Scope, Functions and Storage Management

Mitchell Chapter 7

Implementing Programming Languages

- In this chapter, storage management for block-structured languages is described by the run-time data structures that are used in a simple *reference implementation*.

- Association between names in programs and memory locations is a key aspect.

  - Scope: allows two syntactically identical names to refer to different locations, or two different names to refer to the same location

  - Function calls: require a new memory area to store function parameters and local variables

Reference Implementation

- An implementation of a language
- Designed to define the behavior of the language

- Need not be efficient
- Goal is to understand programming languages (not build a compiler)

  - How blocks are implemented in most languages

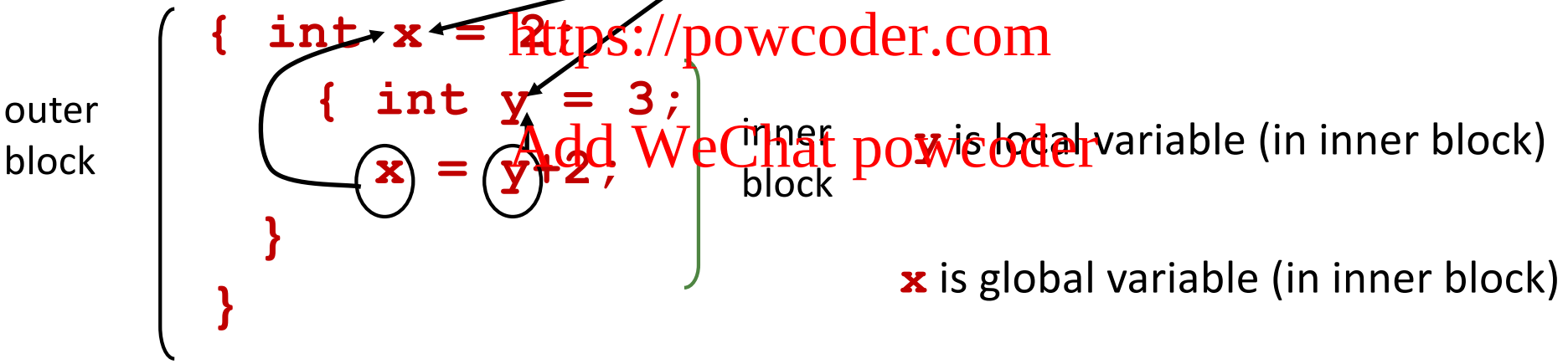
  - When storage needs to be allocated

  - What kinds of data are stored on the run-time stack
  - How executing programs access the data and location they need
  - Simple and direct because goal is understanding programming language
  - Compiler books discuss more efficient methods

Block-Structured Languages

- Blocks
  - A *block* is a region of program text, identified by begin and end markers, that may contain declarations local to this region.

- Nested blocks, local variables
  - Example



- Storage management
  - Enter block: allocate space for variables
  - Exit block: some or all space may be deallocated

Block-Structured Languages

outer block

```
{ int x = 2;
    { int y = 3;
      x = y+2;
    }
}
```

inner block

- Summary
  - The above is C code. This chapter also uses Algol-like pseudo-code and ML. (The ML is translated to OCaml on the slides.)
  - A local variable is a variable declared in a block
  - A global variable is a variable declared in an enclosing block.
  - In this example, in the inner block, **y** is local and **x** is global.
  - In the outer block, **x** is local and **y** is not visible.

Examples

- Blocks in common languages
  - C { … }
  - Algol begin … end
  - ML (OCaml) let … in …

- Two forms of blocks
  - In-line blocks
  - Blocks associated with functions or procedures

- Current Topic
  - block-based memory management, access to local variables, parameters, global variables

Kinds of Blocks (OCaml Examples)

- Simple in-line block

```
let x=3 in
(x,x)
```


- Nested block

```
let x=3 in
    let y = 4 in
    (x,y)
```


- Functions and procedures

```
let f x = x+3 in
f 2
```

Kinds of Function Blocks (in OCaml)

- Functions with static scope (first-order functions)


```
let x=3 in
  let f z = x+z in
  f 5
```

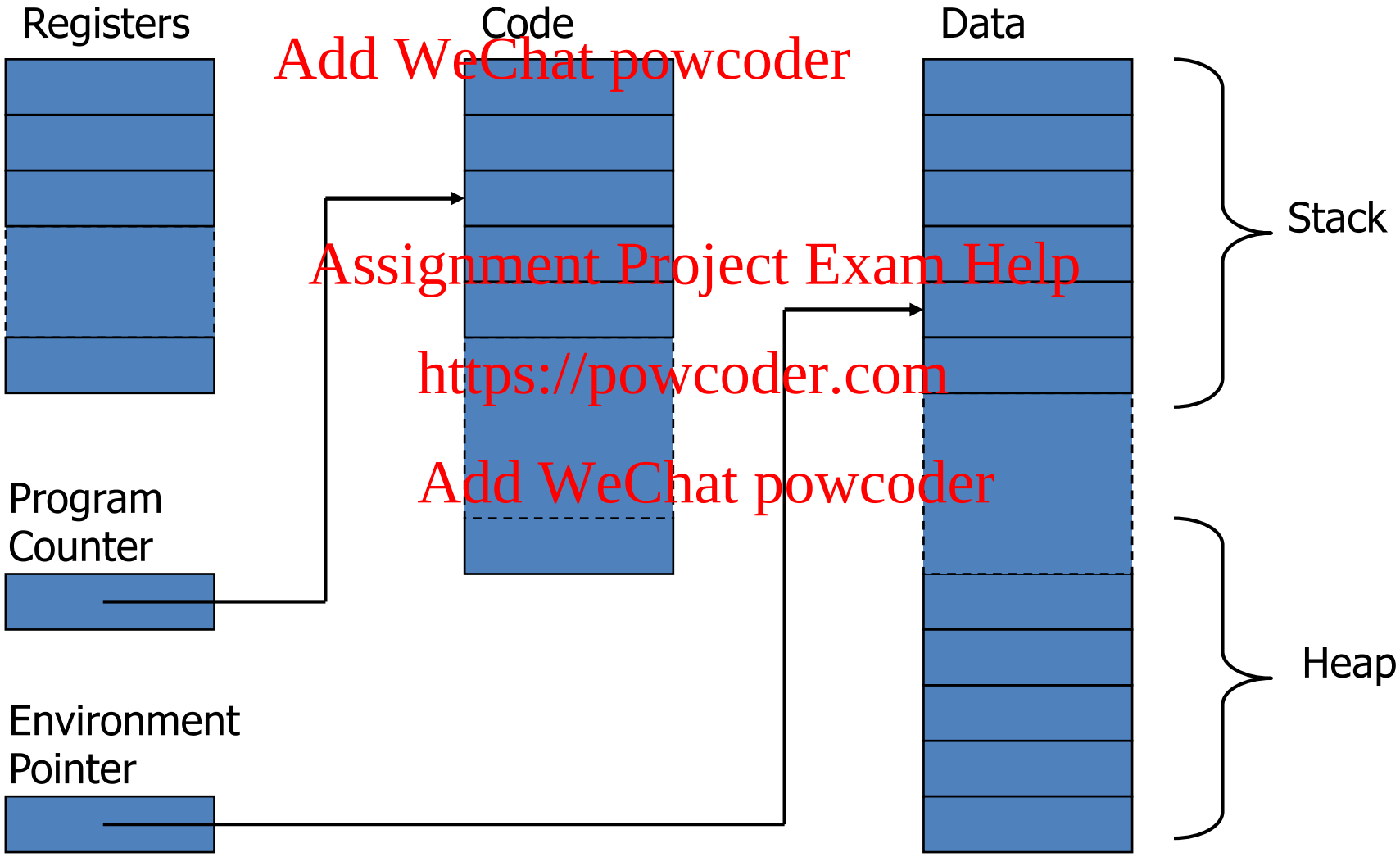
- Functions as arguments and results (higher-order programming)


```
let h x = x+x in
let compose f g =
  (fun x -> g (f x)) in
  compose h h
```

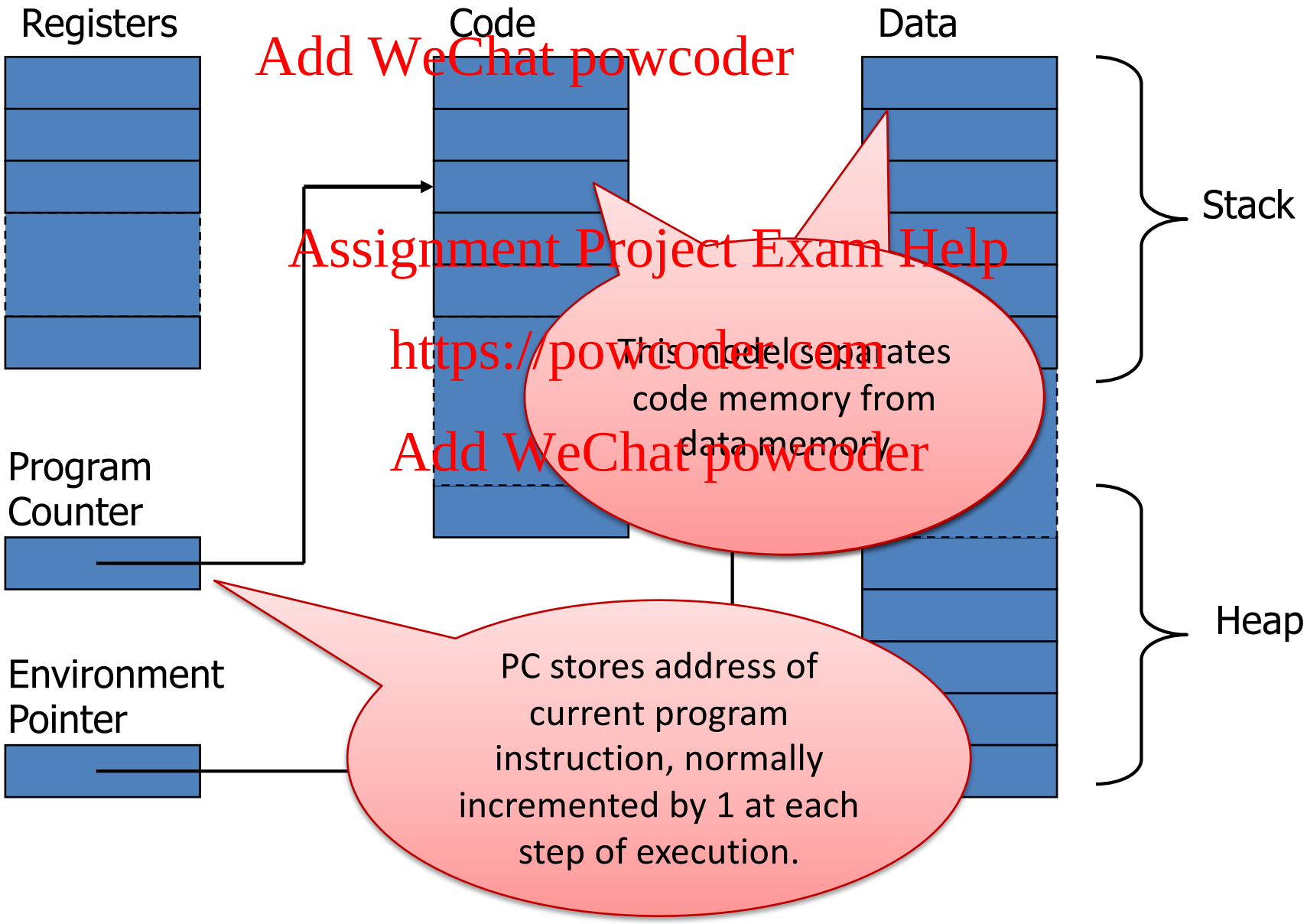

- Functions returned from nested scope (with pointers/references)

```
let counter () =
   let c = ref 0 in
  fun () ->
    let v = !c in
    (c := v+1 ; v)
```

Simplified Machine Model



Simplified Machine Model



Interested in Memory Management 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 (e.g., the cells pointed to by references)

  - Environment pointer points to current stack position

    - On block entry: add *new activation* record to stack
    - On block exit: remove most recent activation record
    - Activation record sometimes called a *stack frame*.

