

Scope, Function Calls and Storage Management

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capitolo 7 del
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Introduzione

- Quando dichiariamo una variabile, il computer dove la memorizza?
- Quali sono le regole per accedere ad una variabile?
- Come vengono passate ai sottoprogrammi i dati?
- Due principali feature:
 - Divisione di un programma in sottoprogrammi
 - Non come il BASIC
 - Non si fanno tutte le variabili prima dell'esecuzione e l'allocazione della memoria avviene dinamicamente
 - Uso della ricorsione

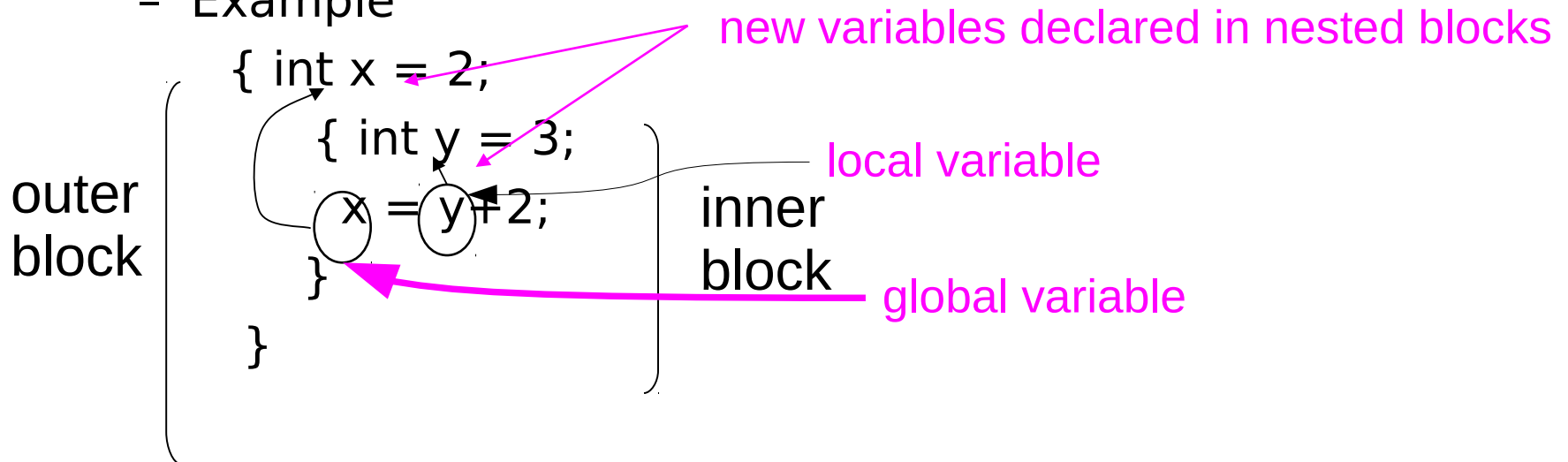
Topics

- Block-structured languages and stack storage
- In-line Blocks
 - activation records
 - storage for local, global variables
- First-order functions
 - parameter passing
 - tail recursion and iteration
- NO - Higher-order functions
 - deviations from stack discipline
 - language expressiveness => implementation complexity

Block-Structured Languages

- Nested blocks, local variables

- Example



- Storage management

- Enter block: allocate space for variables
 - Exits block: some or all space may be deallocated

