When a function represented by a closure is called,
  - Allocate activation record for call (as always)
  - Set the access link in the activation record using the environment pointer from the closure

Function Argument and Closures

```
{ int x = 4;
  { int f(int y){return x*y;}
    { int g(int→int h) {
            int x=7;
            return h(3)+x;
      }
      g(f);
  }
}
```



Summary: Function Arguments

- Use closure to maintain a pointer to the static environment of a function body
- When called, set access link from closure
- All access links point "up" in stack
  - May jump past active records to find global variables
  - Still de-allocate active records using stack (LIFO) order

Return Function as Result

- Language feature
  - Functions that return “new” functions
  - Need to maintain environment of function

- Function “created” dynamically
  - function value is closure = ⟨env, code⟩
  - code *not* compiled dynamically (in most languages)

Example: Return fctn with private state

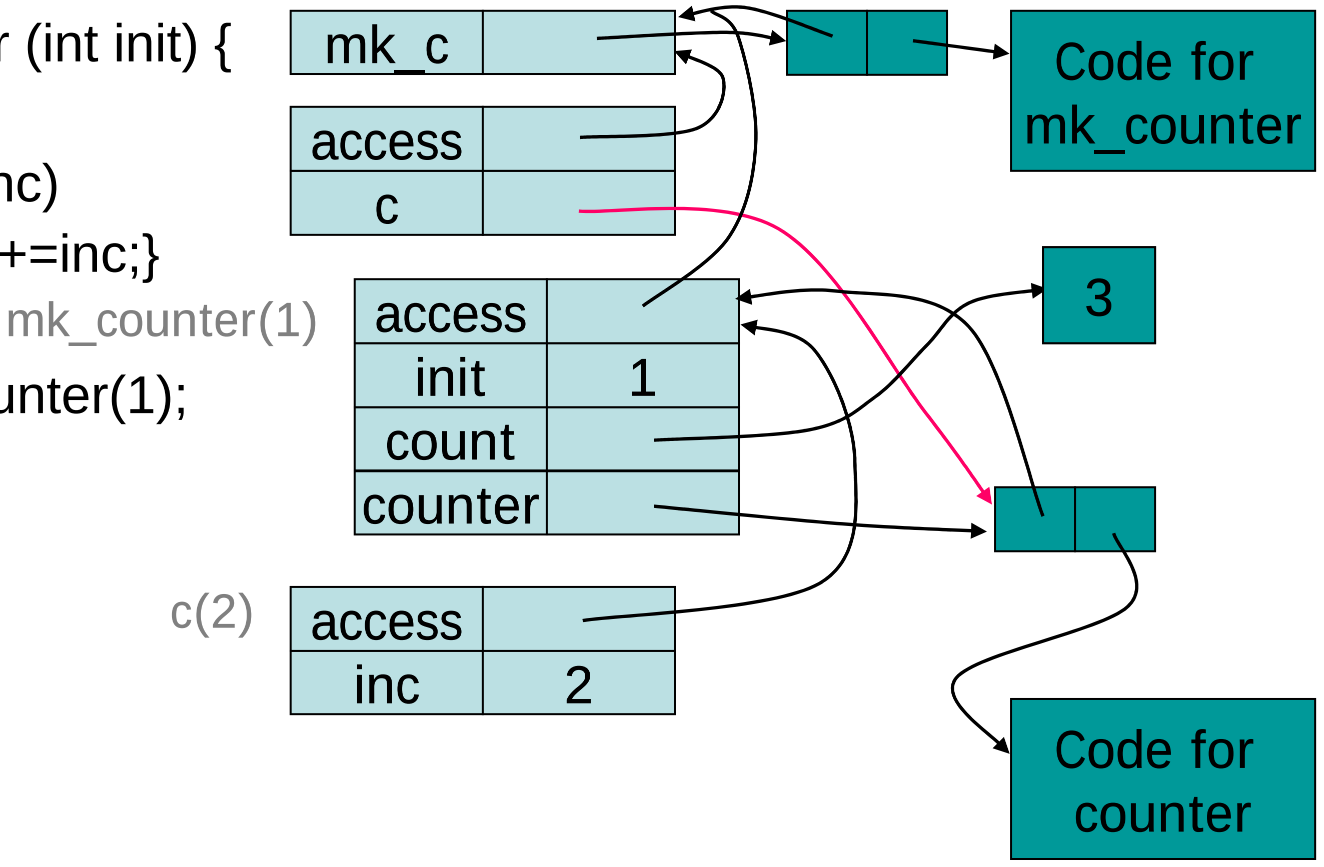
```
{int→int mk_counter (int init) {
      int count = init;
      int counter(int inc)
         { return count += inc;}
      return counter}
  int→int c  = mk_counter(1);
  print c(2) + c(2);
}
```