In-line Blocks

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

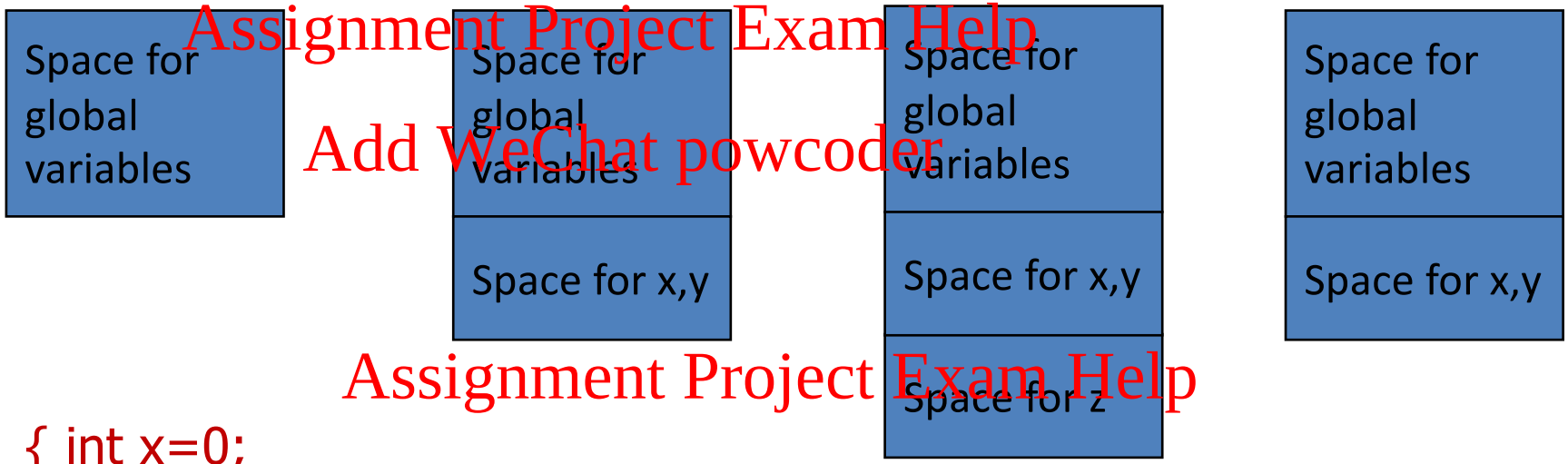
- Example


```
{ 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

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

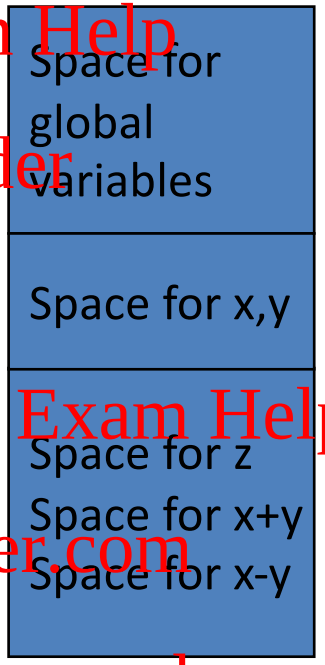
Activation Stack




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

Note: stacks are drawn “upside down” (they grow downward).

Activation Stack




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

Stack with space for intermediate results in the inner block.

Scope and Lifetime

- 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 ≠ scope
- Lines indicate “contour model” of scope.

Blocks in ML: Standard ML vs. OCaml

- let … in … end in Standard ML (SML) forms one block.
- equivalent to {…}…} in C

SML:

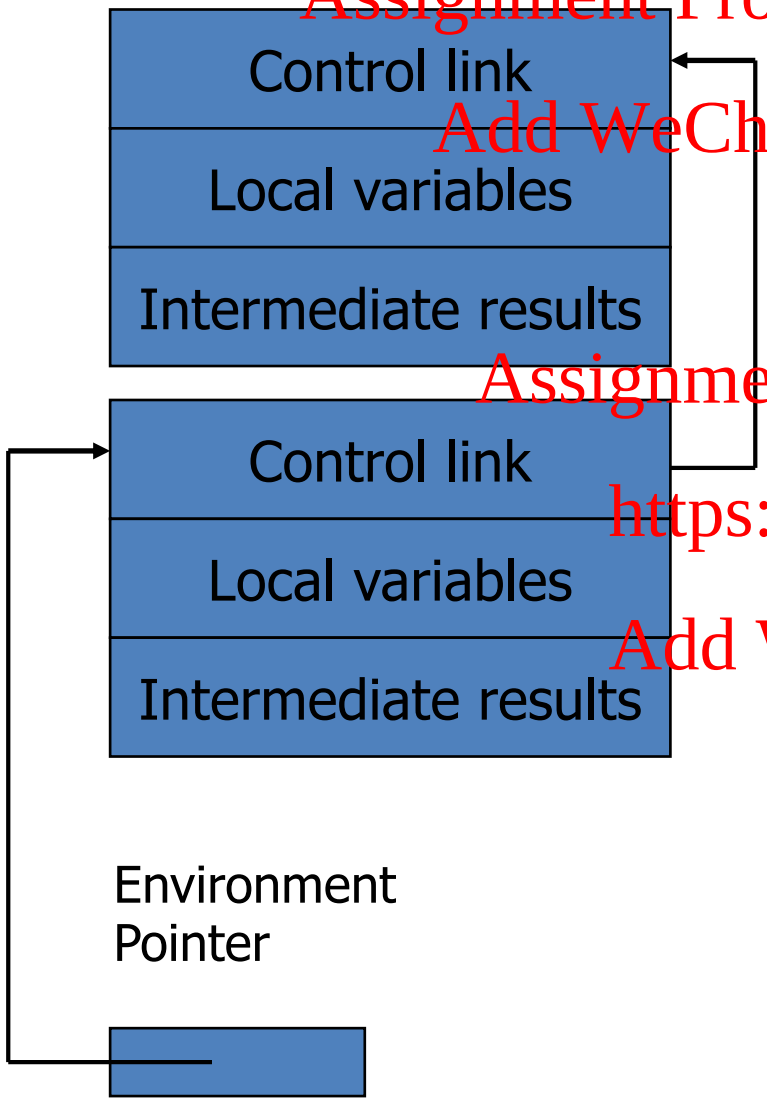
```
let fun g(y) = y+3
    fun h(z) = g(g(z))
in
    h(3)
end
```

OCaml:

```
let g y = y+3 in
let h z = g(g(z)) in
h(3)
```


- In SML, g and h will be given values in the same activation record.
- In OCaml, each let … in … is a separate block, but compilers usually can optimize to combine blocks.
- In SML and OCaml, …in… separates declarations from expressions. In C, declarations and expressions can be mixed.

Activation Record for In-line Block



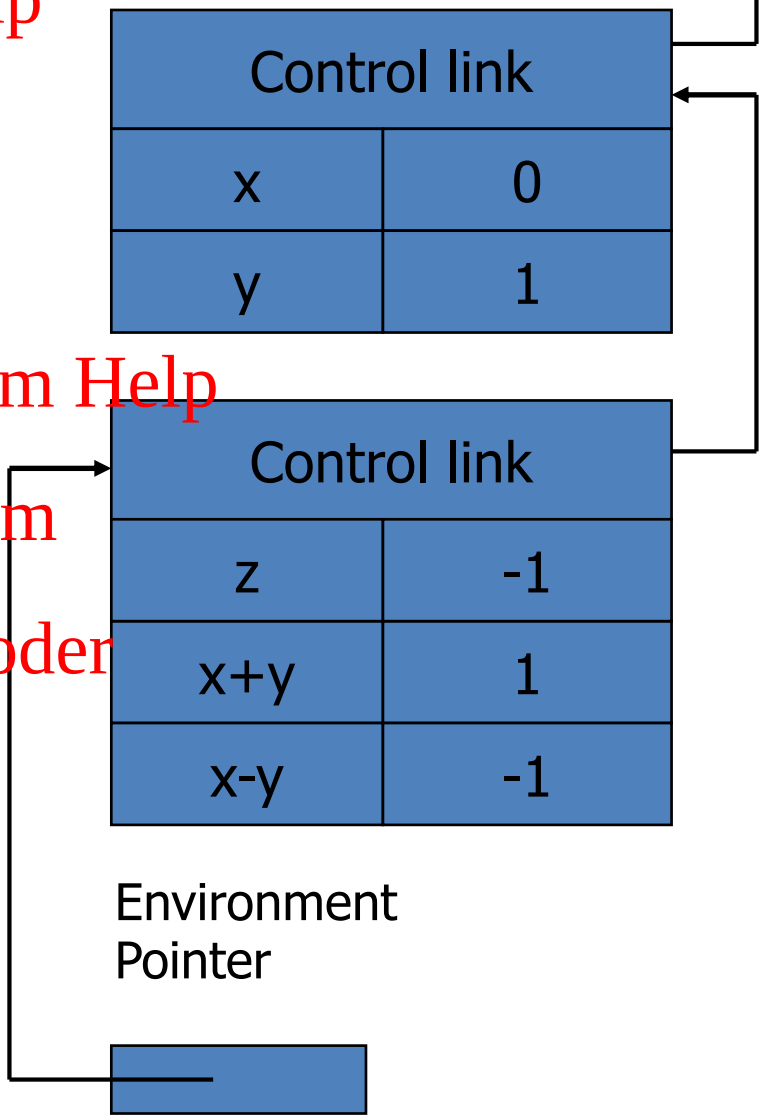
- Control link (Dynamic link)
  - pointer to previous record on stack
- Push record on stack:
  - Set new control link to point to old environment pointer
  - Set environment pointer to new record
- Pop record off stack
  - Follow control link of current record to reset environment pointer

Control links can be optimized away, but assume not for purpose of discussion.

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



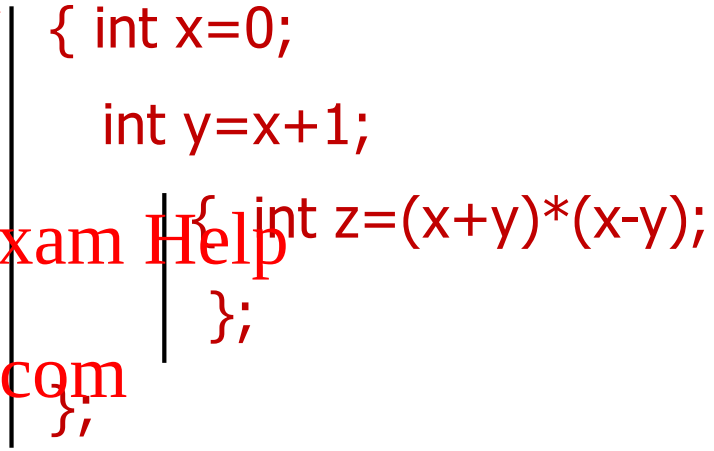
Possible Optimizations

- Compiler can generate code for block entry that is tailored to the size of the activation record (which is known at compile time)

- Compiler can compute number of blocks between current block and location of a global variable and generate lookup code that avoids following pointer chains.

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
  - z is not visible in outer block



- Static scope
  - global refers to declaration in closest enclosing block
- Dynamic scope
  - global refers to most recent activation record

Dynamic and static are the same until we consider function calls.

Functions and Procedures

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

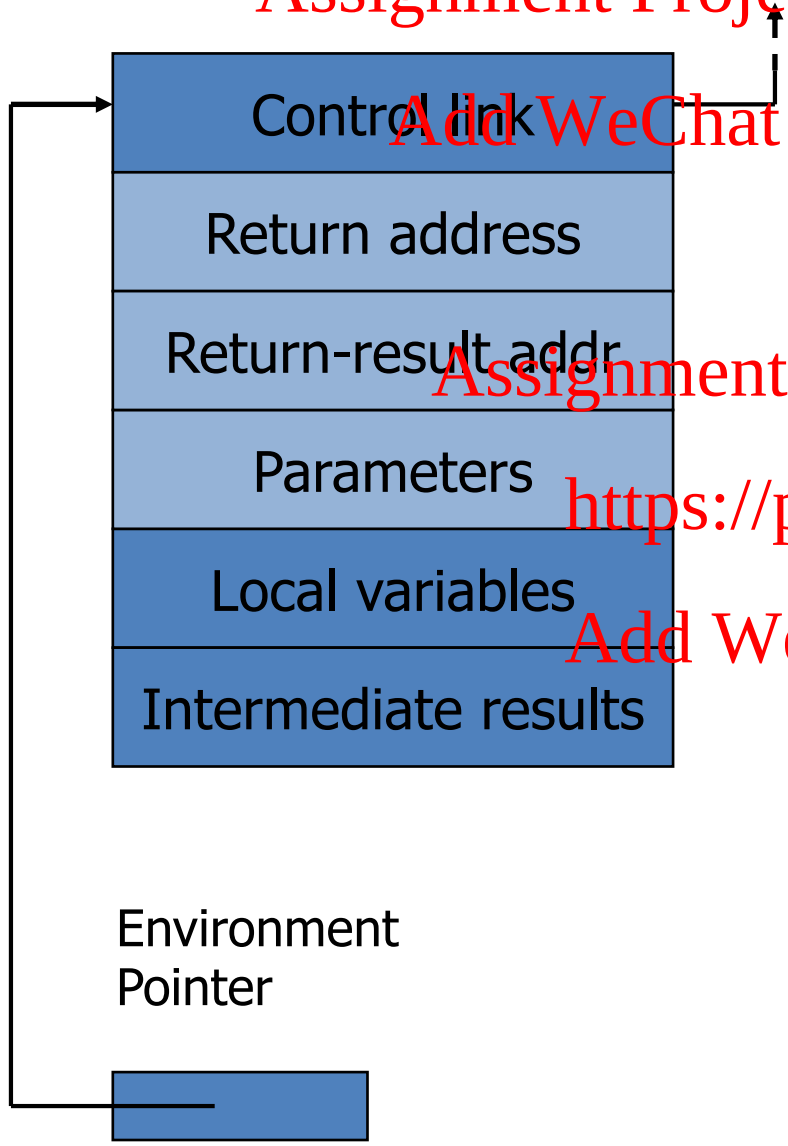

```
procedure P (<parameters>)
    begin
        <local variables>
        <proc body>
    end;
```



