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?

```
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

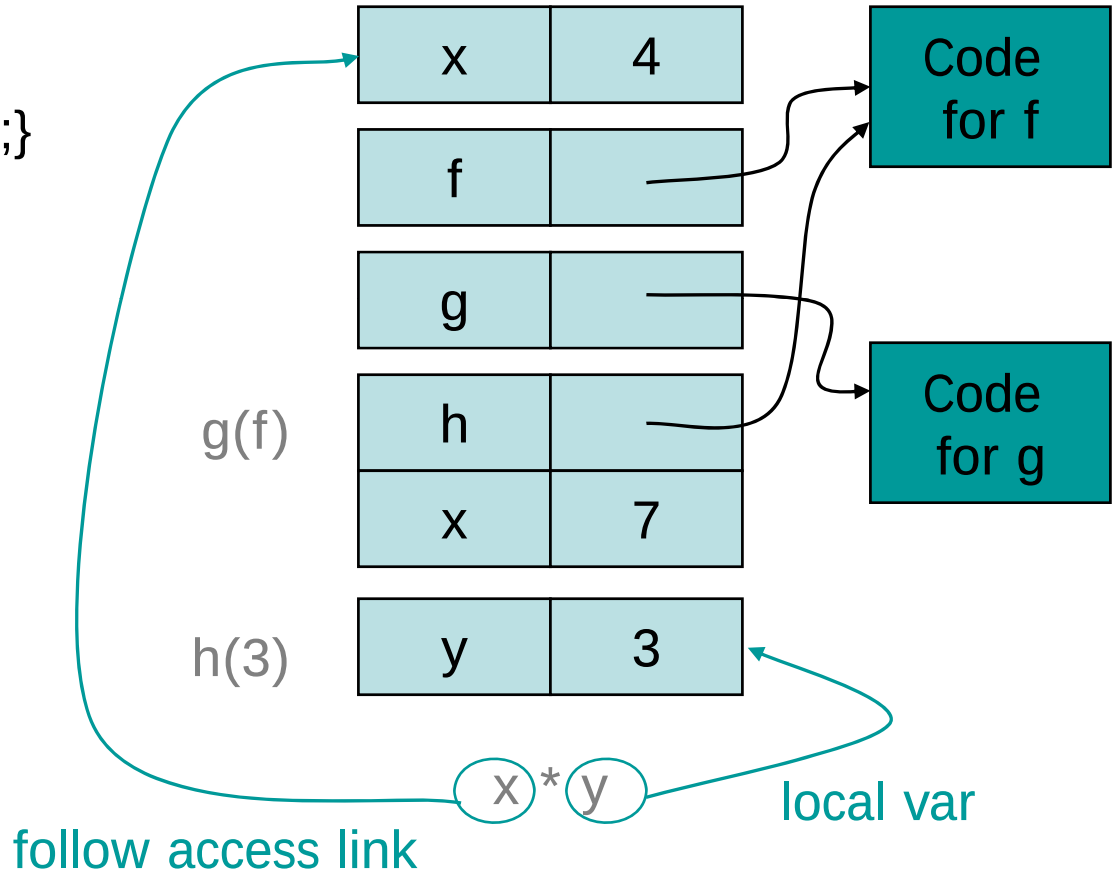
```
{ int x = 4;
   { int f(int y) {return x*y;}
      { int g(int→int h) {
                int x=7;
                return h(3) + x;
             }
          g(f);
      }
   }
}
```

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);
  }
 }
}
```