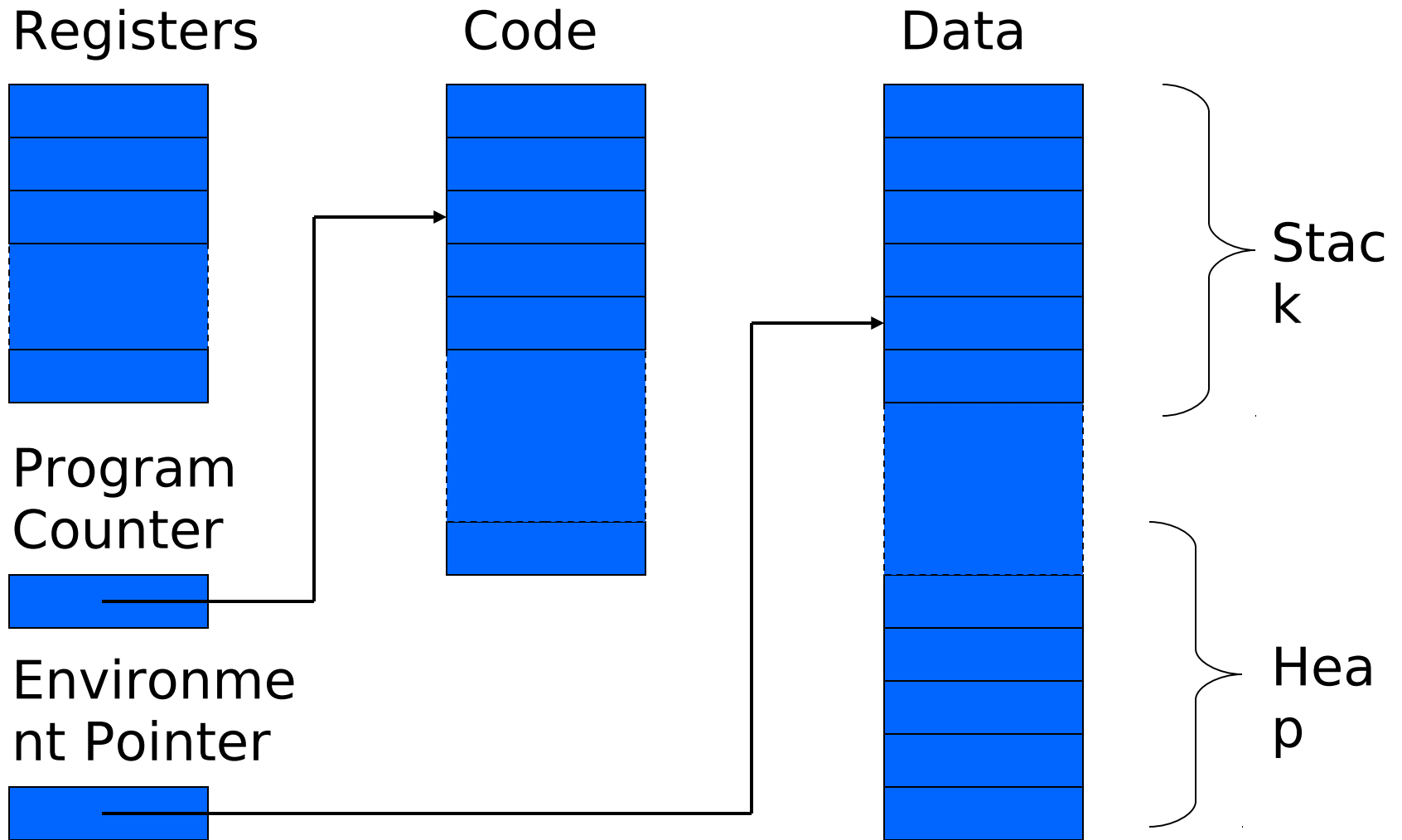
Examples

- Blocks in common languages
 - C/c++/Java { ... }
 - Algol begin ... end
 - ML let ... in ... end
- Two forms of blocks
 - In-line blocks
 - Blocks associated with functions or procedures
- Topic: block-based memory management, access to *local variables, parameters, global vars*
- It allows **recursive functions**

Alcune note

- Alcuni linguaggi (come Fortran) allocavano in modo fisso le variabili
 - Svantaggi ...
- **Block-structured languages:**
 - New variables may be declared at various points in a program
 - Each declaration is visible within a block
 - When a program begins executing the instructions contained in a block, the memory is allocated
 - When a program exits, the memory is freed
 - An identifier that is not declared in the current block is considered global to the block

Simplified Machine Model



Interested in Memory Mgmt Only

- Registers, Code segment, Program counter
 - Ignore registers
 - Details of instruction set will not matter
- Data Segment
 - Stack contains data related to block entry/exit
 - Heap contains data of varying lifetime
 - **Environment pointer** points to current stack position
 - Block entry: add new activation record to stack
 - Block exit: remove most recent activation record

Some basic concepts

- Scope
 - Region of program text where declaration is visible
- Lifetime
 - Period of time when location is allocated to program

```
{ int x = ... ;  
  { int y = ... ;  
    { int x = ... ;  
      ....  
    };  
  };  
};
```

- Inner declaration of x hides outer one.
- Called “hole in scope”
- Lifetime of outer x includes time when inner block is executed
- Lifetime \neq scope
- Lines indicate “contour model” of scope.

In-line Blocks

- Activation record
 - Data structure stored on run-time stack
 - Contains space for local variables
- Example

```
{ int x=0;  
  int y=x+1;  
    { int z=(x+y)*(x-y);  
    };  
};
```

```
Push record with space for x, y  
Set values of x, y  
  Push record for inner block  
  Set value of z  
  Pop record for inner block  
Pop record for outer block
```

Intermediate results on the stack

May need space for variables and intermediate results like $(x+y)$, $(x-y)$

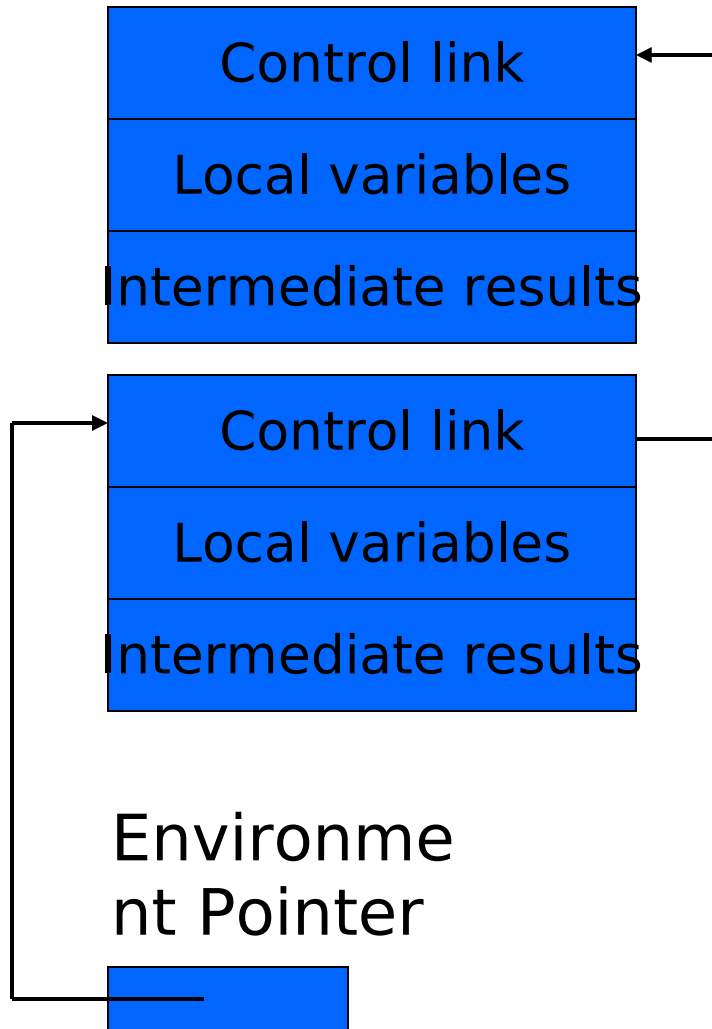
Example:

$\text{Int } z = (x+y) * (x-y)$

Control Link

- EP punta alla cima del record di attivazione corrente
- Record di attivazione ha dimensione variabile
- Come faccio a ripristinare EP quando faccio il pop del record di attivazione che non serve più?
- Uso il control link:
 - Puntatore alla cima del record di attivazione precedente
 - Viene salvato quando creo il record di attivazione
 - Viene ripristinato quando faccio il pop