```
<type> function f(<parameters>)
{
        <local variables>
            <function body>
};
```

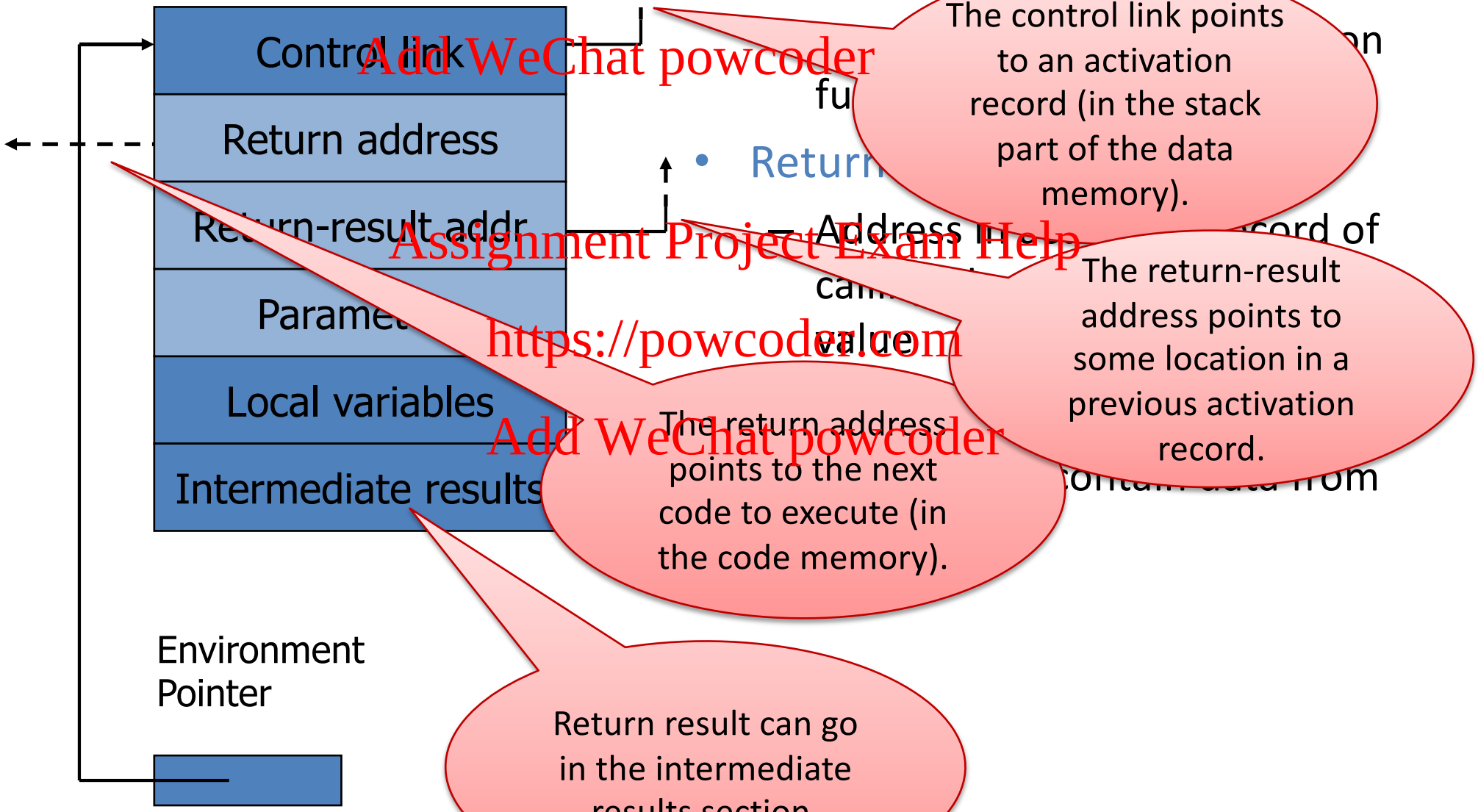

- Activation record must include space for:
  - parameters
  - return address
  - return value (an intermediate result)
  - location to put return value on function exit

Activation Record for Function

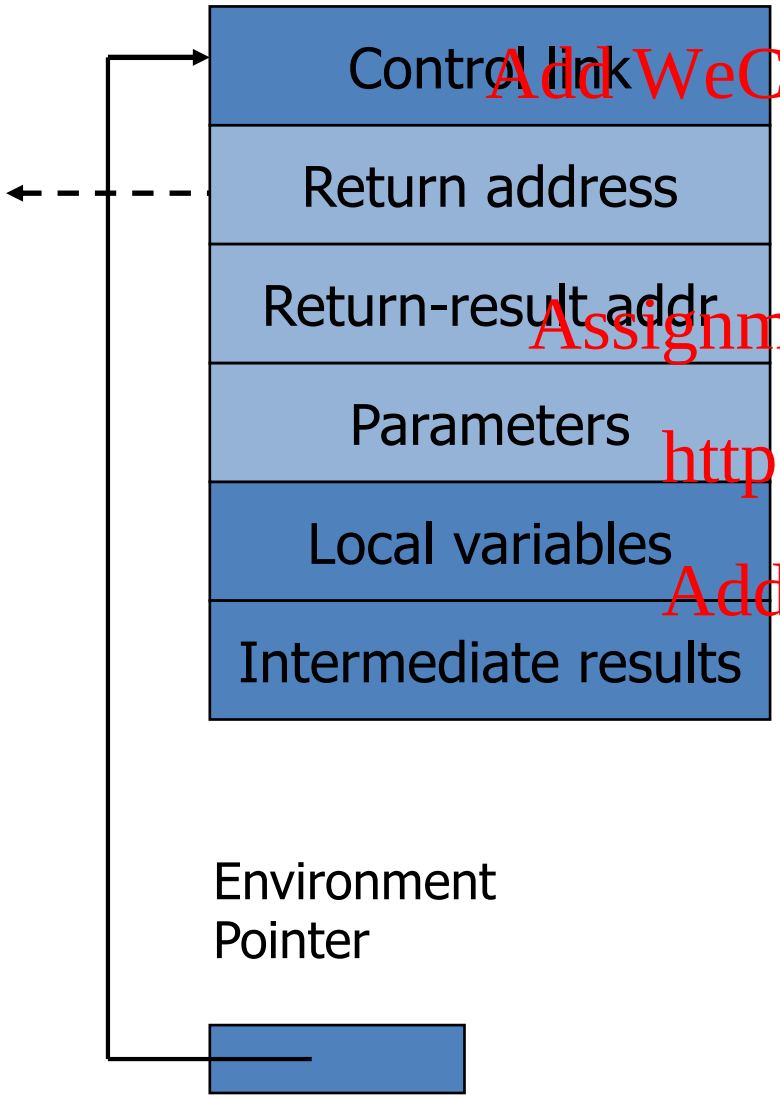


- Return address
  - Location of code to execute on function return
- Return-result address
  - Address in activation record of calling block to receive return value
- Parameters
  - Locations to contain data from calling block

Activation Record for Function



Example



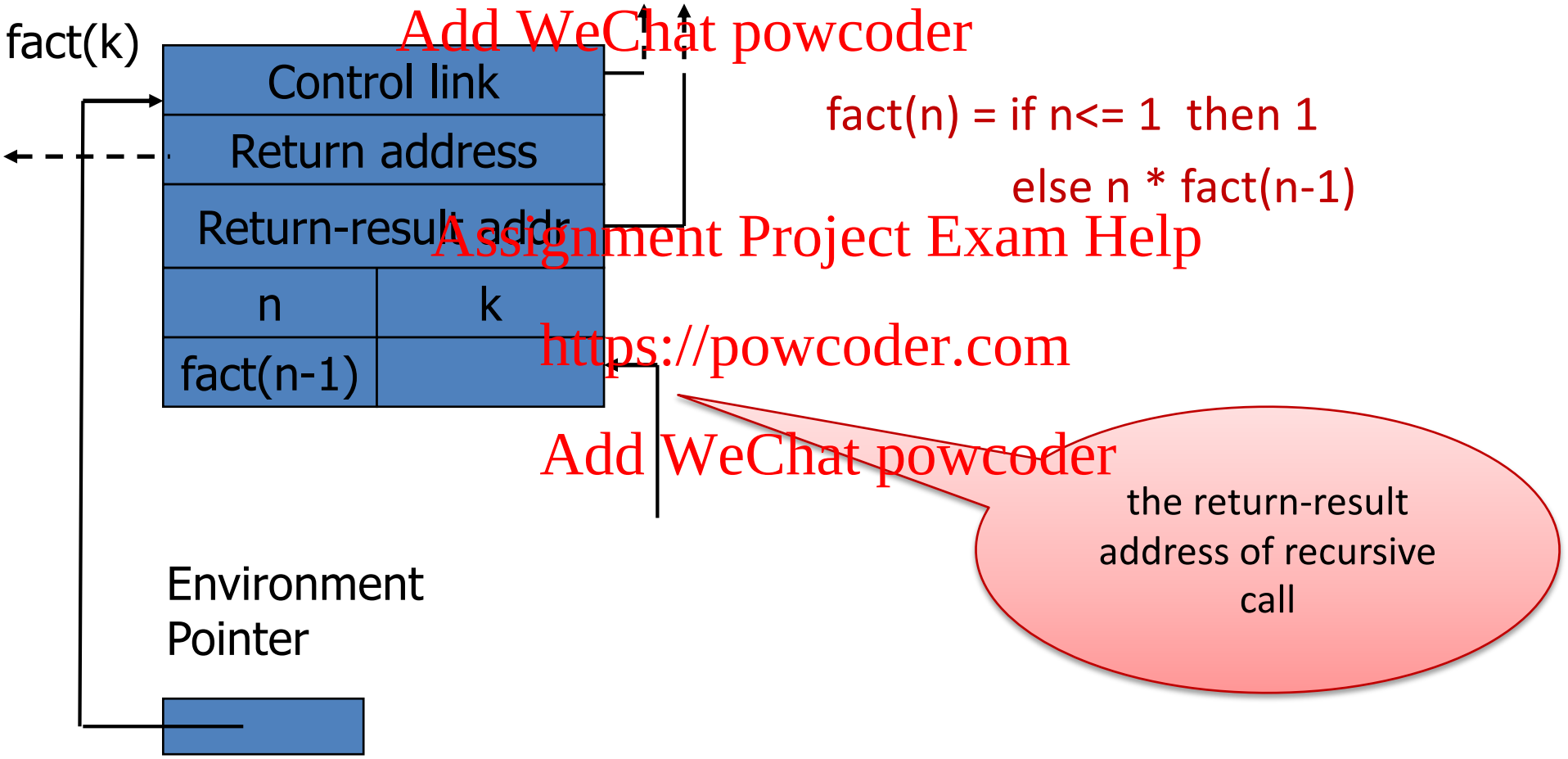
- Function
  - fact(n) = if n<= 1 then 1
    else n * fact(n-1)

- Return-result address
  - location to put the result of the function evaluation fact(n)

- Parameter
  - set to value of n when function is called

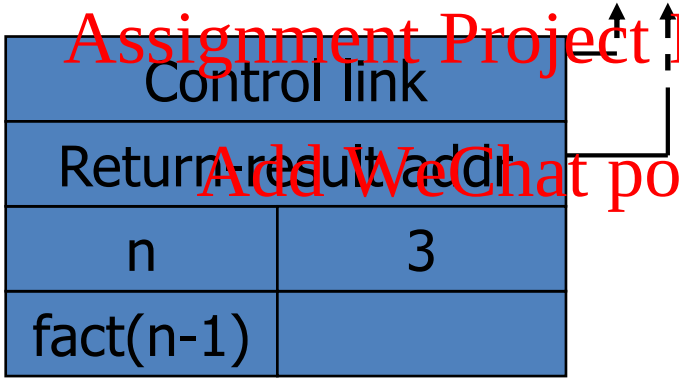
- Local variables
  - none
- Intermediate result
  - value of fact(n-1)

Function Call



Function Call

fact(3)

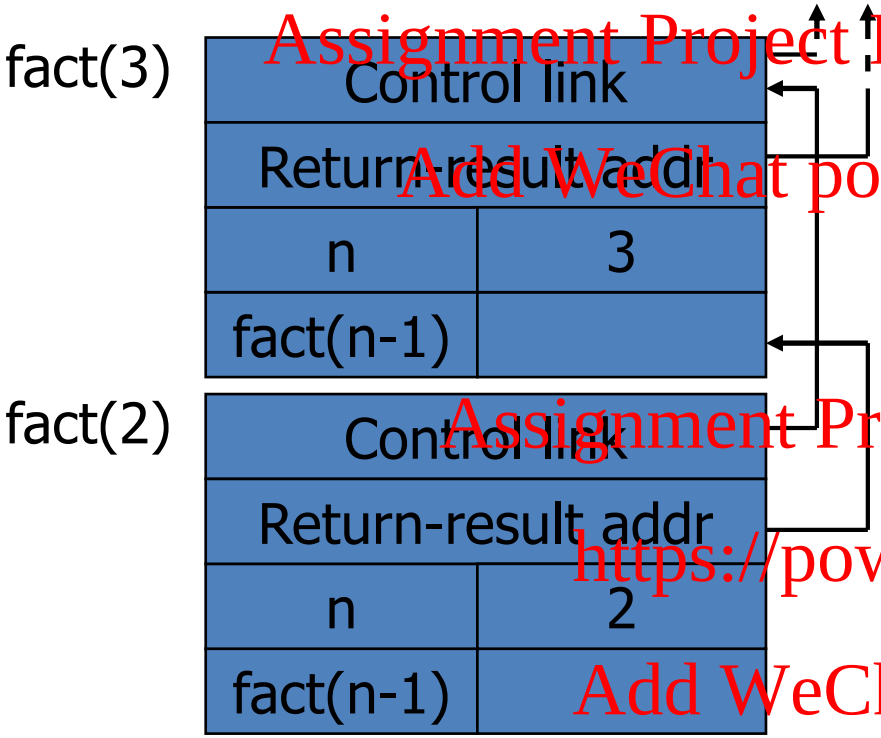


fact(n) = if n<= 1 then 1

else n * fact(n-1)

(Return address omitted)

Function Call



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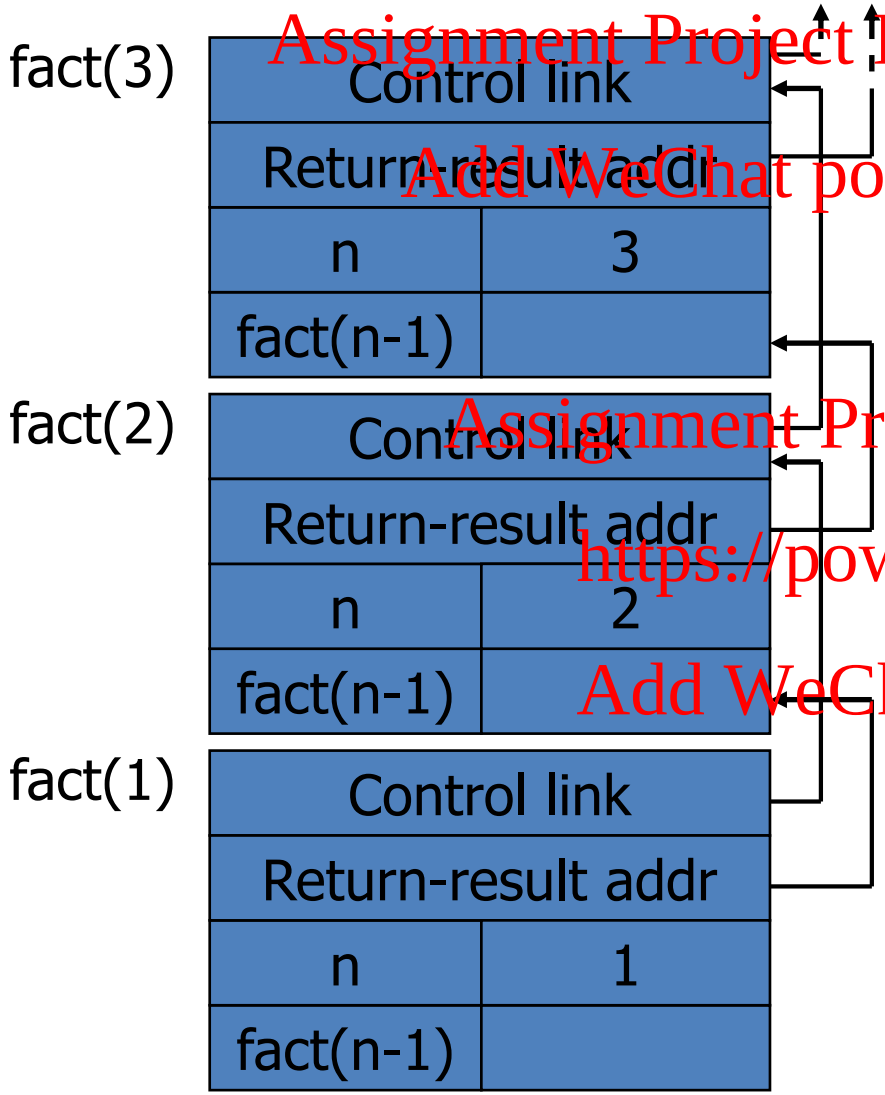
else n * fact(n-1)

(Return address omitted)

Function Call

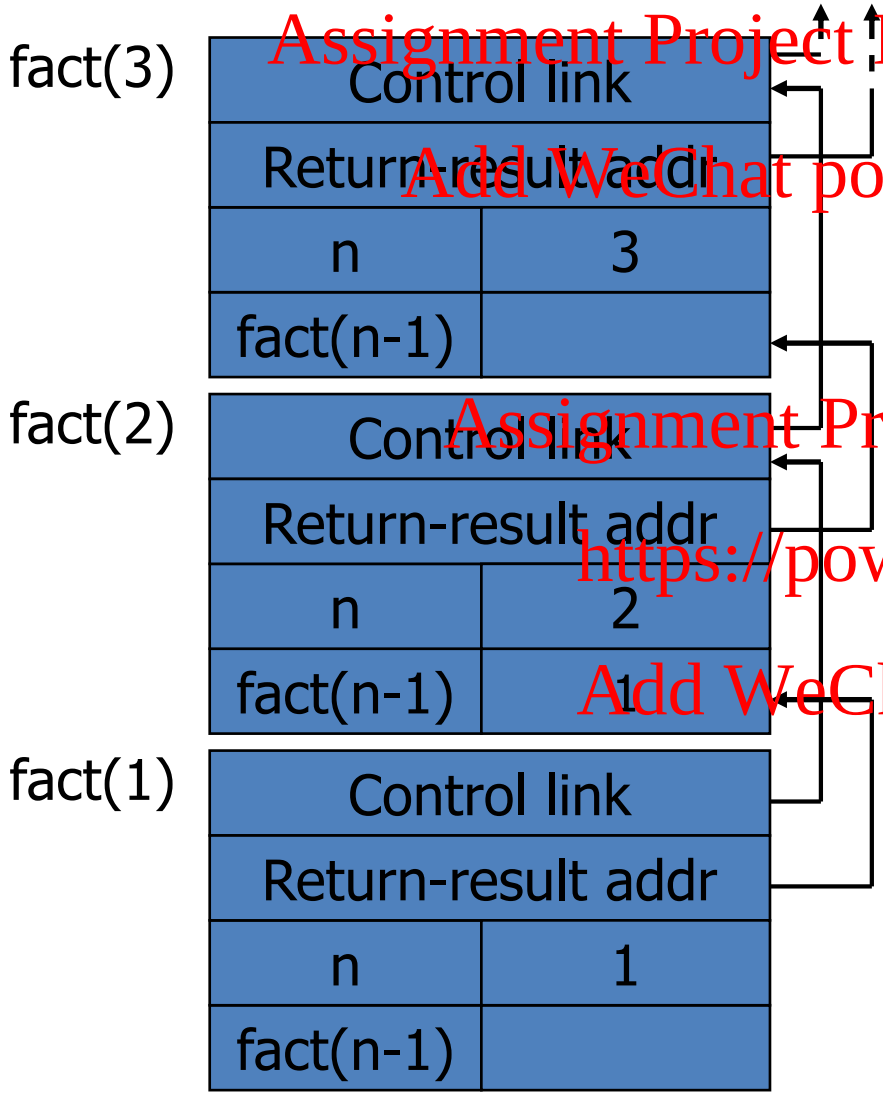


fact(n) = if n<= 1 then 1

else n * fact(n-1)

(Return address omitted)

Function Return



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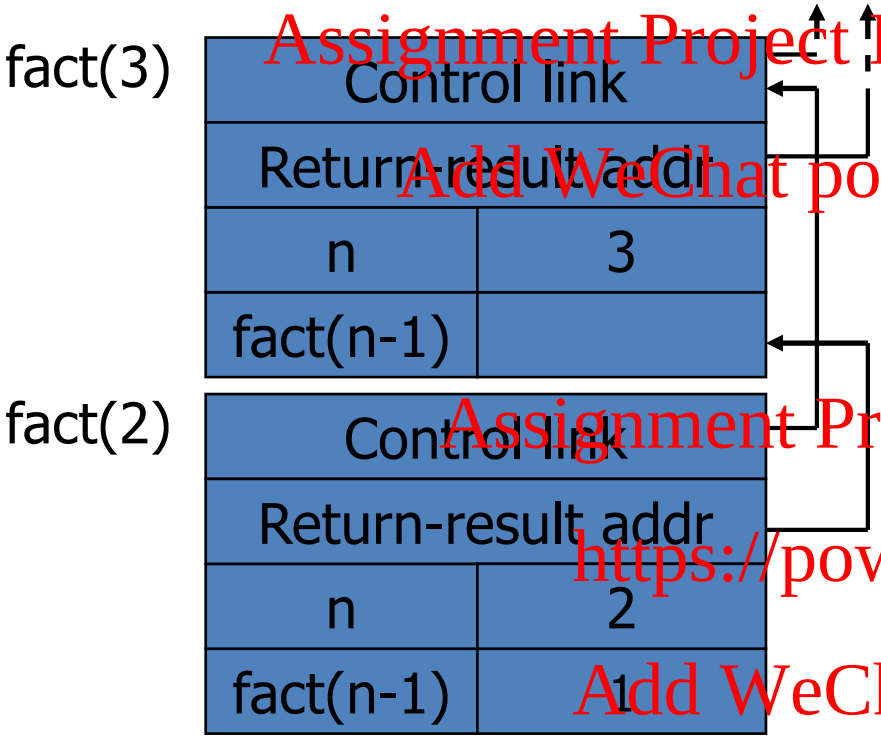
else n * fact(n-1)

(Return address omitted)

Function Return

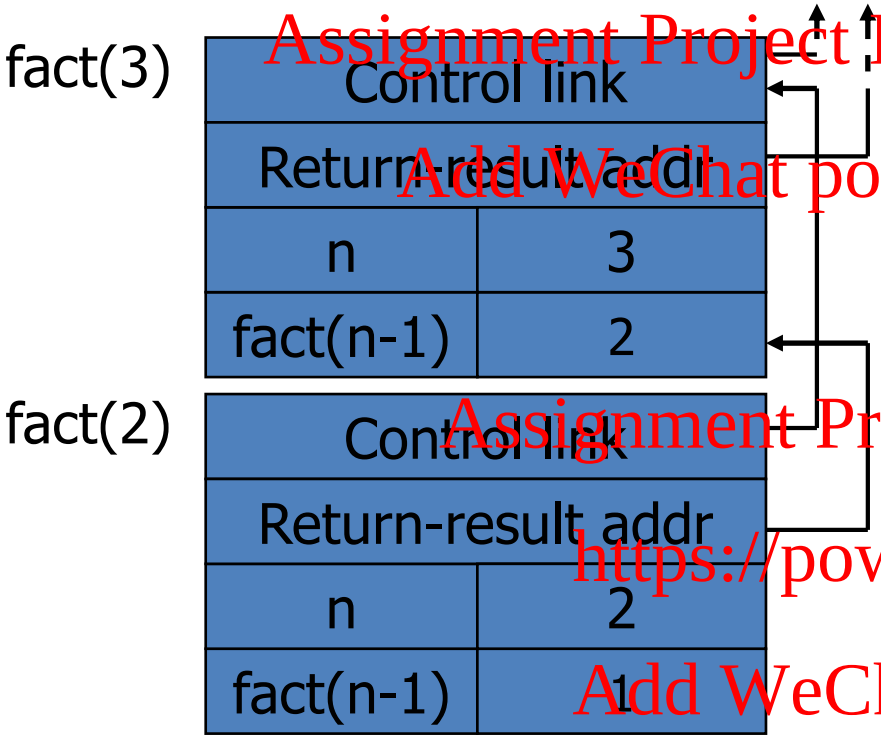


fact(n) = if n<= 1 then 1

else n * fact(n-1)

(Return address omitted)

Function Return

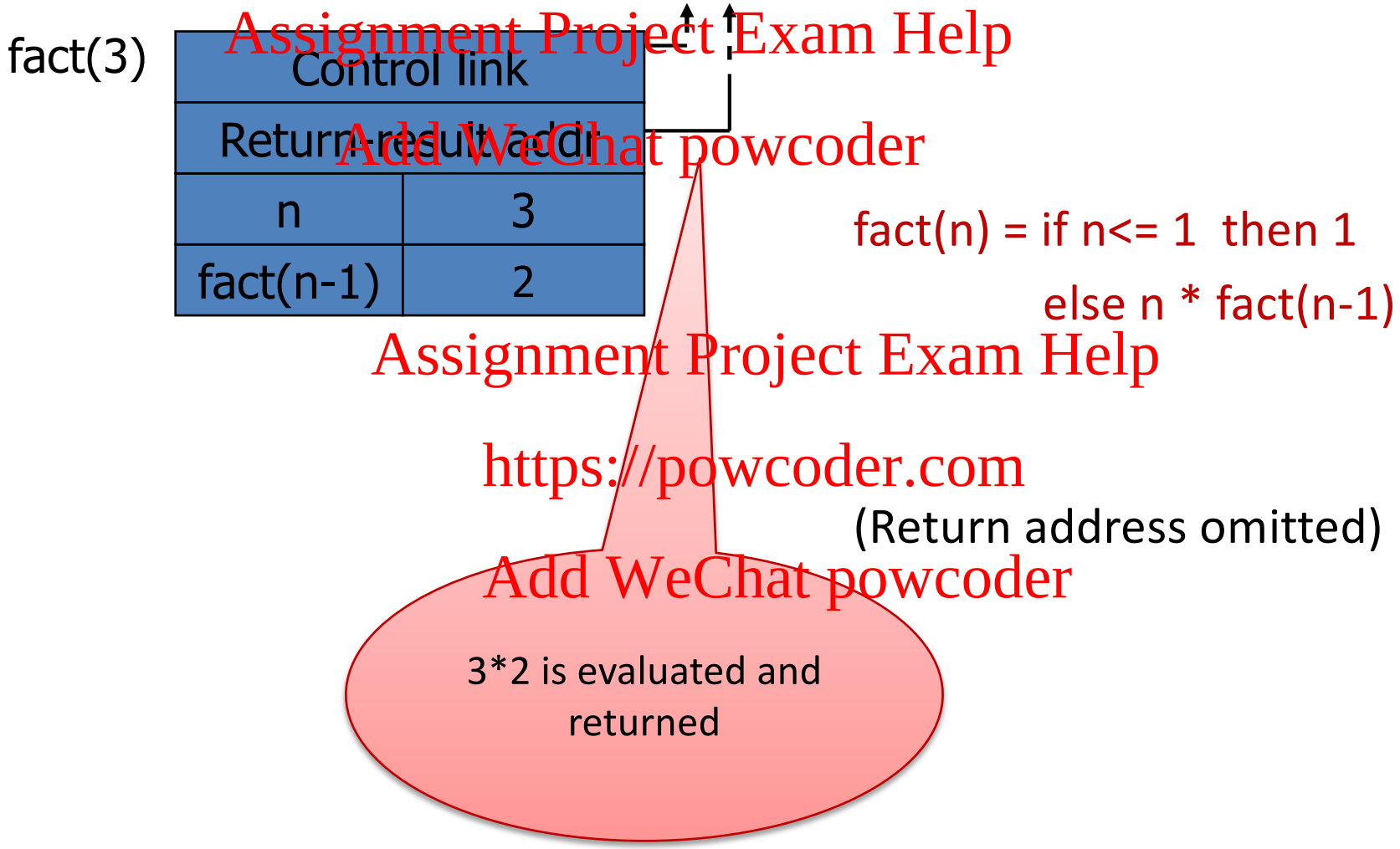


fact(n) = if n<= 1 then 1

else n * fact(n-1)

(Return address omitted)

Function Return



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

Parameter Passing