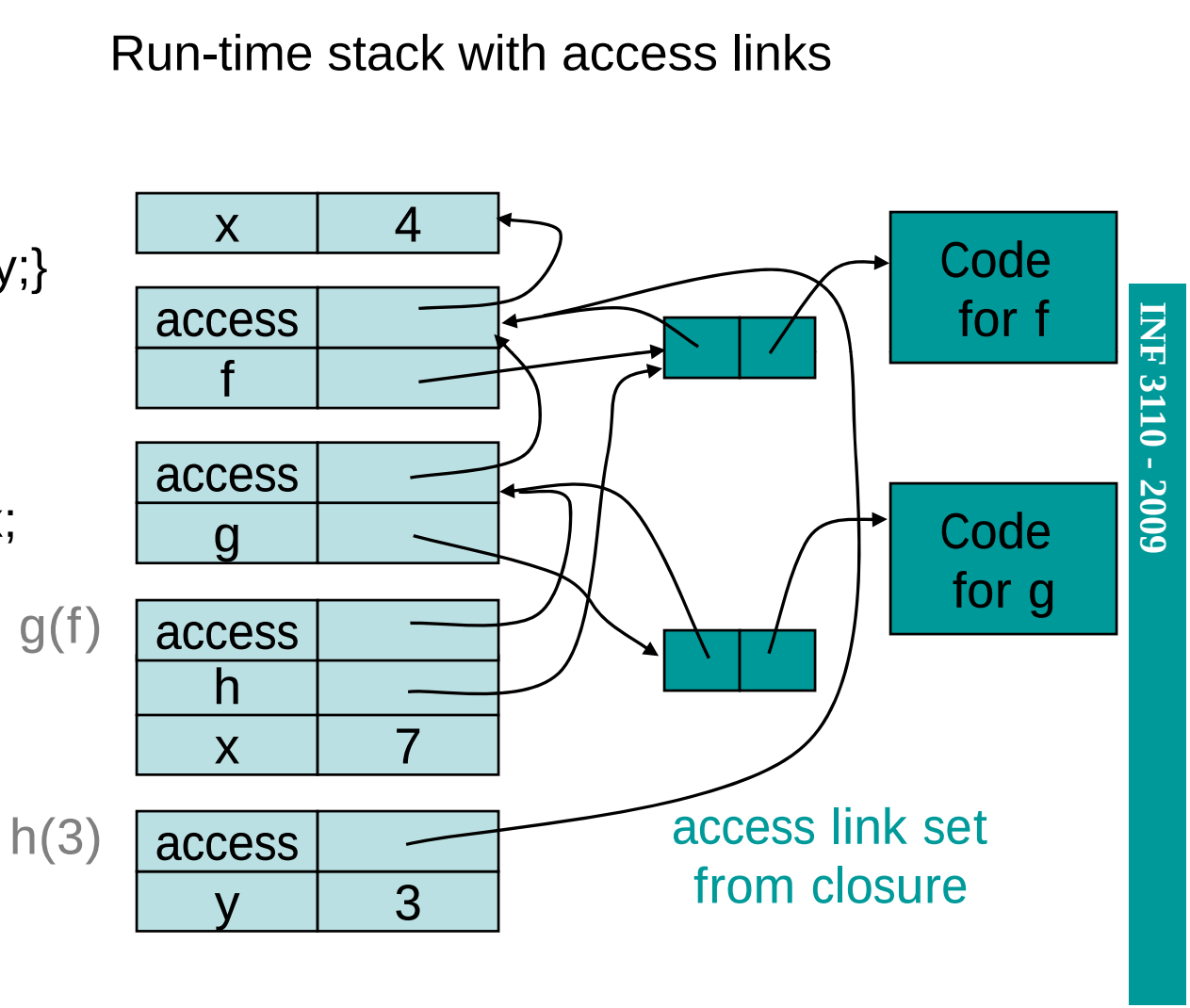
How is access link for h(3) set?