Function to “make counter” returns a closure

How is correct value of count determined in call c(2) ?

Function Results and Closures

```
{int→int mk_counter (int init) {
      int count = init;
      int counter(int inc)
         { return count+=inc;}
      return counter}
  int→int c = mk_counter(1);
  print c(2) + c(2);
}
```



Call changes cell value from 1 to 3

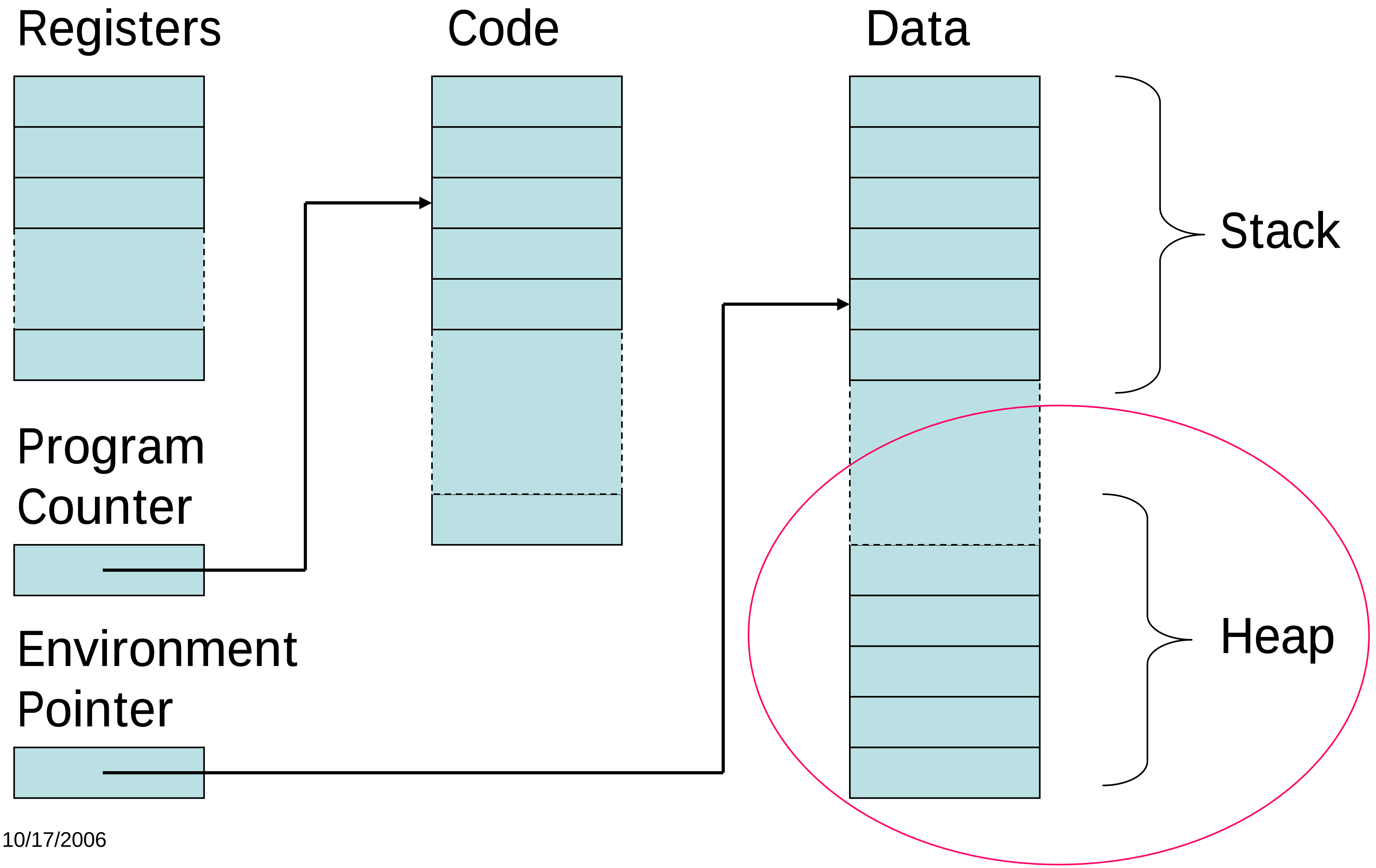
Summary: Return Function Results

- Use closure to maintain static environment
- May need to keep activation records after return
  - Stack (lifo) order fails!
- Possible “stack” implementation
  - Forget about explicit de-allocation
  - Put activation records on heap
  - Invoke garbage collector as needed
- How to achieve the effect of function parameters in e.g. Java??

```