```
proc p (int x, int y) {
   if (x > y) then ... else ...;
   ...
   x := y*2+3;
   ...
}
p (z, 4*z+1);
```


- The identifiers x and y are *formal parameters* of the procedure p.
- The *actual parameters* in the call to p are z and 4*z+1.
- The way that actual parameters are evaluated and passed to the function depends on the kind of parameter-passing mechanism that is used (different for different languages).

ML Imperative Features

- 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

- Recall ML (OCaml) reference cells and assignment

  - Different types for location and contents

x : int	non-assignable integer value
y : int ref	location whose contents must be integer
!y	the contents of cell y
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-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 location)

- Pass-by-reference
  - Caller places L-value (address) of actual parameter in activation record
  - Function can assign to variable that is passed

Example

Pseudo-code:

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


pass-by-reference

OCaml:

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


pass-by-value


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

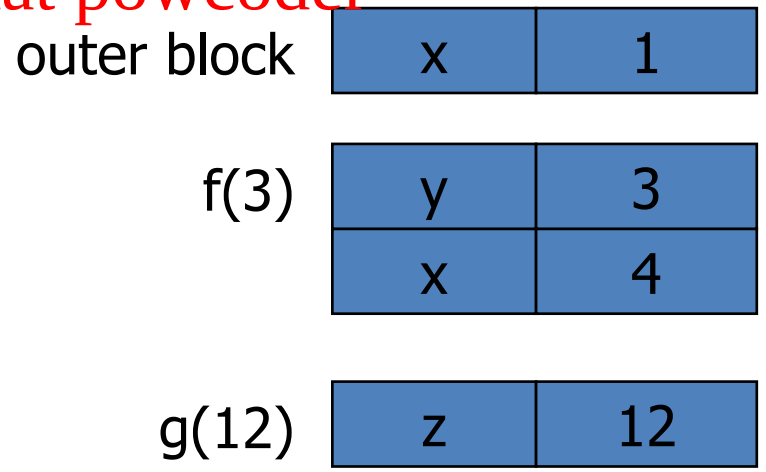
Access to Global Variables

- Two possible scoping conventions, recall:
  - Static scope: global refers to declaration in closest enclosing block
  - Dynamic scope: global refers to most recent activation record
  - As before, each let … in … is a separate block, but only at the top level. Inside function definitions a series of let … in … declarations in parentheses will be considered local variables of the function.

- Example


```
let x = 1 in
let g z = x + z in
let f y =
  (let x = y + 1 in
   g (y*x)) in
f 3
```

Skeleton of Activation Stack



Which x is used for expression x+z?

Access to Global Variables

Which x is used for expression x+z?

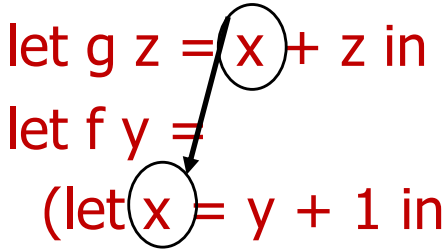
- Dynamic Scope

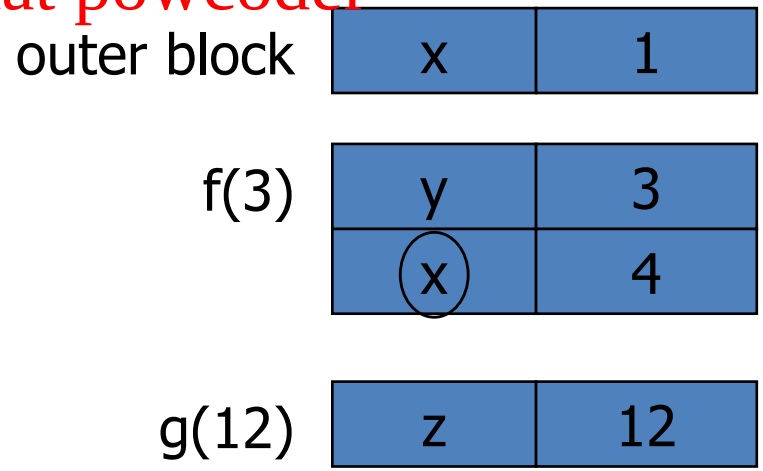
  Under dynamic scope, the identifier x in x+z will be interpreted as the one from the most recently created activation record, namely x=4.

  How do we implement access to global variables?

  Answer: follow the control link (which is also called a *dynamic link*).