Activation record for in-line block



- Control link
 - pointer to previous record on stack
- Push record on stack:
 - Set new control link to point to old env ptr
 - Set env ptr to new record
- Pop record off stack
 - Follow control link of current record to reset environment pointer

Example

```
{ int x=0;
  int y=x+1;
  { int z=(x+y)*(x-y);
  };
};
```

Push record with space for x, y (set control link = old env pointer, set env pointer)

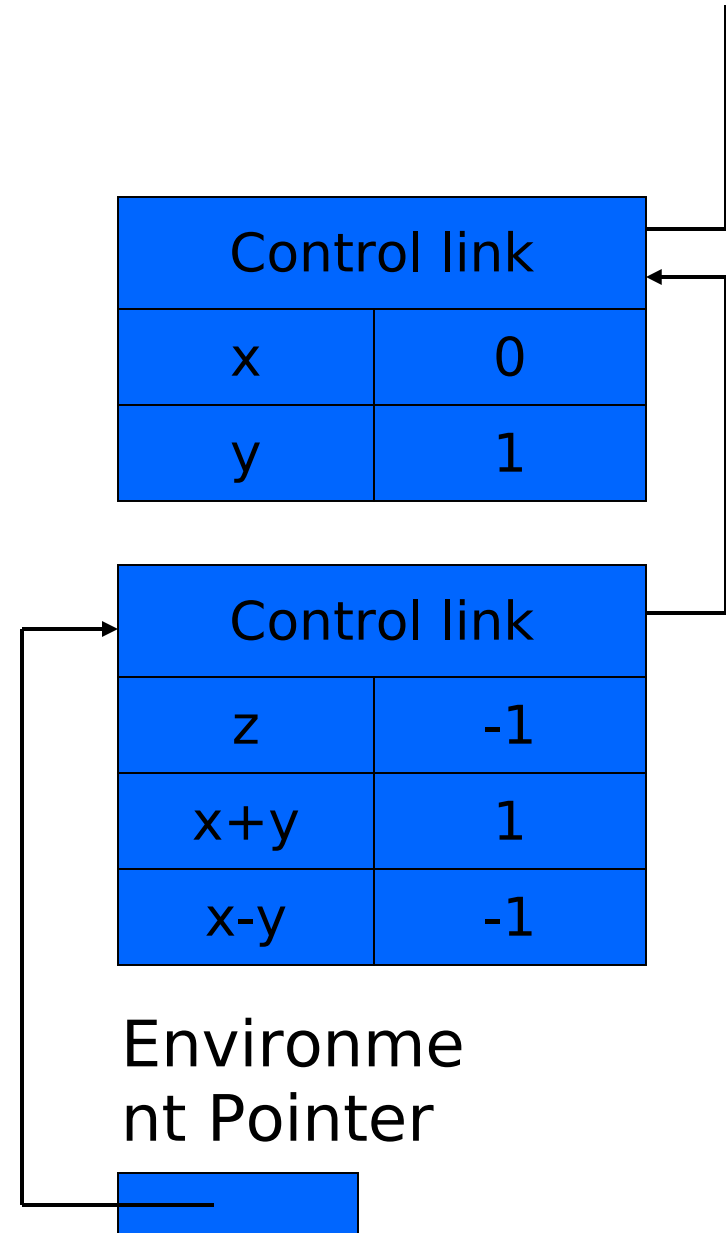
Set values of x, y

Push record for inner block

Set value of z

Pop record for inner block (set env pointer to control link)

Pop record for outer block



Scoping rules

- Global and local variables
 - x, y are local to outer block
 - z is local to inner block
 - x, y are global to inner block

```
{ int x=0;
  int y=x+1;
  { int z=(x+y)*(x-
    y);
  };
};
```

◆ Static scope

- global refers to declaration in closest enclosing block

◆ Dynamic scope

- global refers to most recent activation record

These are same until we consider function calls.

Esercizio 7.1

Functions and procedures

- Syntax of procedures (Algol) and functions (C)

procedure P (<pars>)

begin

<local vars>

<proc body>

end;

<type> function f(<pars>)

{

<local vars>

<function body>

};