class CwF {int f(int i) {…} };

int fsum(CwF ref, int[] a) {
  int sum= 0;
  for (i= 1, i<aa.length, i++)
     sum= sum + ref.f(a[i]);
  return sum
}

int aa[] = new aa[95];
int ip1(int i); {...};
int ip2(int i); {...};
```

```
class CwFip1 extends CwF {
   int f(int i) {return ip1(i)}
};
class CwFip2 extends CwF {
   int f(int i) {return ip2(i)}
};

CwFip1 refIp1 = new CwFip1;
CwFip1 refIp2 = new CwFip2;

fsum(refIp1, aa)
fsum(refIp2, aa)
```

Simplified Machine Model

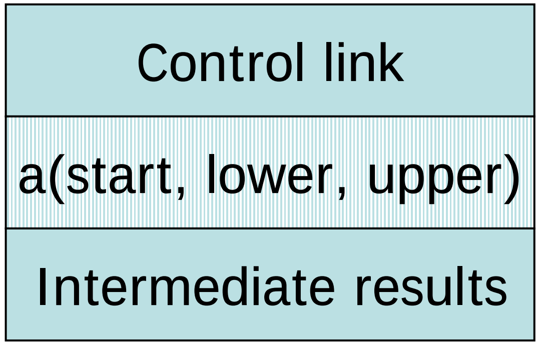


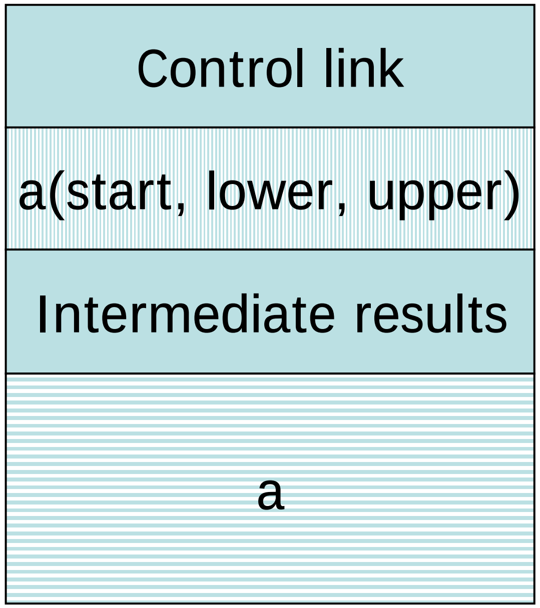
Dynamic languages – I

```
      { int n;
        n= …;
            {  int a[n];
             };
      };
```

At compilation
Each dynamic array gets a *descriptor* (start of array, lower, upper).
Array-access via this descriptor.