```
let x = 1 in
let g z = x + z in
let f y =
  (let x = y + 1 in
   g (y*x)) in
f 3
```





Access to Global Variables

Which x is used for expression x+z?

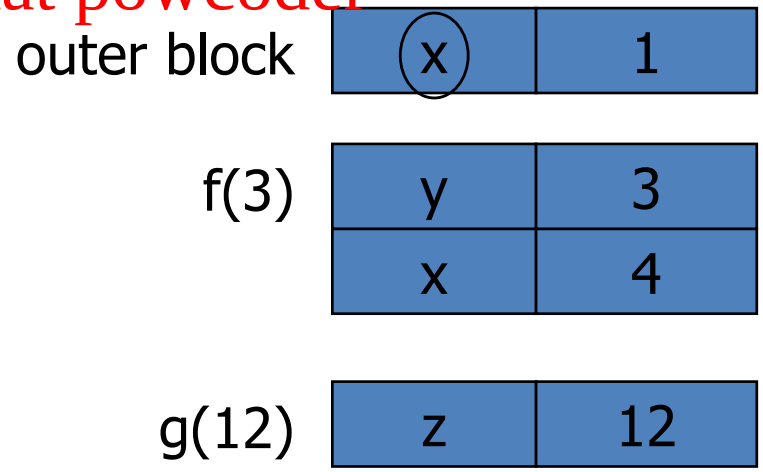
- Static Scope

Under static scope, the identifier x in x+z refers to the declaration of x from the closest enclosing program block, looking upward from the place that x+z appears in the program. Thus, x=1.

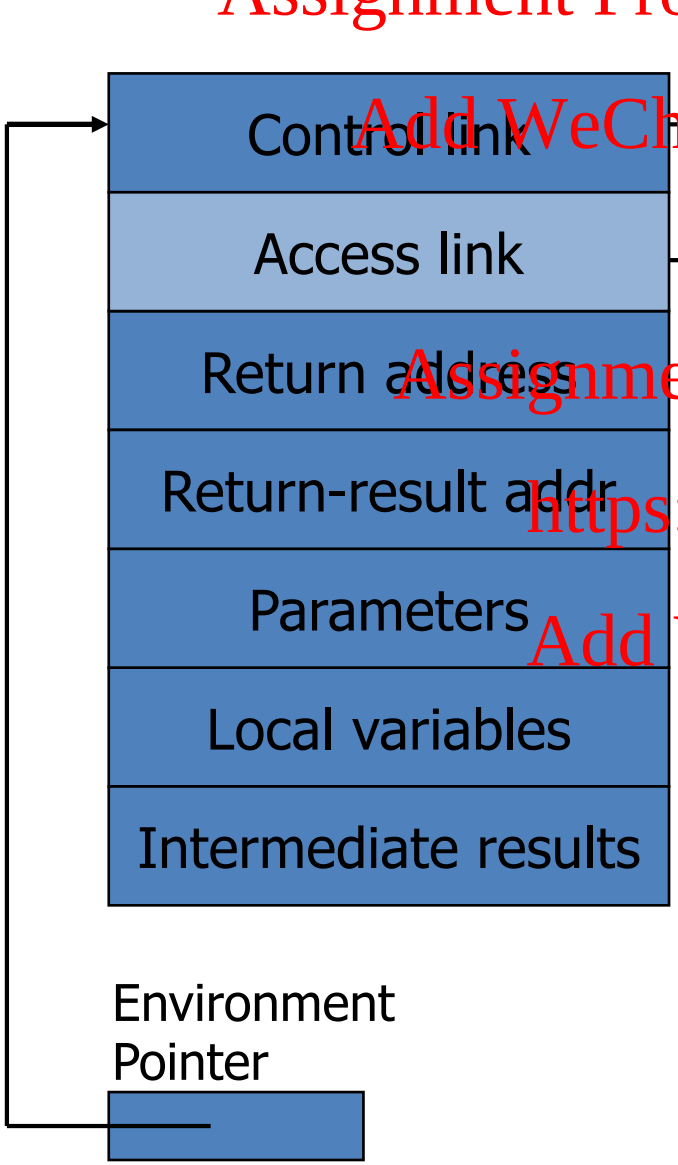
OCaml is static.

How do we implement access to global variables in this case?


```
let x = 1 in
let g z = x + z in
let f y =
  (let x = y + 1 in
   g (y*x)) in
f 3
```

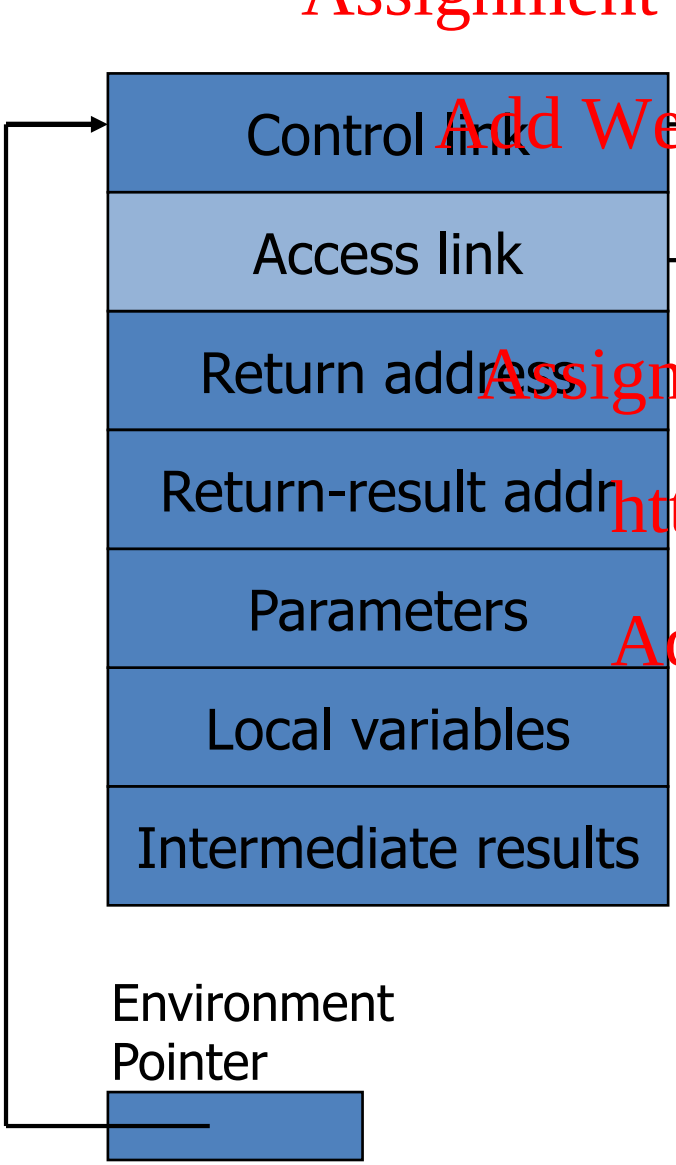


Activation Record for Static Scope



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

Access Links for Static Scope



- Access link
  - The *access link* (also called a *static link*) of an activation record points to the activation record of the closest enclosing block in the program.

- Inline blocks
  - In-line blocks do not need them; the control link points to the closest enclosing block.

- Functions
  - The closest enclosing block is determined by where the function is declared, which is often different from the point where the function is called.

Static Scope with Access Links


```
let x = 1 in
  let g z = x + z in
      let f y =
          (let x = y + 1 in
           g (y*x)) in
      f 3
```

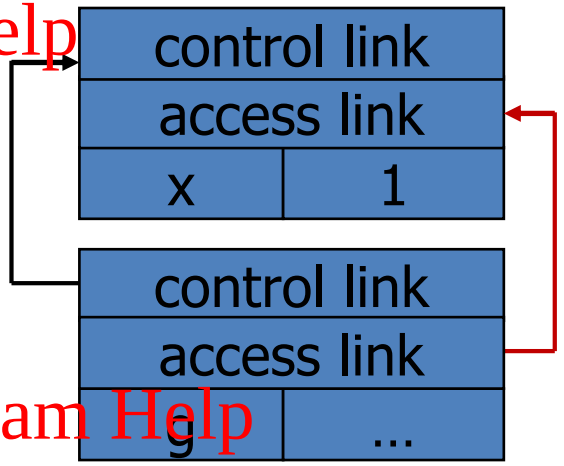
outer block

control link	
access link	
x	1

Static Scope with Access Links


```
let x = 1 in
    let g z = x + z in
        let f y =
            (let x = y + 1 in
             g (y*x))
        in
        f 3
```

outer block



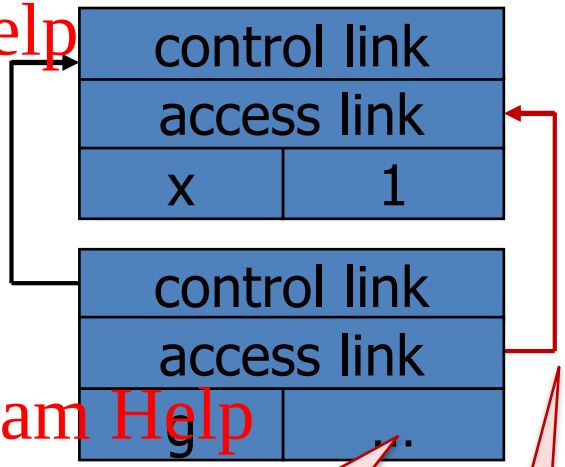
Use access link to find global variable:

- Access link is always set to frame of closest enclosing lexical block

Static Scope with Access Links


```
let x = 1 in
    let g z = x + z in
        let f y =
            (let x = y + 1 in
             g (y*x))
        in
        f 3
```

outer block



includes pointer to code

For declarations, access link and control link are the same.

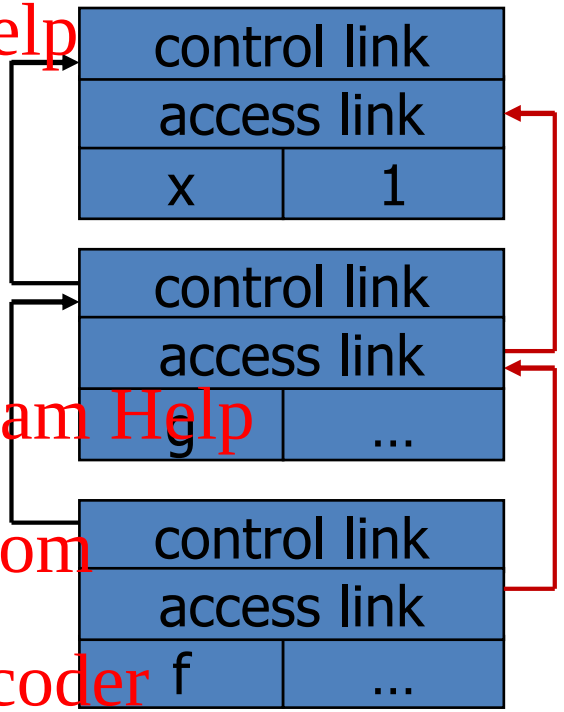
Use access link to find global variable:

- Access link is always set to frame of closest enclosing lexical block

Static Scope with Access Links