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);
    }
  }
}
```



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 function with private state

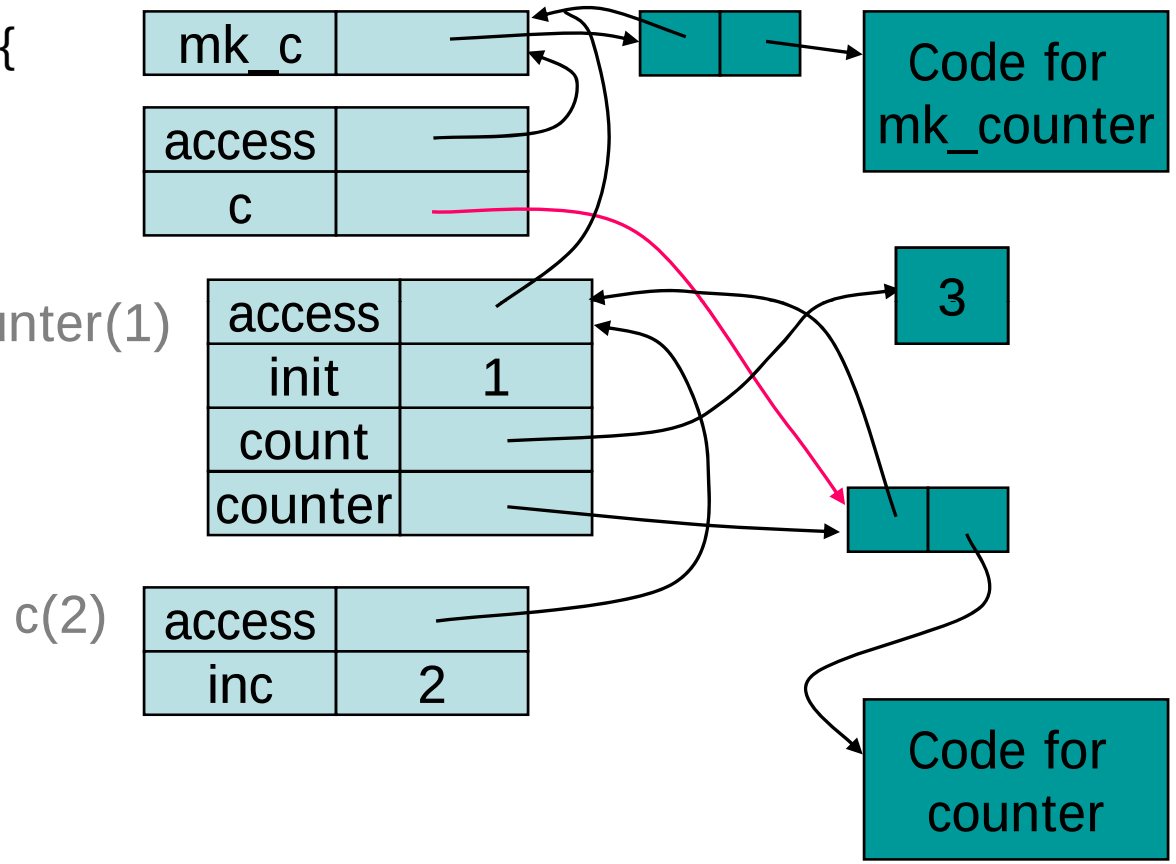
```
{ int→int mk_counter (int init) {
      int count = init;
      int counter(int inc)
         { return count += inc;}
      return counter
  }
  int→int c  = mk_counter(1);
  print c(2) + c(2);
}
```

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

By-name parameters

```
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

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

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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

loc i = 3
i = a(i): i=a(3): i=6
a(6)=i: a(6)=3

By macro expansion

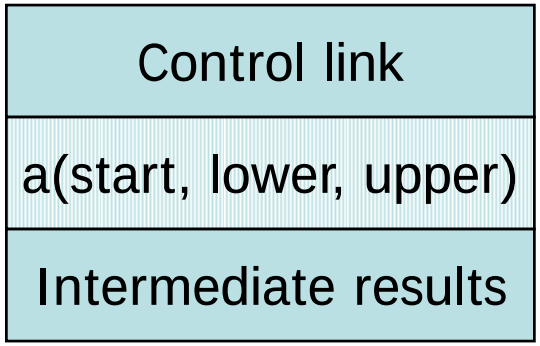
```
i = i;        -- local i = 0
i = a[i];     -- local i = a[0]
a[i] = i;     -- a[0] = 0
```

```
class CwF {int f(int i) {…} };

fsum(CwF ref, int[] a) {
  int sum= 0;
  for (i= l, 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); {...};
```