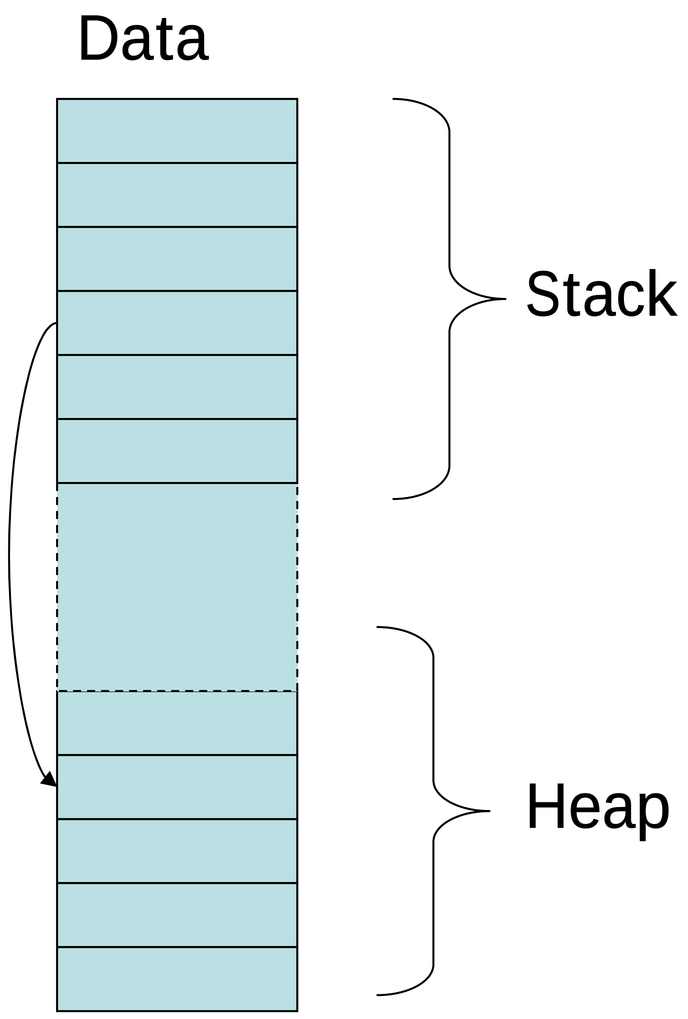
At execution
Dynamic array-declaration: extend the activation record with necessary space and update the values of the descriptor.





Dynamic langauges - II

```
{
  class Node {
    Object contents
    Node left, right;
  };
  {
    Node n;
    ...
    n = new Node();
    ...
  }
};
```



Garbage Collection

- If not automatic
  - explicit delete(n)
  - Programmers responsibility, dangling references
- If automatic
  - Simple reference counting
  - When needed versus real-time
  - One-sweep versus generation-based