```
let x = 1 in
    let g z = x + z in
        let f y =
            (let x = y + 1 in
             g (y*x))
        in
        f 3
```

outer block



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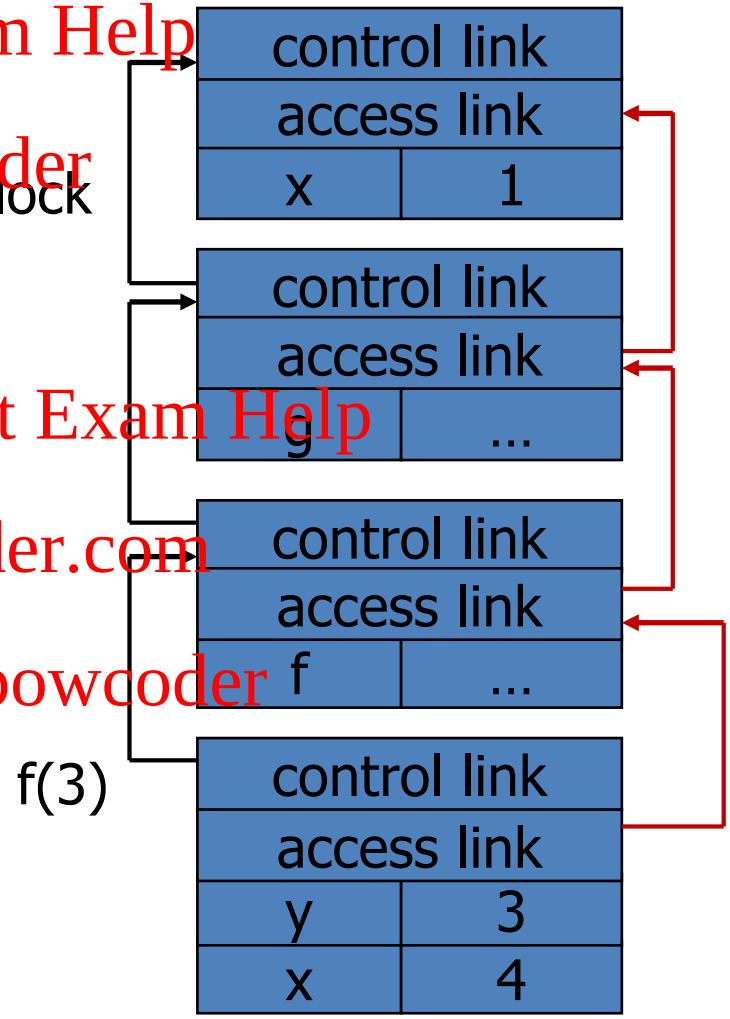

Use access link to find global variable:

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

Static Scope with Access Links


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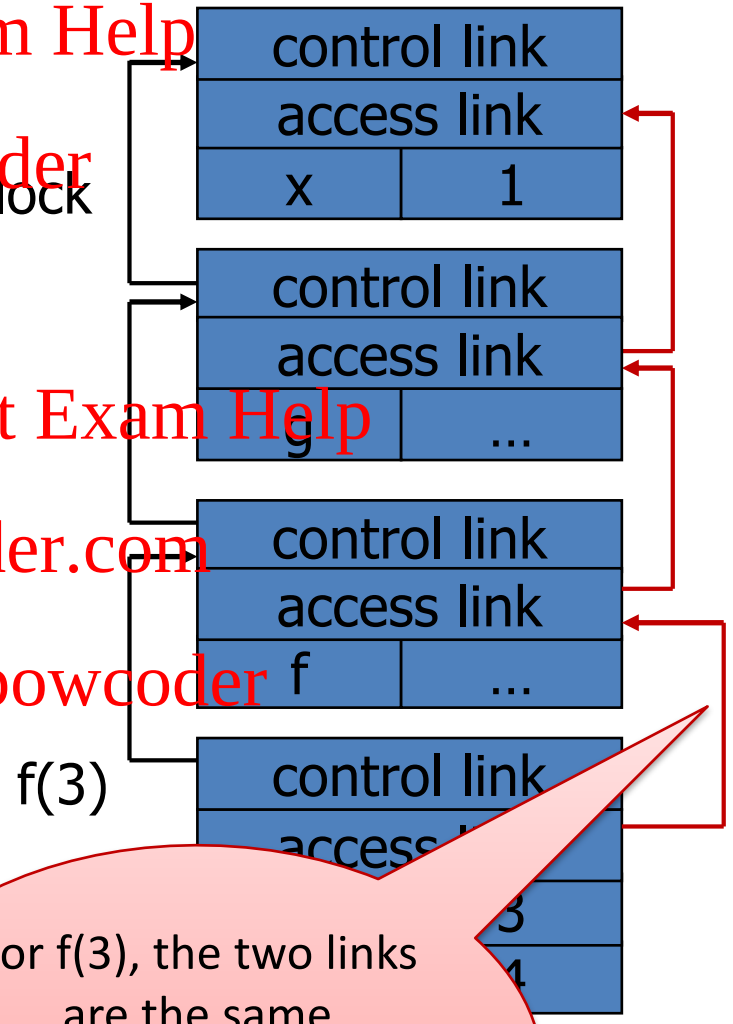

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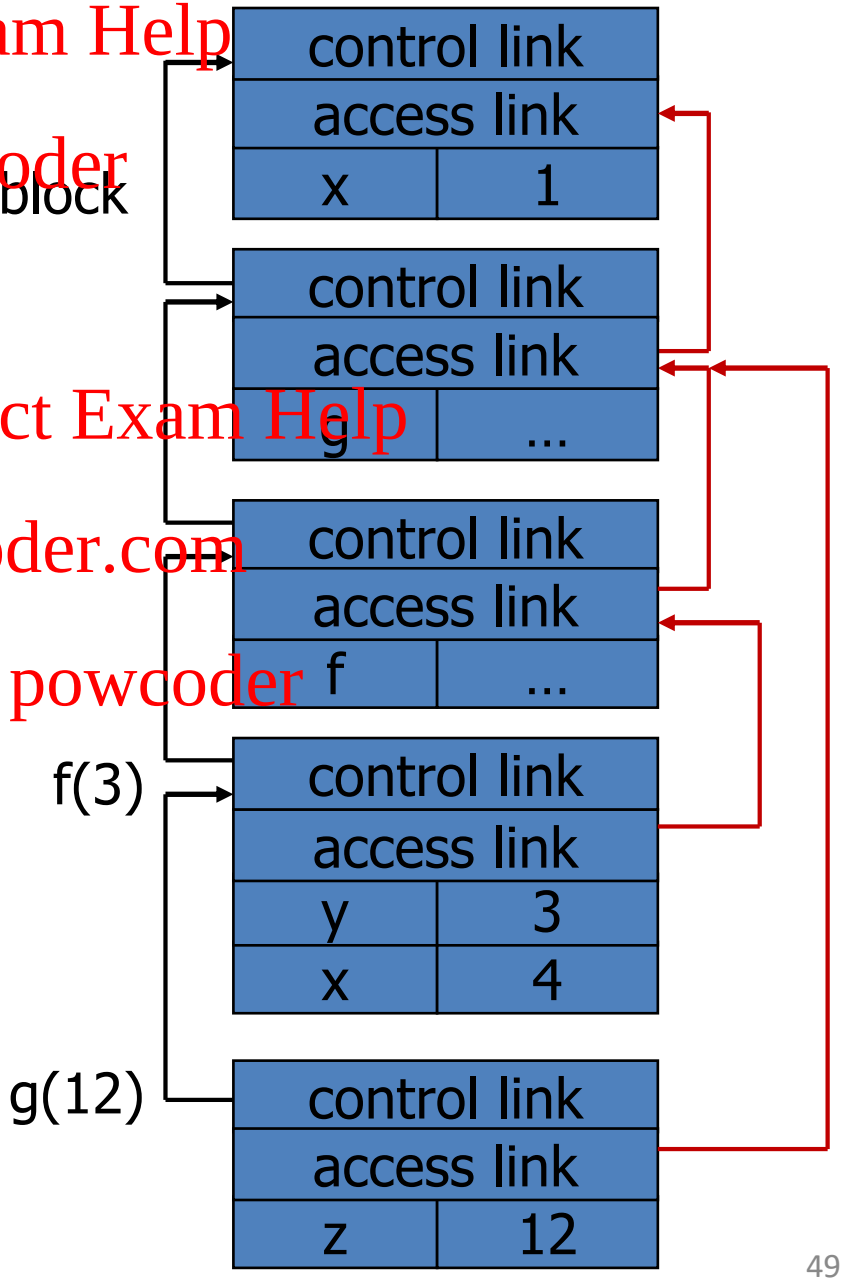

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Static Scope with Access Links


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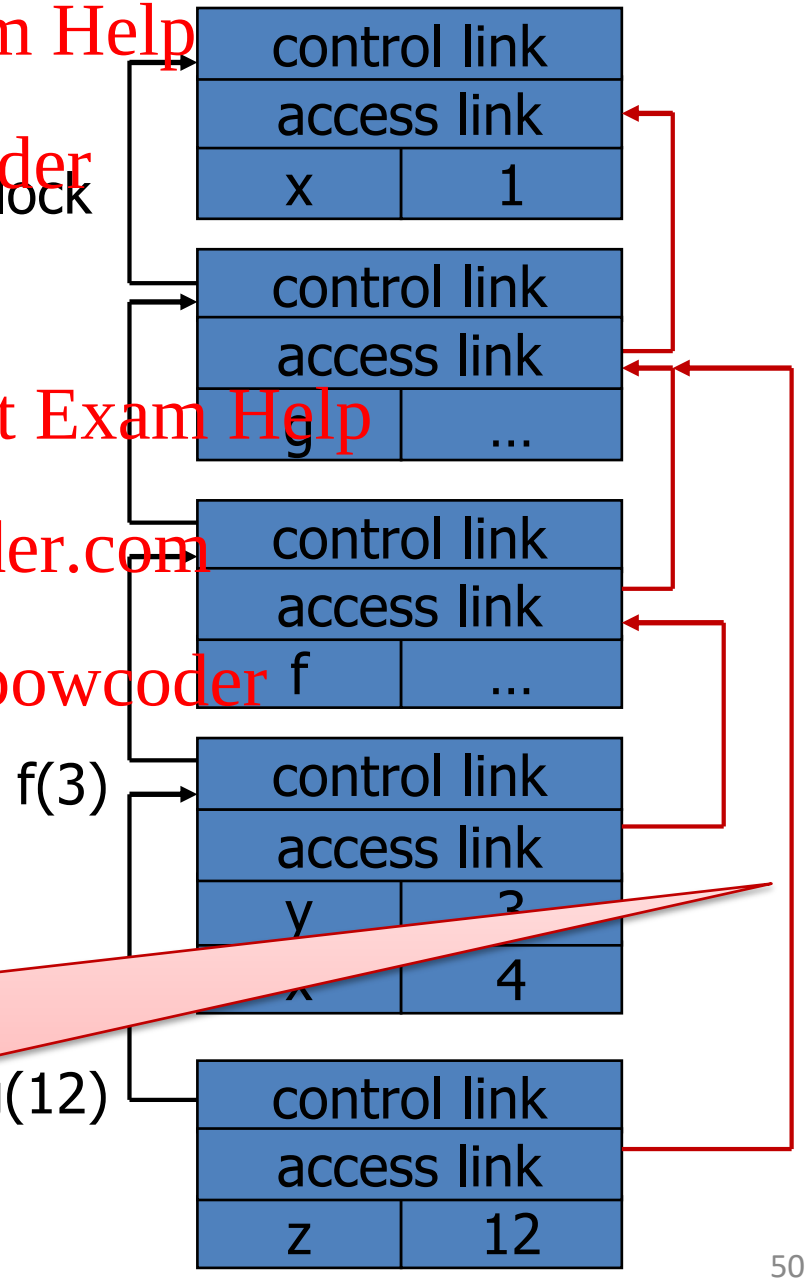
        f 3
```

outer block



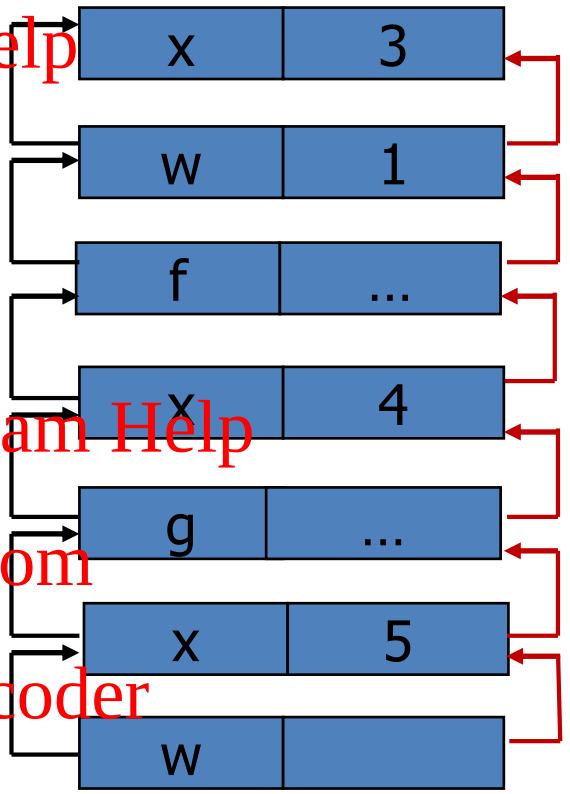
Use access link to find global variable:

- Access link is alwa[illegible] to frame of closest e[illegible]k
- For functi[illegible] that cont[illegible] declaratio[illegible]

The compiler can figure this out from program text (g called from inside f)

Another Example


```
let x = 3 in
  let w = 1 in
    let f y = w+x+y in
      let x = 4 in
        let g z = f (x*z) in
          let x = 5 in
            let w = g x in
            w
```

Access links are red.

Control links are black.

Another Example


```
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  let w = 1 in
    let f y = w+x+y in
      let x = 4 in
        let g z = f (x*z) in
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            let w = g x in
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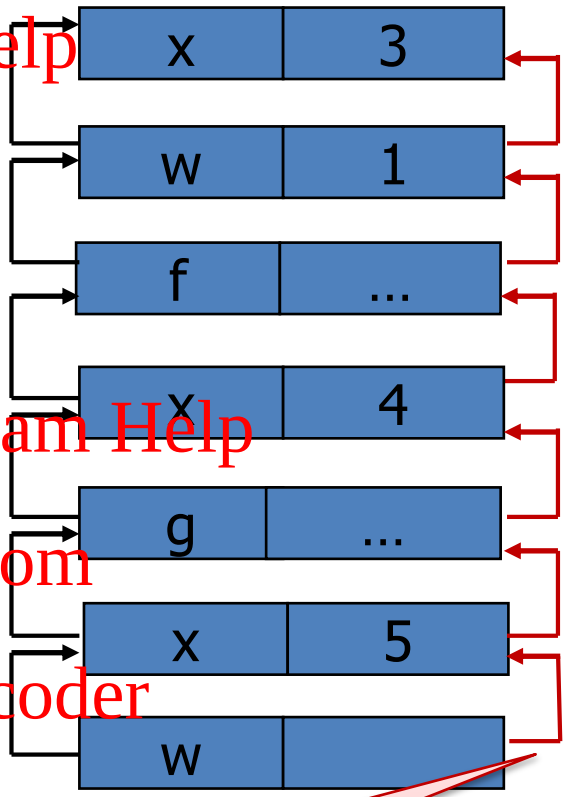

Follow access link to find the value of x for function call (g x). Value is 5.

Another Example


```
let x = 3 in
  let w = 1 in
    let f y = w+x+y in
      let x = 4 in
        let g z = f (x*z) in
          let x = 5 in
            let w = g x in
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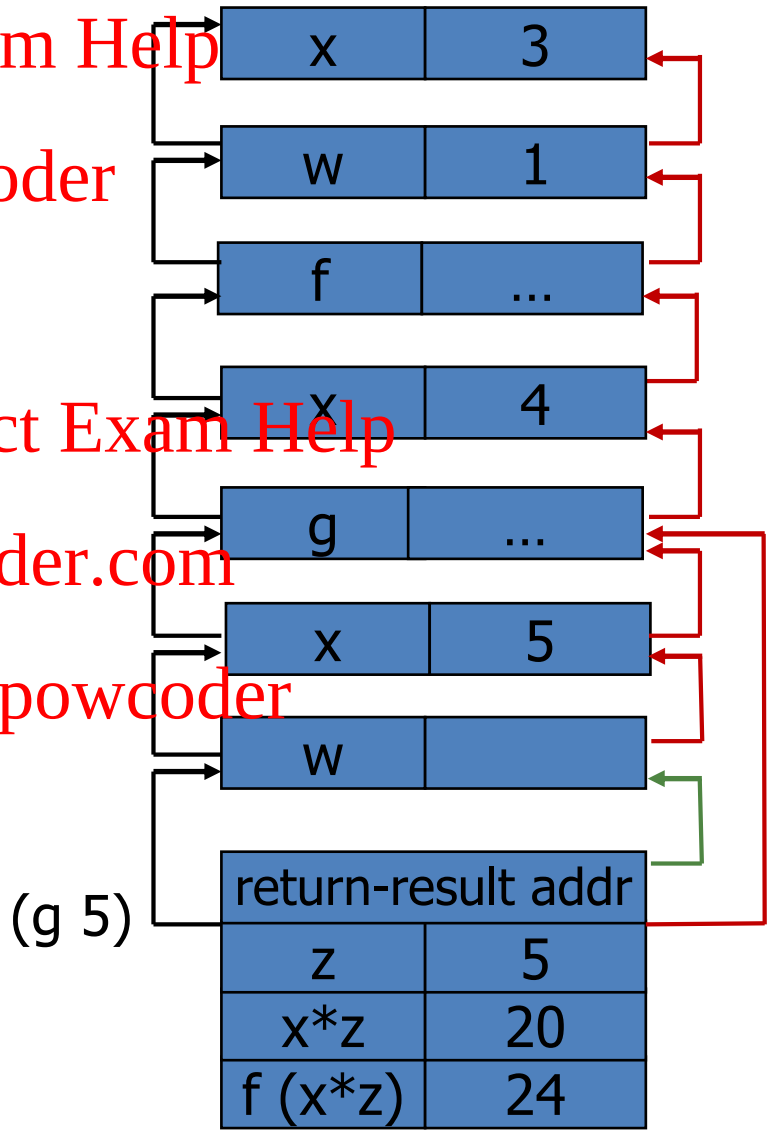
```


Access links are red.

Control links are black.

Return-result addr links are green.

Note that access and control links point to a block and return-result links point to a single location in a block.



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let x = 3 in
  let w = 1 in
    let f y = w+x+y in
      let x = 4 in
        let g z = f (x*z) in
          let x = 5 in
            let w = g x in
            w
```