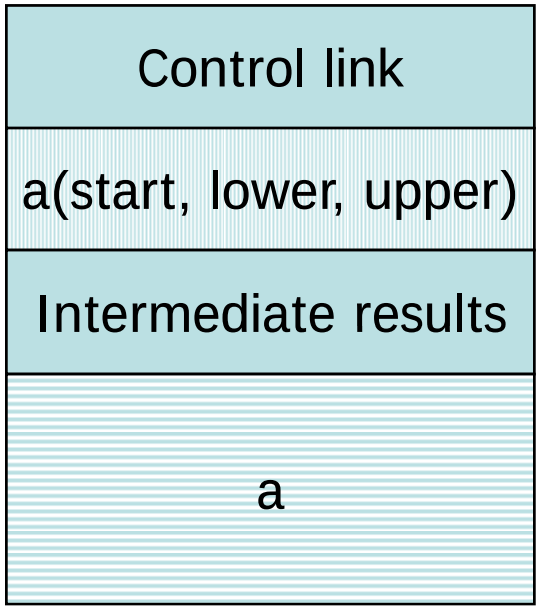
```
class CwFip1 extends CwF {
   int f(int i) {return ip1(i)}
};
class CwFip2 extends CwF {
   int f(int i) {return ip2(i)}
};

CwFip1 refIp1 = new CwFip1();
CwFip1 refIp2 = new CwFip2();

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

Dynamic languages – I

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