- Activation record must include space for

- parameters

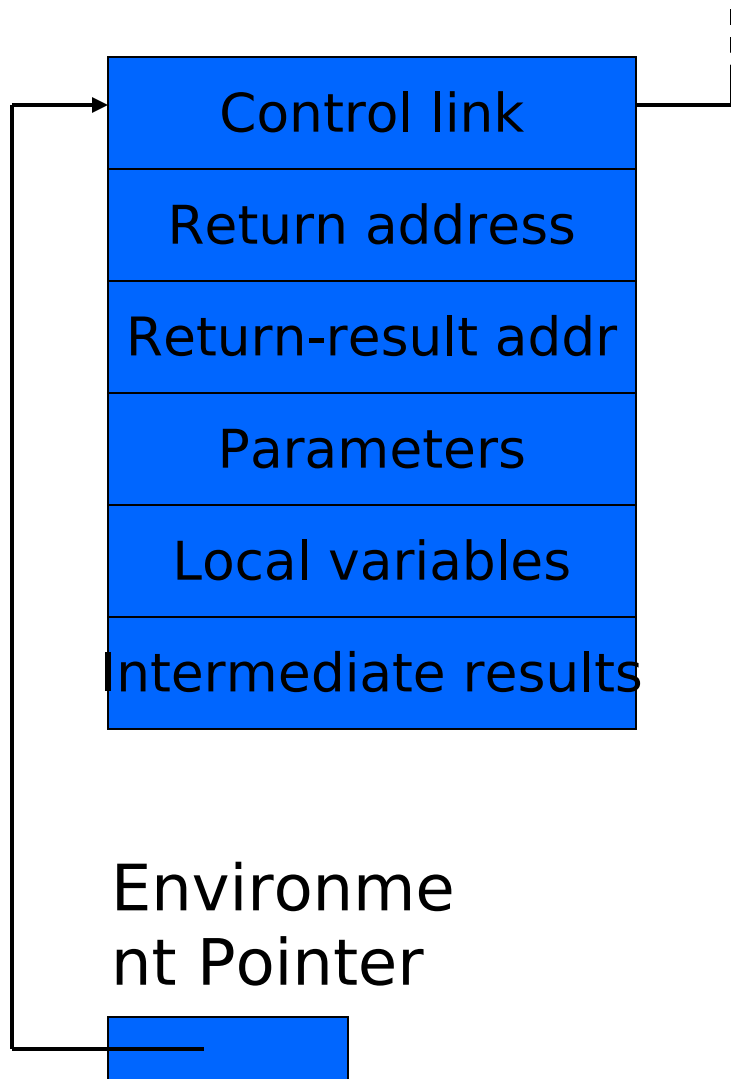
- return address

- Local variables

(and intermediate result)

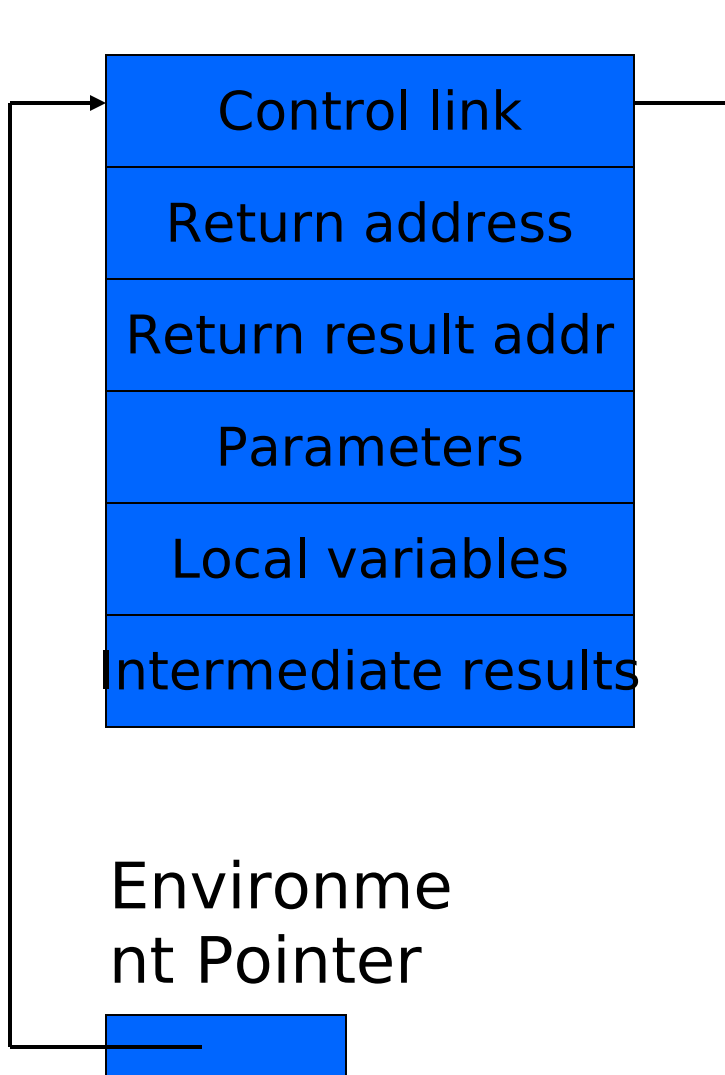
- location to put return value on function exit

Activation record for function



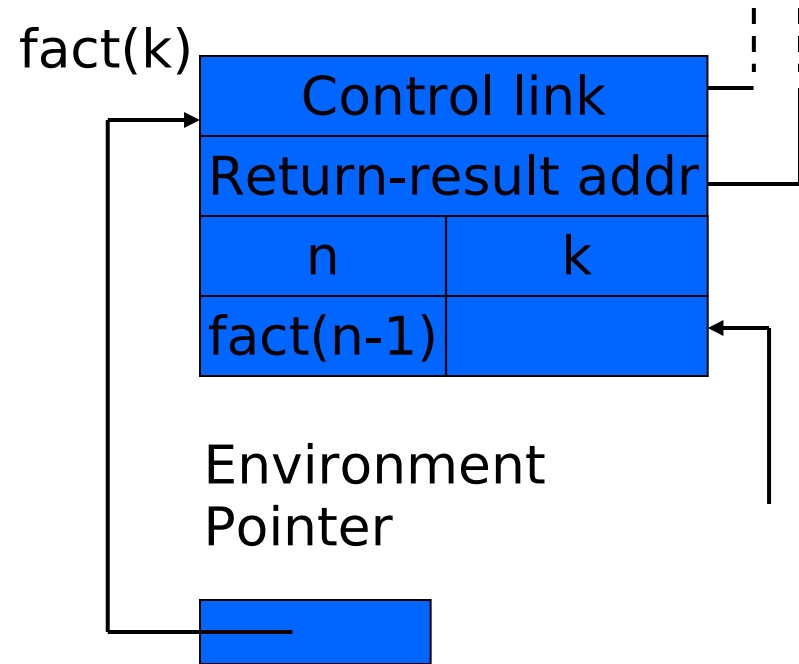
- Return address
 - Location of code to execute on function return
- Return-result address
 - Address in activation record of calling block to receive return address
- Parameters
 - Locations to contain data from calling block

Example



- Function
fact(n) = if $n \leq 1$ then 1
 else $n * \text{fact}(n-1)$
- Return result address
 - location to put fact(n)
- Parameter
 - set to value of n by calling sequence
- Intermediate result
 - locations to contain value of fact(n-1)