Summary: Classes of languages

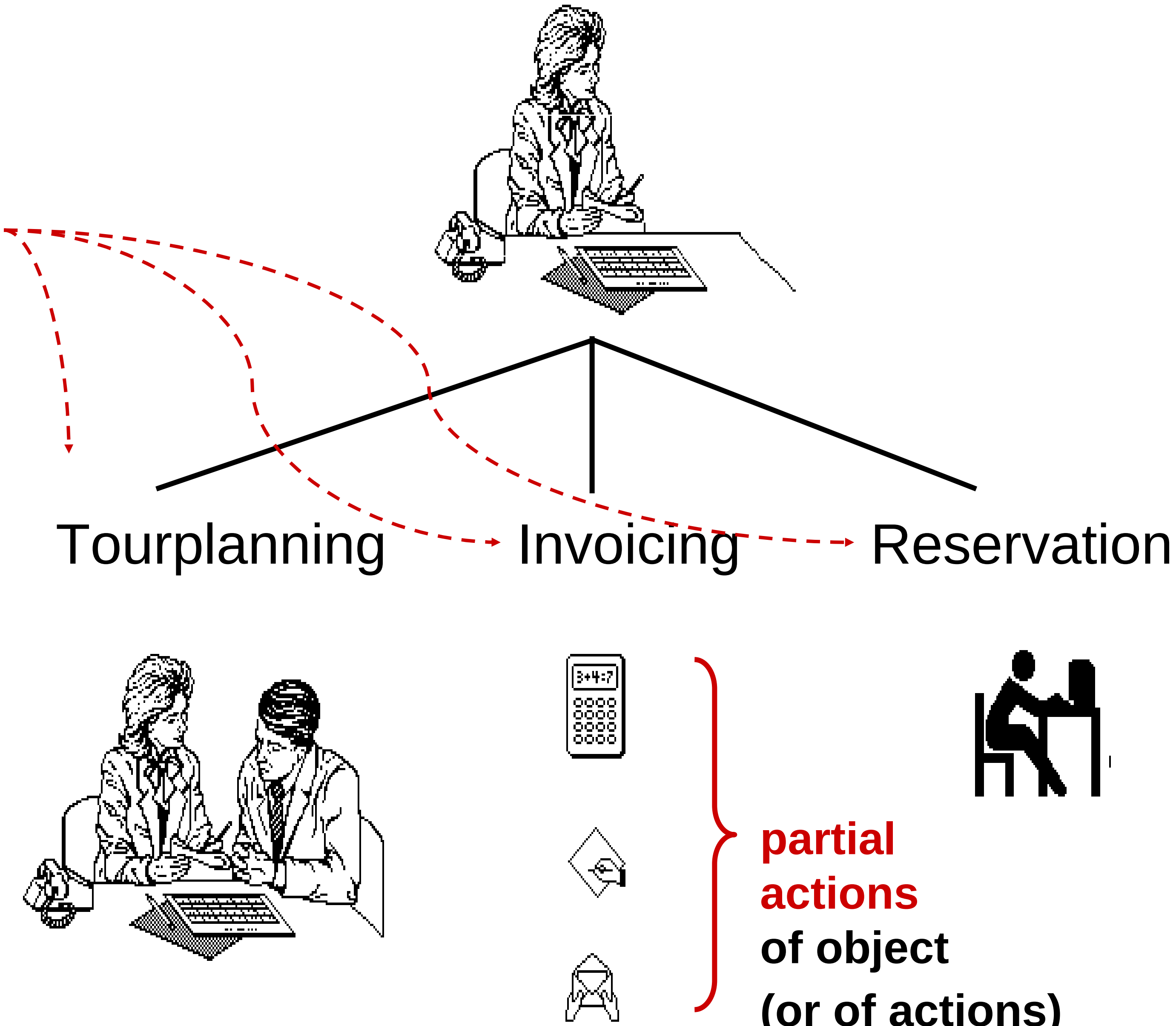
- Static languages
  - Memory requirement can be determined before program execution,
  - not recursion
- Stack-based languages
  - Use of memory follows a LIFO-stack organization and cannot be determined before execution
  - Memory allocated when scopes (inner block or functions) are entered
  - Memory de-allocated when scope is exited
- Dynamic languages
  - Memory is allocated when needed
  - Cannot be organized in a stack, but in a heap