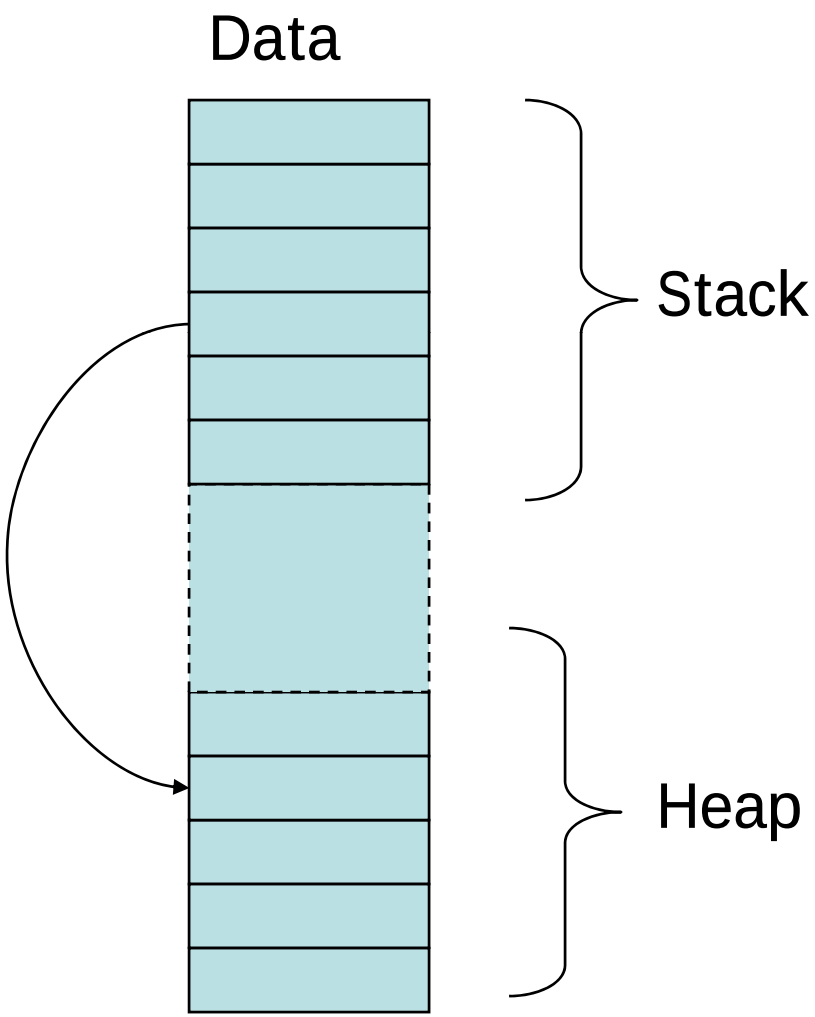
At compilation
Each dynamic array gets a *descriptor* (start of array, lower, upper).
Array-access via this descriptor.



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

Dynamic languages - II

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

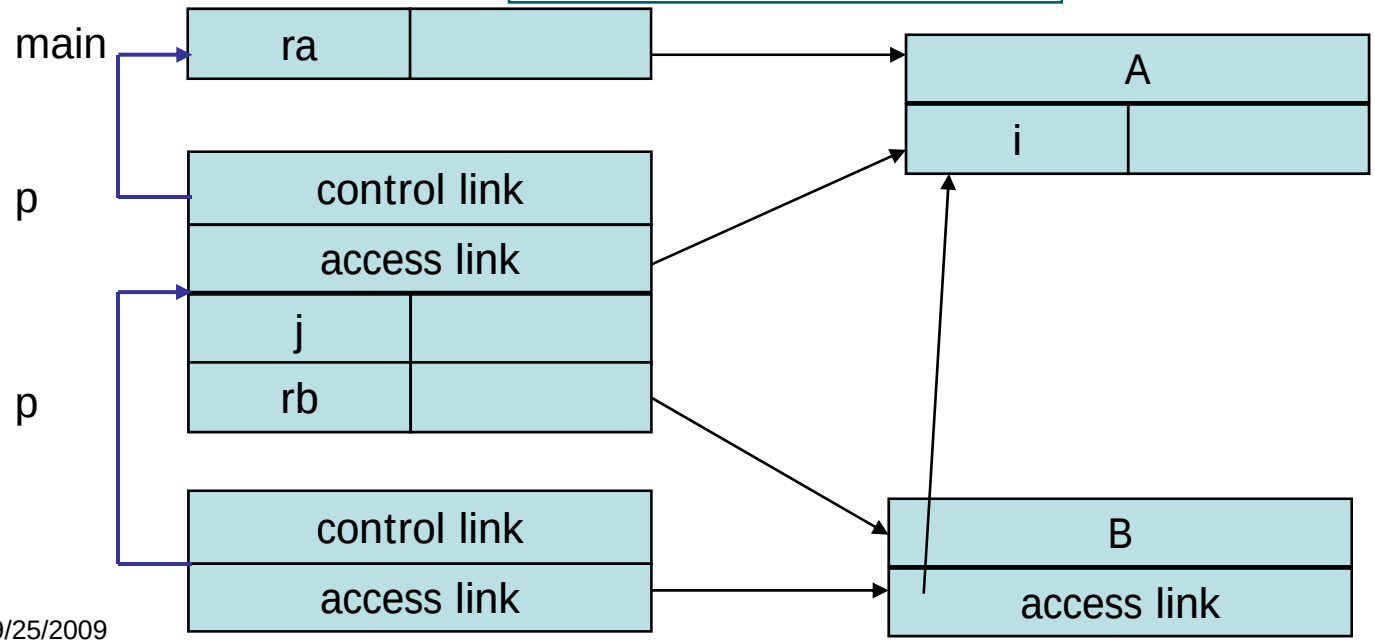


Access links for object oriented languages