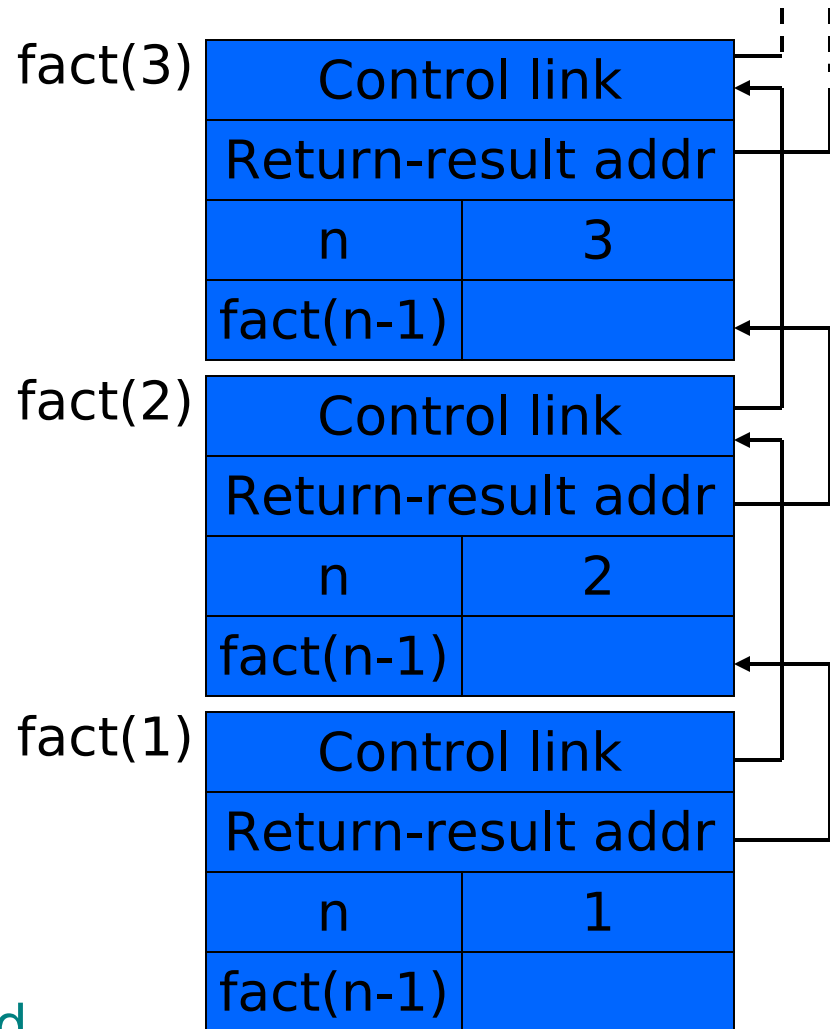
Function call



`fact(n) = if $n \leq 1$
then 1`

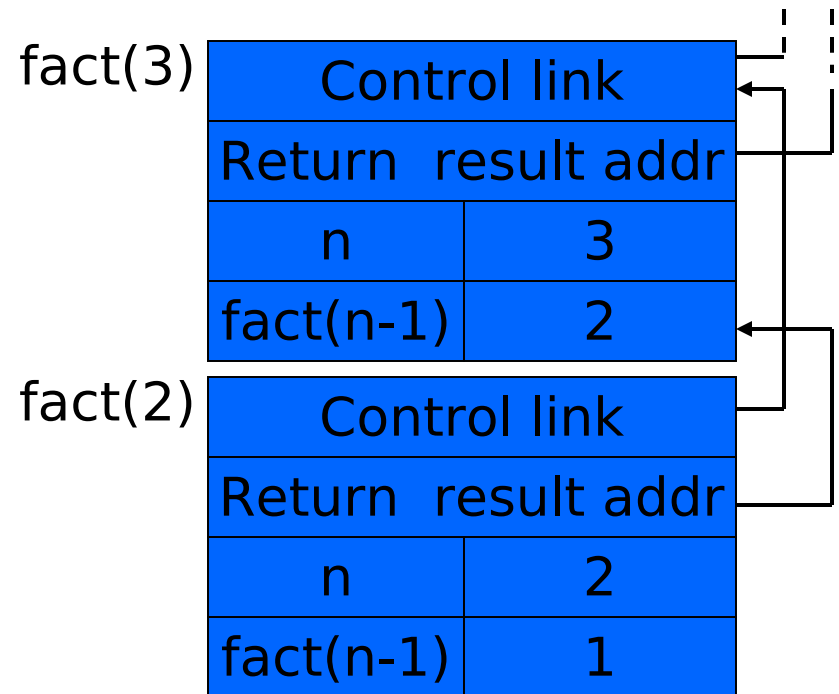
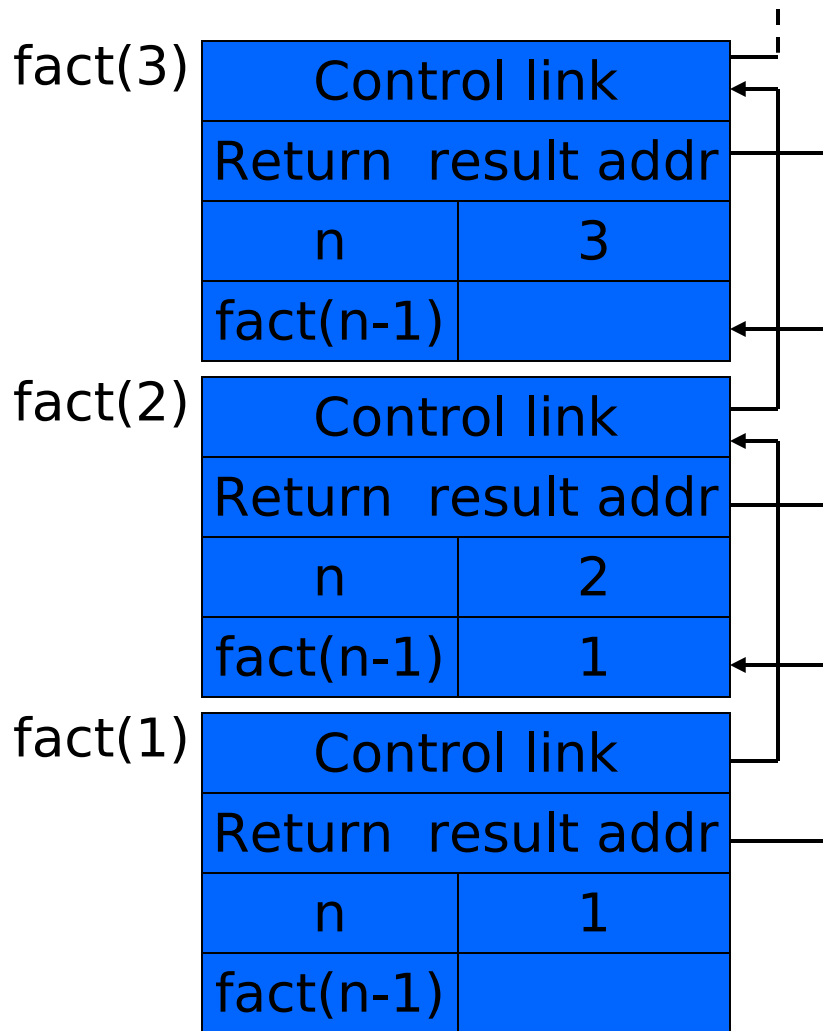
`else $n * \text{fact}(n-$`