Access link

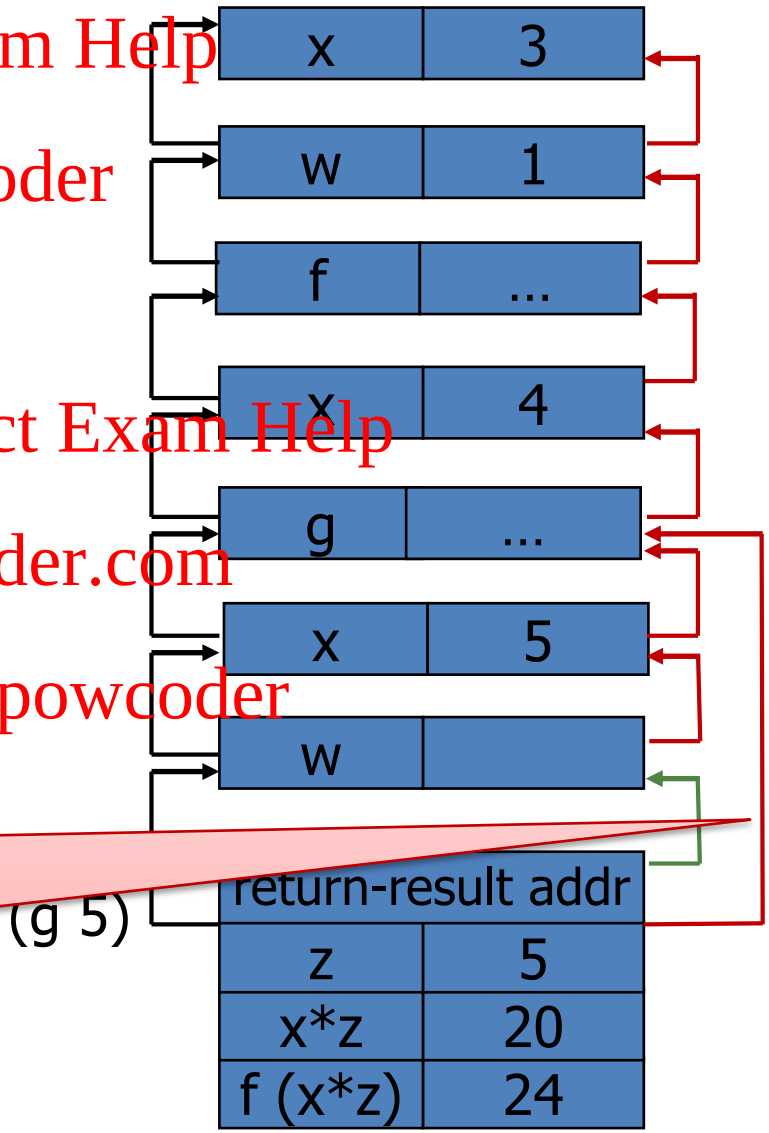
Control

Return

gre

Note tha links point and return-result links point to a single location in a block.

Follow access link to find the value of x used in expression x*z. Value is 4, and thus x*z is 20.



Another Example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let x = 3 in
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    let f y = w+x+y in
      let x = 4 in
        let g z = f (x*z) in
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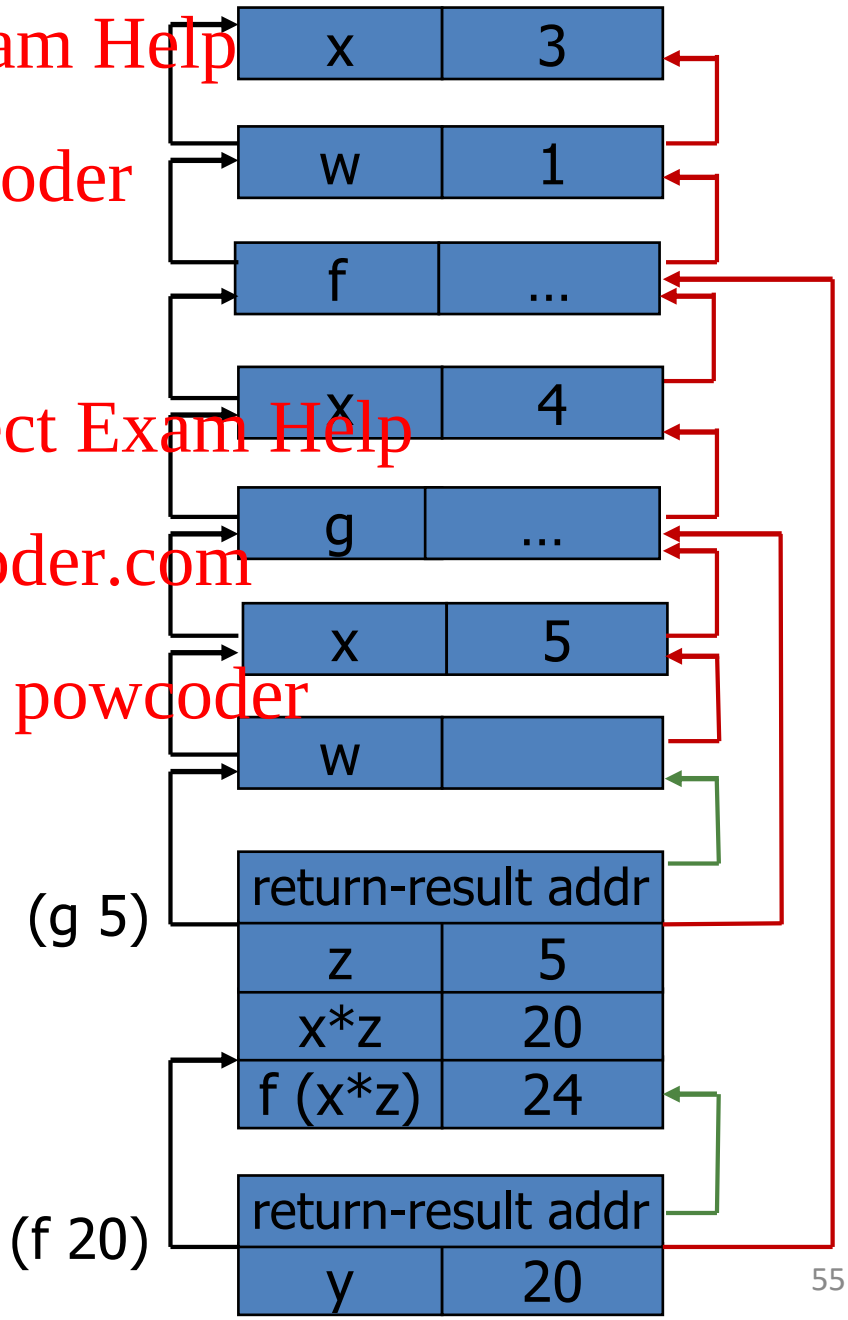

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  let w = 1 in
    let f y = w+x+y in
      let x = 4 in
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          let x = 5 in
            let w = g x in
            w
```


Access link

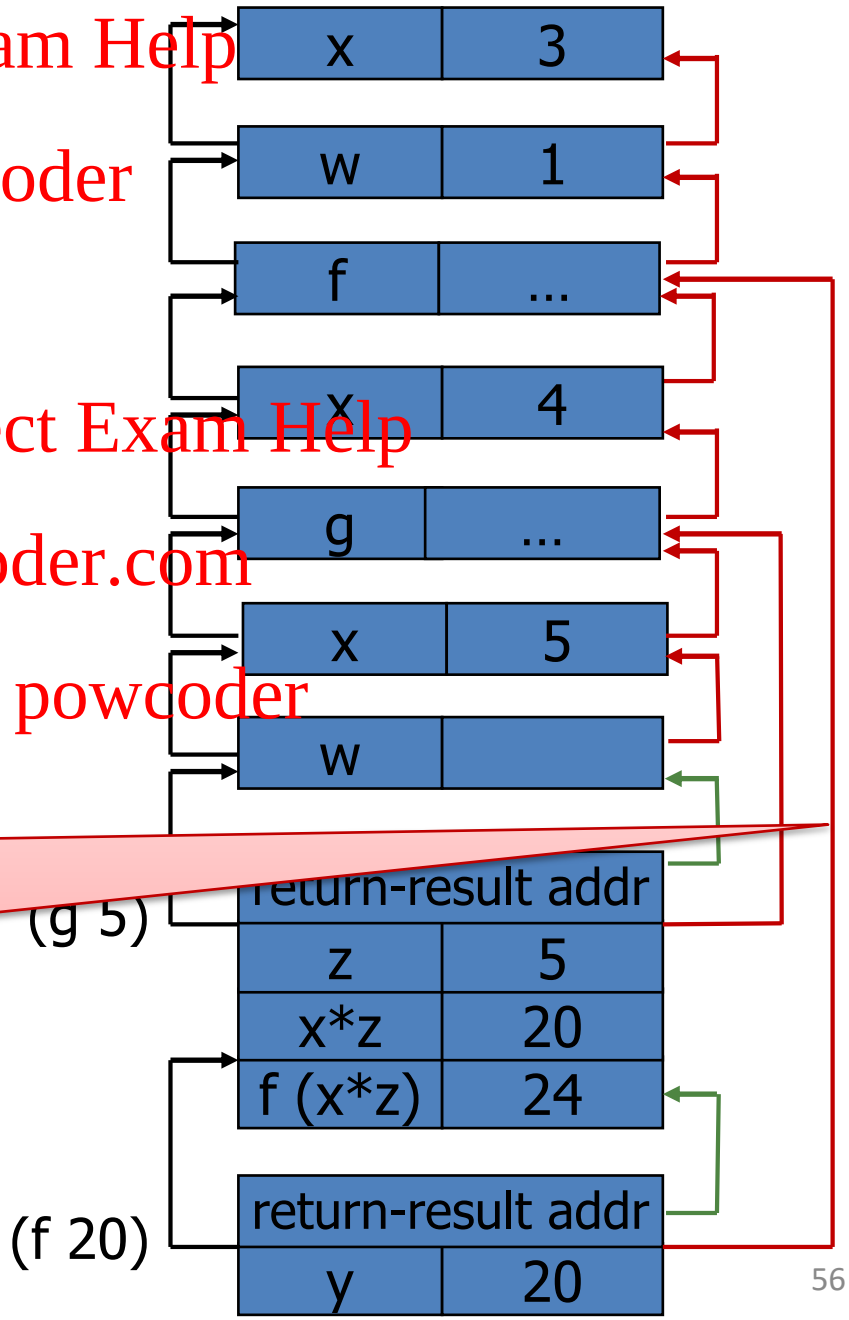
Control

Retur

gre

Note tha links poin and return-result links point to a single location in a block.

Follow access links to find the values of w and x used in expression w+x+y. Must follow 3 links to get to x.



Tail Recursion (First-Order Case)

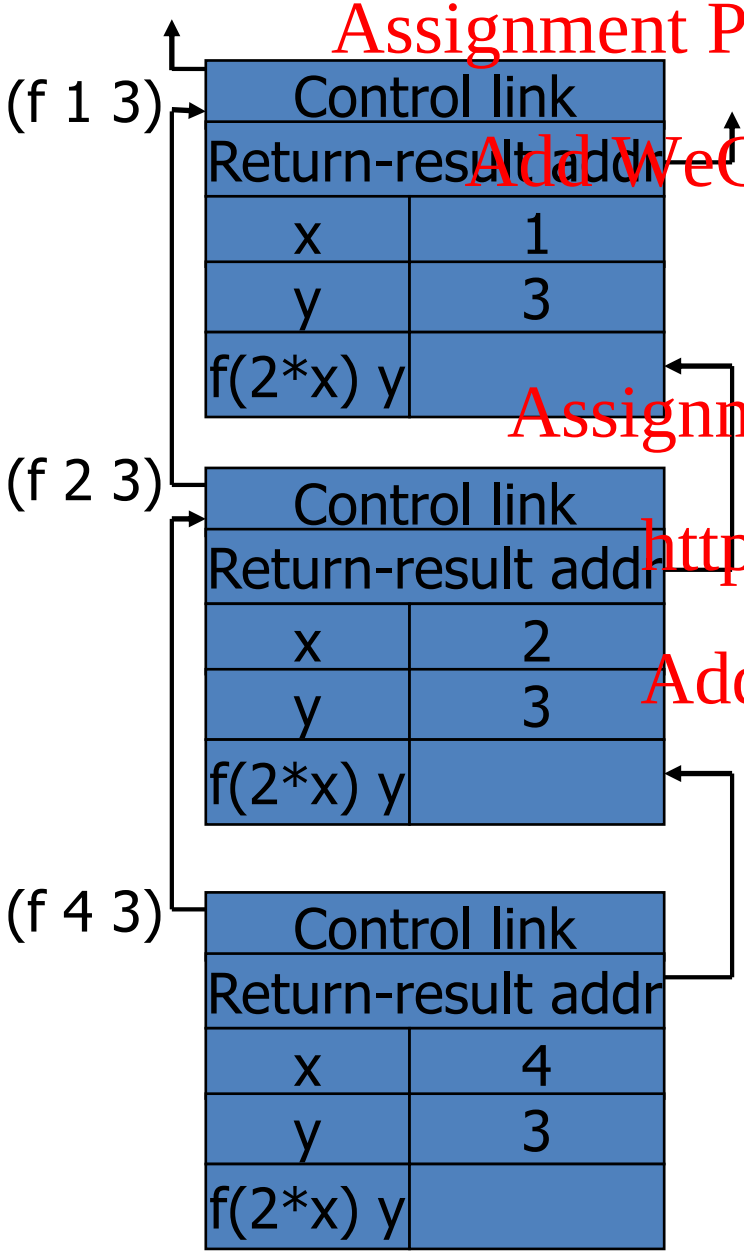
- Function g makes a *tail call* to function f if
  - Return value of function f is return value of g

- Example

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

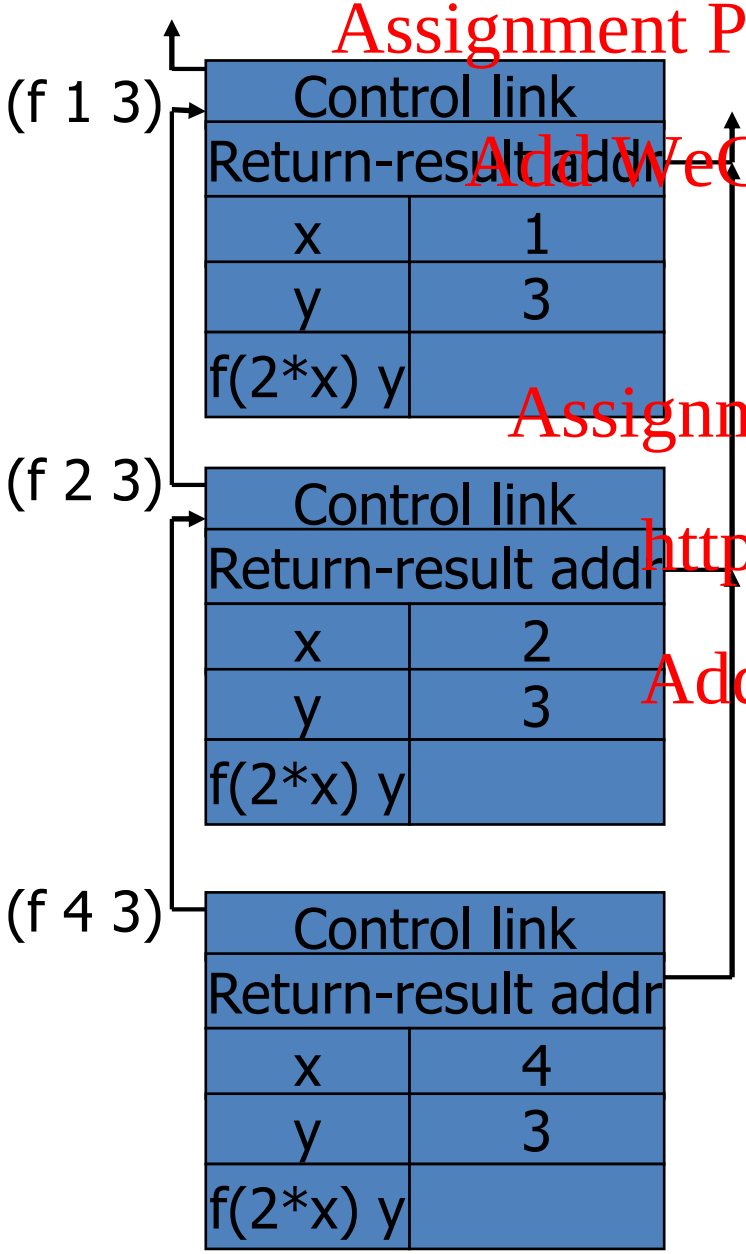
- A function f is *tail recursive* if all recursive calls in the body are tail calls to f.

Example: Calculate least power of 2 greater than y