```
class Program {
   public static void
   main(String[] args) {
      A ra = new A();
      ra.p();
   };
};
```

```
class A {
   int i = 1;
   class B {
      void p(){ i = 2; };
   };
   void p() {
      B rb = new B();
      int j=i;
      rb.p();
   };
};
```

- Access links for method activations may be objects
- Objects may also have access links (classes in classes, or classes in methods)



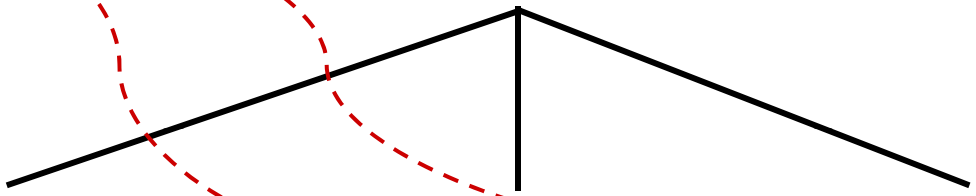
Garbage Collection

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

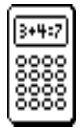
Stack organization in perspective

concurrent objects

objects with alternating actions



Tourplanning Invoicing Reservation



partial actions of object (or of actions)

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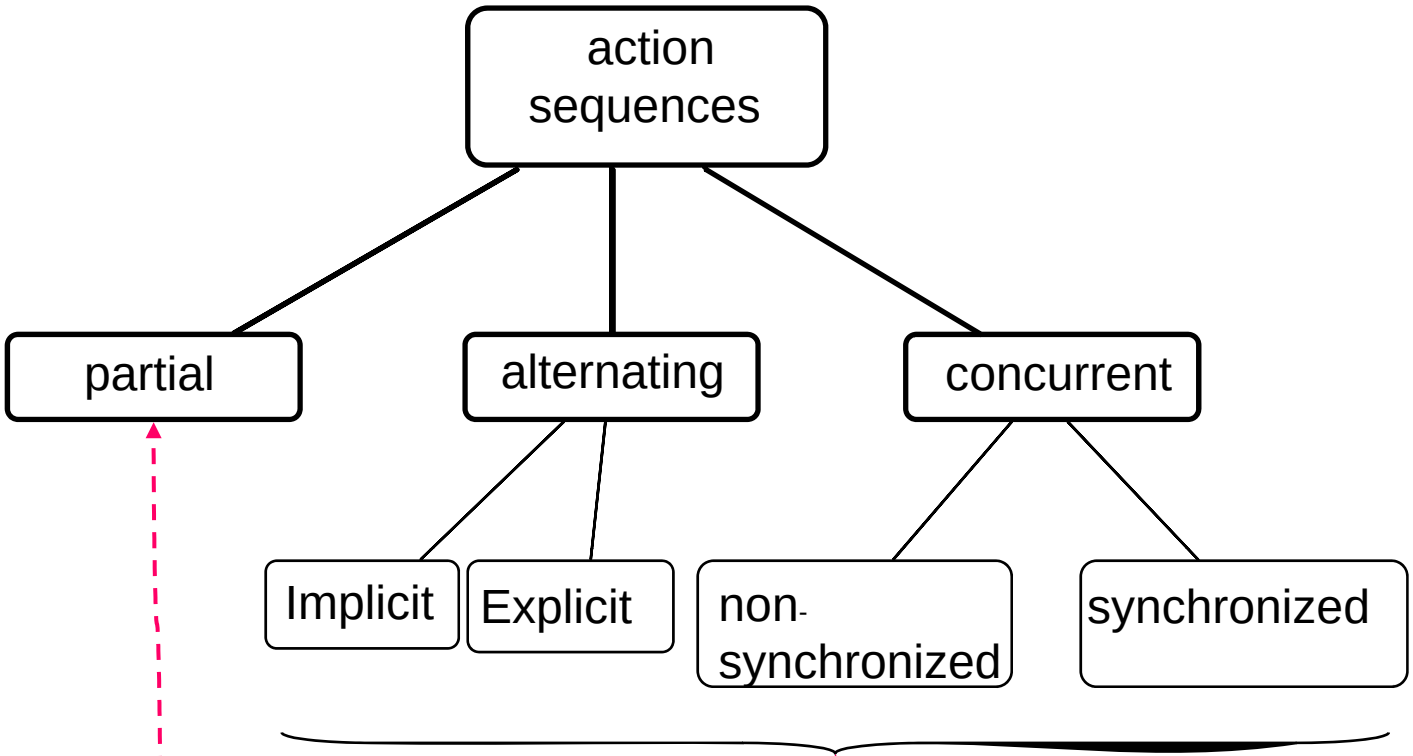

Activation records
Stack organization

Objects - heap organization
Each object may have a stack

Functions within functions
Methods within methods

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