`1)` Return address omitted; would
be ptr into code segment



Function return next slide →

Function return



`fact(n) = if n <= 1`
`then 1`
`else n * fact(n-`
`1)`

Topics for first-order functions

- Parameter passing
 - use ML reference cells to describe pass-by-value, pass-by-reference
- Access to global variables
 - global variables are contained in an activation record higher “up” the stack
- Tail recursion
 - an optimization for certain recursive functions

See this yourself: write factorial and run under debugger

ML imperative features (review)

- General terminology: L-values and R-values
 - Assignment $y := x+3$
 - Identifier on left refers to **location**, called its L-value
 - Identifier on right refers to **contents**, called R-value
- ML reference cells and assignment (anche in C++)
 - Different types for location and contents
 - $x : \text{int}$ non-assignable integer value
 - $y : \text{int ref}$ location whose contents must be integer
 - $!y$ the contents
 - $\text{ref } x$ expression creating new cell initialized to x
 - ML form of assignment
 - $y := x+3$ place value of $x+3$ in location (cell) y
 - $y := !y + 3$ add 3 to contents of y and store in location y

Parameter passing

- Pass-by-reference
 - Caller places L-value (address) of actual parameter in activation record
 - Function can assign to variable that is passed
- Pass-by-value
 - Caller places R-value (contents) of actual parameter in activation record
 - Function cannot change value of caller's variable
 - Reduces aliasing (alias: two names refer to same loc)

Example

pseudo-code

```
function f (x) =  
  { x := x+1; return x  
  };  
var y : int = 0;  
print f(y)+y;
```

pass-by-ref
→

→
pass-by-value

Standard ML

```
fun f (x : int ref) =  
  ( x := !x+1; !x );  
y = ref 0 : int ref;  
f(y) + !y;
```

```
fun f (z : int) =  
  let x = ref z in  
    x := !x+1; !x  
  end;  
y = ref 0 : int ref;  
f(!y) + !y;
```

Example

pseudo-code

```
function f (x) =  
  { x := x+1; return x  
  };  
var y : int = 0;  
print f(y)+y;
```

pass-by-ref
→

→
pass-by-value

C++

```
int f (int & x) {  
  x = x+1;  
  return x;  
}  
int y = 0;  
cout<< f(y) + y;
```

```
int f (int x) {  
  x = x+1;  
  return x;  
}
```

```
int y = 0;  
cout<< f(y) + y;
```

Passaggio di puntatori

- Il passaggio di puntatori è un passaggio per valore, ma si usa (in C) per ottenere lo stesso effetto del passaggio per riferimento.
- Es.:

```
int f(int* x) {  
    *x = *x+1;  
    return *x;  
}  
  
int y = 0;  
printf(f(&y) + y);
```

Se si vuole, si può evitare la modifica del parametro attuale mediante copia:

```
int f(int* x) {  
    int z = *x;  
    return z+1;  
}  
  
int y = 0;  
printf(f(&y) + y);
```

Passaggio di puntatori a puntatori

- Esercizio di passaggio di puntatore a puntatore
- Uso più frequente per modificare un puntatore.

Passaggio degli array in C

- Come si passano gli array in C
- Si possono passare come array:
 - `void foo(int arr[5])`
 - When an array is passed as a parameter, only the memory address of the array is passed (not all the values). An array as a parameter is declared similarly to an array as a variable, but no bounds are specified. The function doesn't know how much space is allocated for an array. See the example below.
 - Ma arr è semplicemente un puntatore di interi, non c'è alcuna informazione sulla dimensione dell'array !!!
 - Vedi esempio !!!