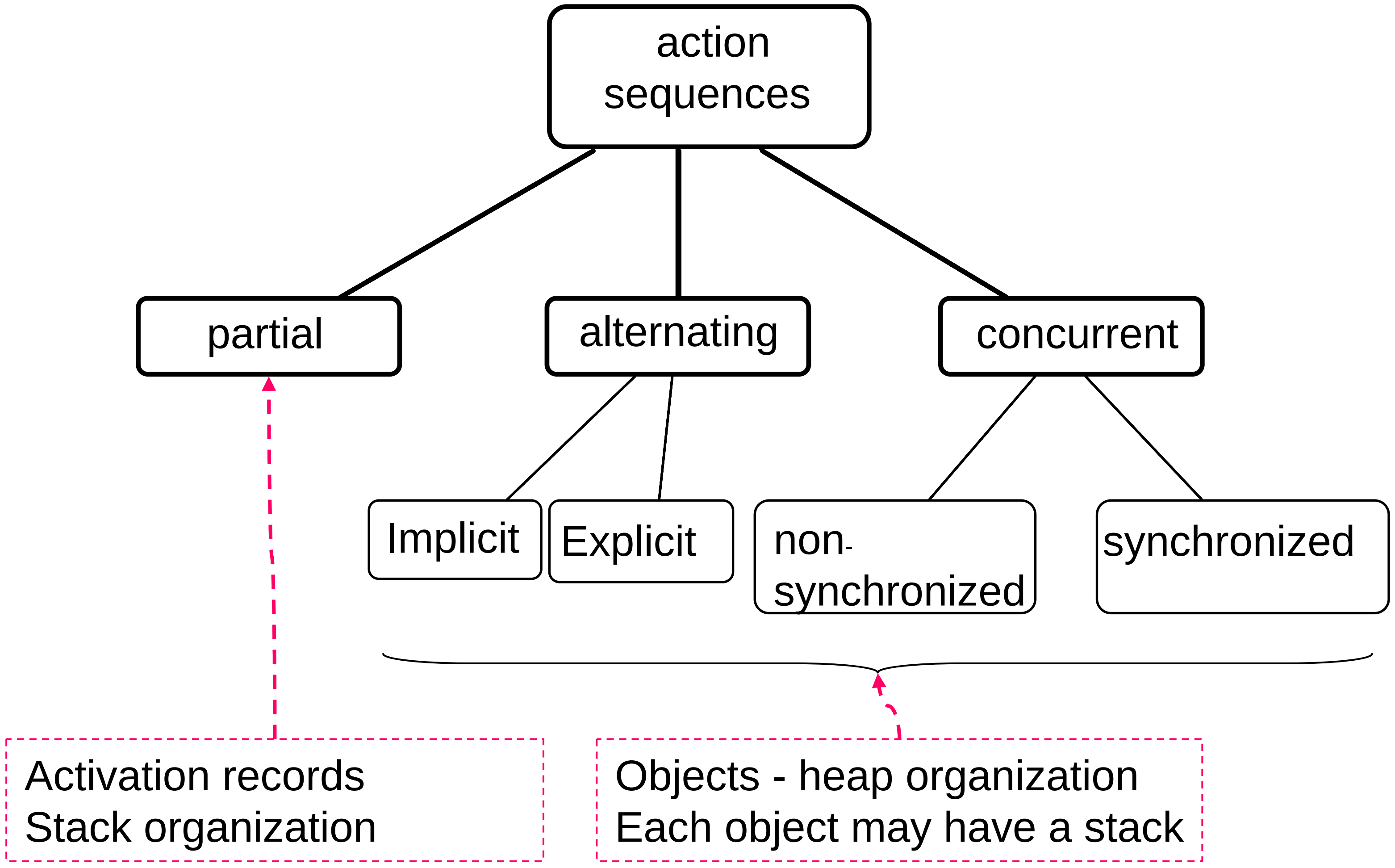
Example – static language

```
main()
{
  int i, j;
  get(i, j);
  while (i != j)
    if (i > j)
       i = j;
    else
       j = i;
  print(i);
}
```

Stack organization revisited

concurrent objects


objects
with
alternating
actions
Tourplanning
Invoicing
Reservation
3+4=7
partial
actions
of object
(or of actions)



Functions within functions
Methods within methods

Coroutines: suspend, resume, ...
Threads: run(), runnable()