Parameter passing & activation record

- pass by value: the value of the actual parameter is copied in the activation record as value of the formal parameter
- pass by ref: the address of the actual parameter is copied in the activation record

Osservazioni

- Il passaggio per riferimento ha però alcuni svantaggi:
 - Indirezione ulteriore sullo stack
 - Side effect non desiderati - vedi esercizio sul libro
 - Vedi es 7.4
 - Come passare le costanti??
- Passaggio per nome: il nome del par. Formale viene sostituito con il par. Attuale
 - Vedi esercizio 5.2
- Fate esercizi 7.3, 7.5, 7.6. 7.7 7.8

Access to global variables

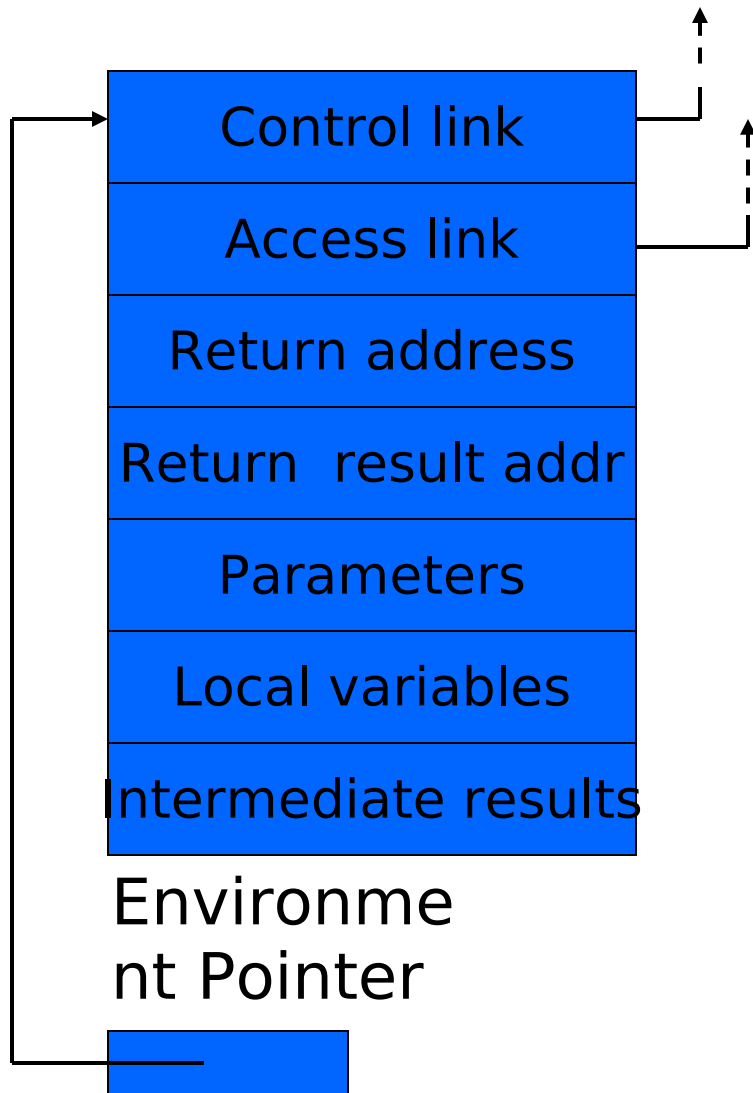
- Two possible scoping conventions
 - Static scope: refer to closest enclosing block
 - Dynamic scope: most recent activation record on stack
- Example

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

outer block	<table border="1"><tr><td>x</td><td>1</td></tr></table>	x	1		
x	1				
f(3)	<table border="1"><tr><td>y</td><td>3</td></tr><tr><td>x</td><td>4</td></tr></table>	y	3	x	4
y	3				
x	4				
g(12)	<table border="1"><tr><td>z</td><td>12</td></tr></table>	z	12		
z	12				

Which x is used for expression
x+z ?

Activation record for static scope



- Control (dynamic) link
 - Link to activation record of previous (calling) block
- Access (static) link
 - Link to activation record of closest enclosing block in program text
- Difference
 - Control link depends on dynamic behavior of prog
 - Access link depends on static form of program text

Complex nesting structure

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



Simplify to

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

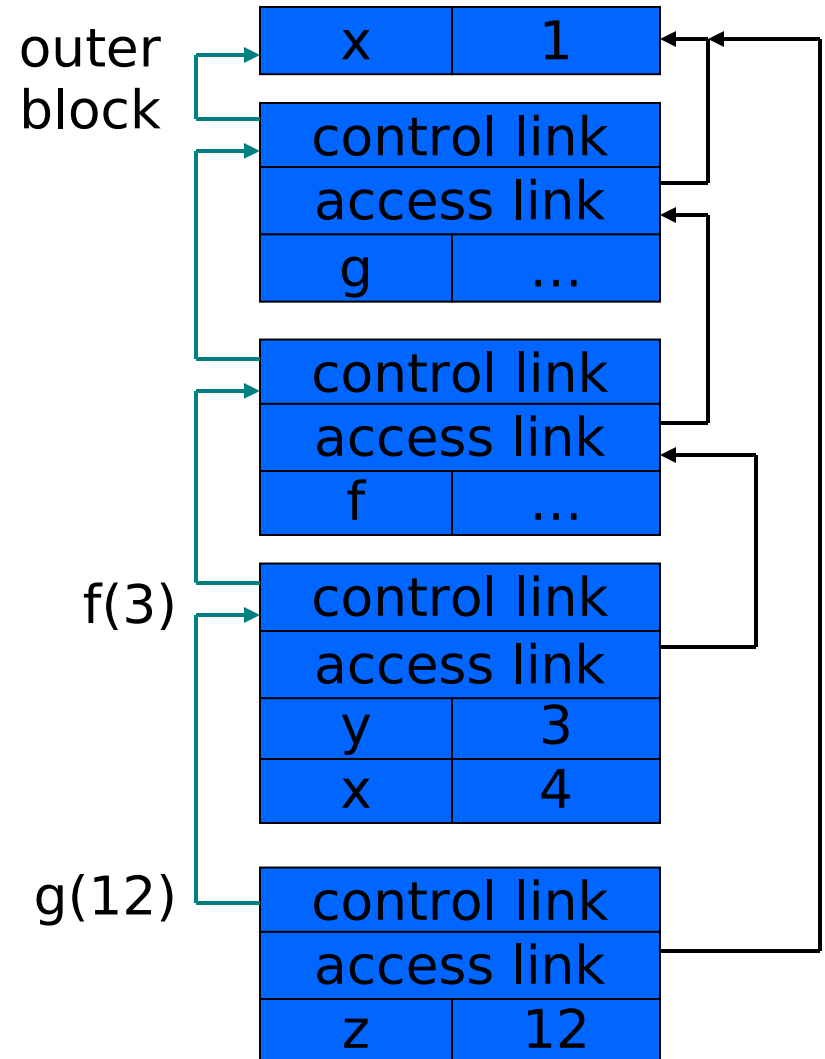
Simplified code has same block nesting, if we follow convention that each declaration begins a new block.

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



Ricorsione

- Una funzione matematica è definita ricorsivamente quando nella sua definizione compare un riferimento (chiamata) a se stessa.

- Esempio: Funzione fattoriale su interi non negativi:

$$f(n) = n!$$

definita ricorsivamente come segue:

$$1 \text{ se } n=0$$

$$f(n) = n * f(n-1) \text{ se } n > 0$$

Esempi di problemi ricorsivi:

1) Somma dei primi n numeri naturali:

- $somma(n) = 0$ se $n=0$
- $n + somma(n-1)$ altrimenti

2) Ricerca di un elemento el in una sequenza di interi:

- falso se sequenza terminata, altrimenti
- $ricerca(el, sequenza) = vero$ se $el = primo(sequenza)$, altrimenti
- $ricerca(el, resto(sequenza)) =$

Programmi ricorsivi

- Molti linguaggi di programmazione offrono la possibilità di definire funzioni/procedure ricorsive.
- Calcolo del fattoriale di un numero:

```
int fattoriale(unsigned int n){  
if (n<=1) return 1;  
else return n*fattoriale(n-1);  
}
```

Esempi (2)

- Alcune volte è necessario “complicare” la segnatura del metodo per renderlo ricorsivo:
- Ricerca di un elemento in un array (Java)

// cerca x in array a a partire dalla posizione pos

```
boolean search(int x, int[] a, int pos){
```

```
    if(pos >= a.length) return false;
```

```
    if(a[pos] == x) return true;
```

```
    // non trovato nella posizione pos vai alla prossima
```

```
    return search(x,a,pos+1);
```

```
}
```

Esempi (2 in C)

- In C spesso si passa anche la dimensione dell'array
- Ricerca di un elemento in un array (C)
- Array passato come puntatore

// cerca x in array a con lunghezza n

```
int search(int x, int* a, int n){  
    if(n == 0) return 0;  
    if(a[0] == x) return 1;  
    // non trovato nella posizione a[0] vai alla prossima  
    return search(x,a+1,n-1);  
}
```


Tail recursion (first-order case)

- Function g makes a *tail call* to function f if
 - Return value of function f is return value of g
- Example

fun $g(x)$ = if $x > 0$ then return $f(x)$ else return $f(x) * 2$

tail call not a tail call

- Optimization
 - Can pop activation record on a tail call
 - Especially useful for recursive tail call
 - next activation record has exactly same form

Example

Calculate least power of 2 greater than y

$f(1,3)$

control		↑
return val		↑
x	1	
y	3	

```
fun f(x,y) = if x>y
  then ret x
  else ret f(2*x, y);
f(1,3) + 7;
```

control		↑
return val		↑
x	1	
y	3	

control		↑
return val		↑
x	2	
y	3	

control		↑
return val		↑
x	4	
y	3	

Optimization

- Set return value address to that of caller

Question

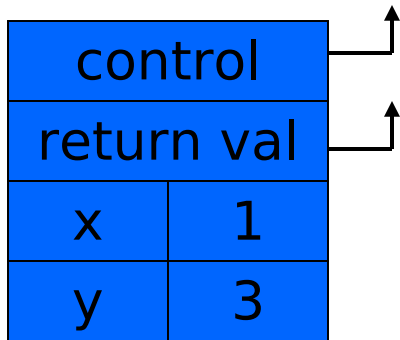
- Can we do the same with control link?

Optimization

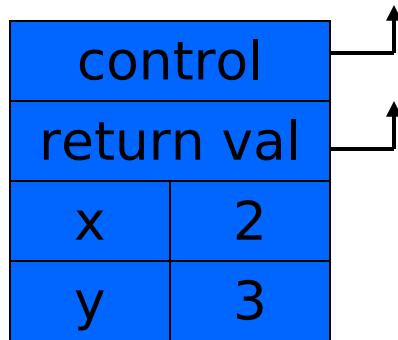
- avoid return to caller

Tail recursion elimination

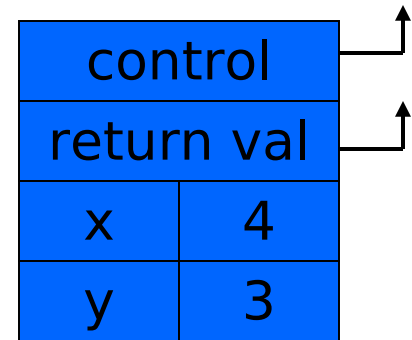
f(1,3)



f(2,3)



f(4,3)



```
fun f(x,y) = if x>y
  then x
  else f(2*x, y);
f(1,3);
```

Optimization

- pop followed by push = reuse activation record in place

Conclusion

- Tail recursive function equiv to iterative loop

Tail recursion and iteration

f(1,3)

control		↑
return val		↑
x	1	
y	3	

f(2,3)

control		↑
return val		↑
x	2	
y	3	

f(4,3)

control		↑
return val		↑
x	4	
y	3	

```
fun f(x,y) = if x > y  
  then x  
  else f(2*x, y);  
f(1,y);
```

test

loop body

initial value

```
fun g(y) = {  
  x := 1;  
  while not(x > y) do  
    x := 2*x;  
  return x;  
};
```

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

Summary of scope issues

- Block-structured lang uses stack of activ records
 - Activation records contain parameters, local vars, ...
 - Also pointers to enclosing scope
- Several different parameter passing mechanisms
- Tail calls may be optimized
- Function parameters/results require closures
 - Closure environment pointer used on function call
 - Stack deallocation may fail if function returned from call
 - Closures *not* needed if functions not in nested blocks