```
let rec f x y =
    if x>y
    then x
    else f (2*x) y in
(f 1 3) + 7
```

Example: Calculate least power of 2 greater than y

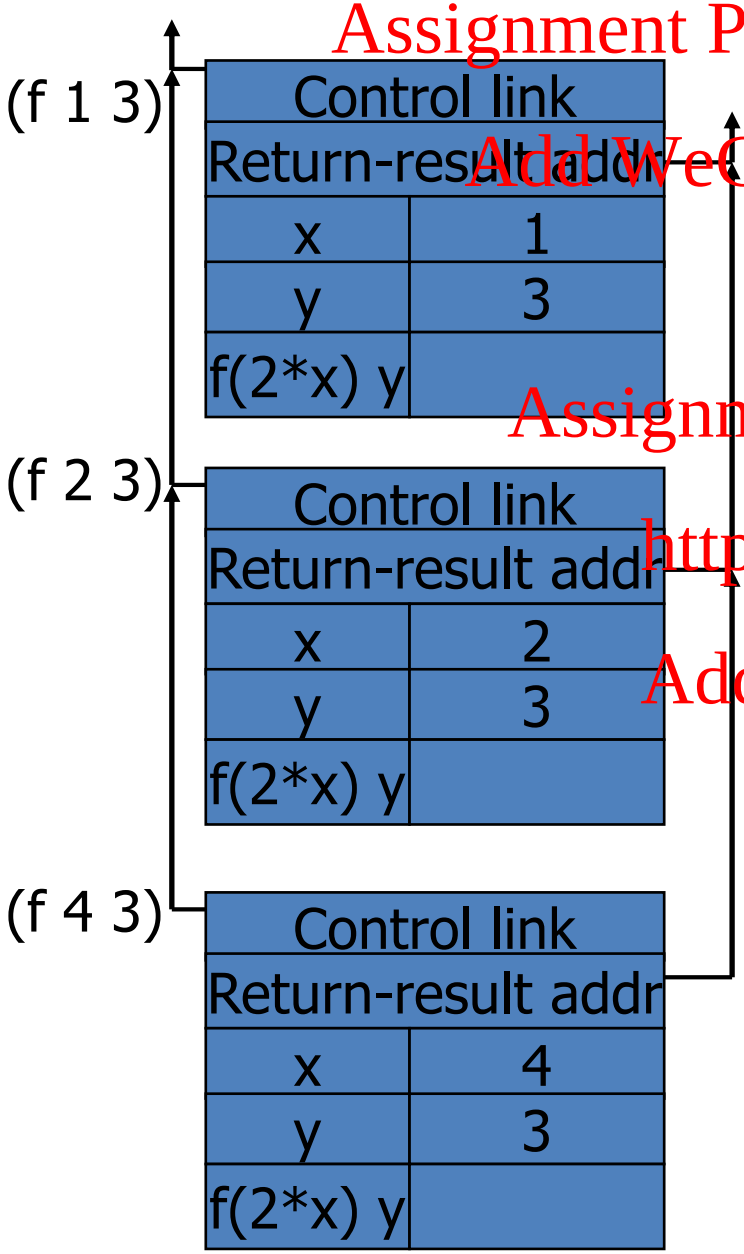



```
let rec f x y =
    if x>y
    then x
    else f (2*x) y
in
(f 1 3) + 7
```

- Optimization 1
  - Set return-result address to the return-result address of caller.
  - Can we do the same with the control link?

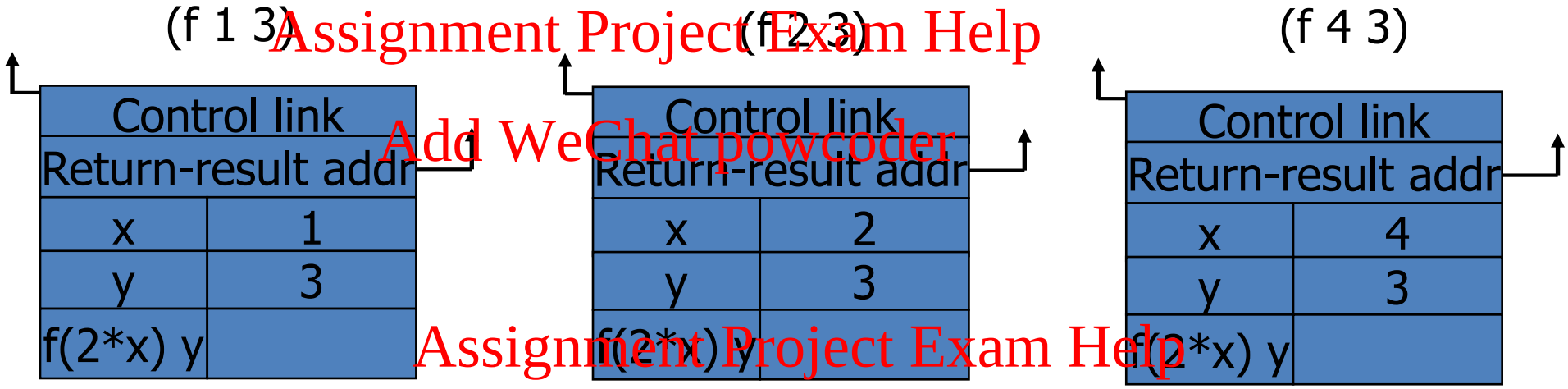
    Yes, since the activation records are not needed after final result is determined and passed all the way up.

Example: Calculate least power of 2 greater than y



- Optimization 2
  - When 3rd call finishes, we can pop 3rd and 2nd activation records together.
  - In fact, we can pop all three.
- Optimization 3
  - The activation record for the first call is no longer needed when the second call begins; pop the first before allocating the second.
- Optimization 4
  - Even better, don't deallocate and reallocate, just reuse.

Tail Recursion Elimination




```
let rec f x y =
    if x>y
    then x
    else f (2*x) y in
(f 1 3) + 7
```


- Conclusion
  - Tail recursive function equivalent to iterative loop

Tail Recursion and Iteration

(f 1 3)

Control link	
Return-result addr	
x	1
y	3
f(2*x) y	4

(f 2 3)

Control link	
Return-result addr	
x	2
y	3
f(2*x) y	4

(f 4 3)

Control link	
Return-result addr	
x	4
y	3
f(2*x) y	


```
let rec f x y  =
    if x>y
    then x
    else f (2*x) y in
(f 1 3) + 7
```

test

loop body

initial value

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

Higher-Order Functions

- A language has first-class functions if functions can be:
  - Declared within any scope
  - Passed as arguments to other functions
  - Returned as results of functions

- 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

Pass Function as Argument


```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
      (let x = 7
       in
       h(3) + x) in
    g(f)
```



```
{ 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?

Pass Function as Argument


```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
      (let x = 7
       in
       h(3) + x) in
    g(f)
```

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

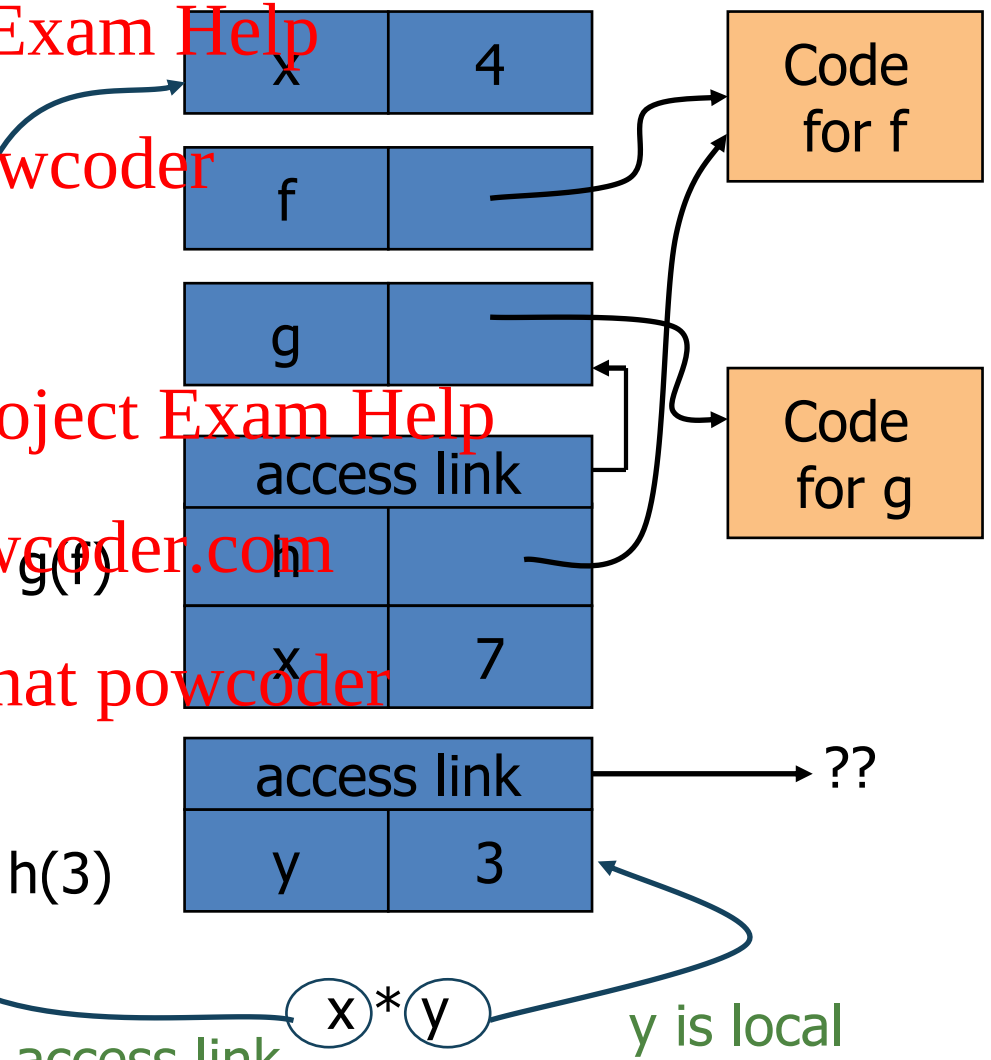
The body of f contains the global variable x. This is the environment of f.

There are two dec ns o
Which one is used for

When f is called inside g (because f is the value of parameter h), the value of x must be retrieved from the activation record of the outer block (static scope).

Static Scope for Function Argument


```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
      (let x = 7
       in
       h(3) + x) in
    g(f)
```



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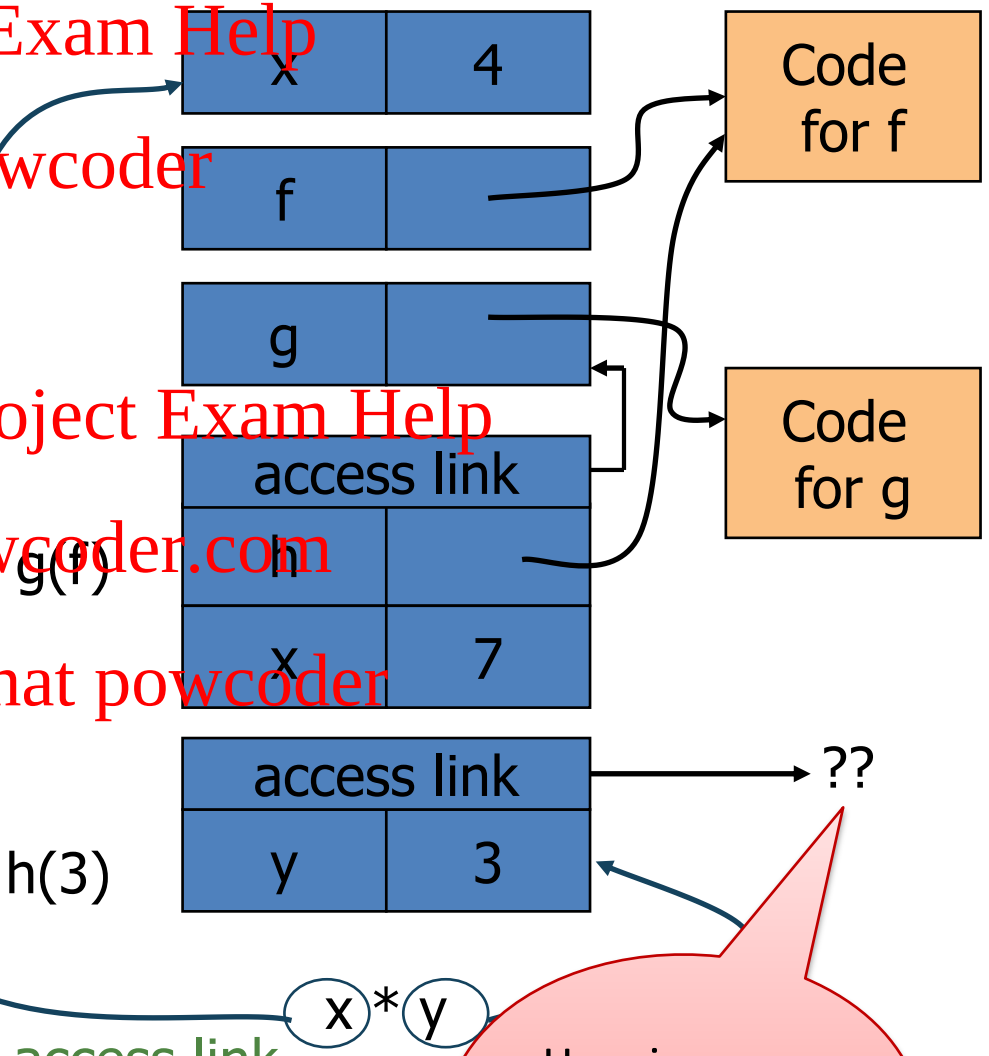
    g(
```

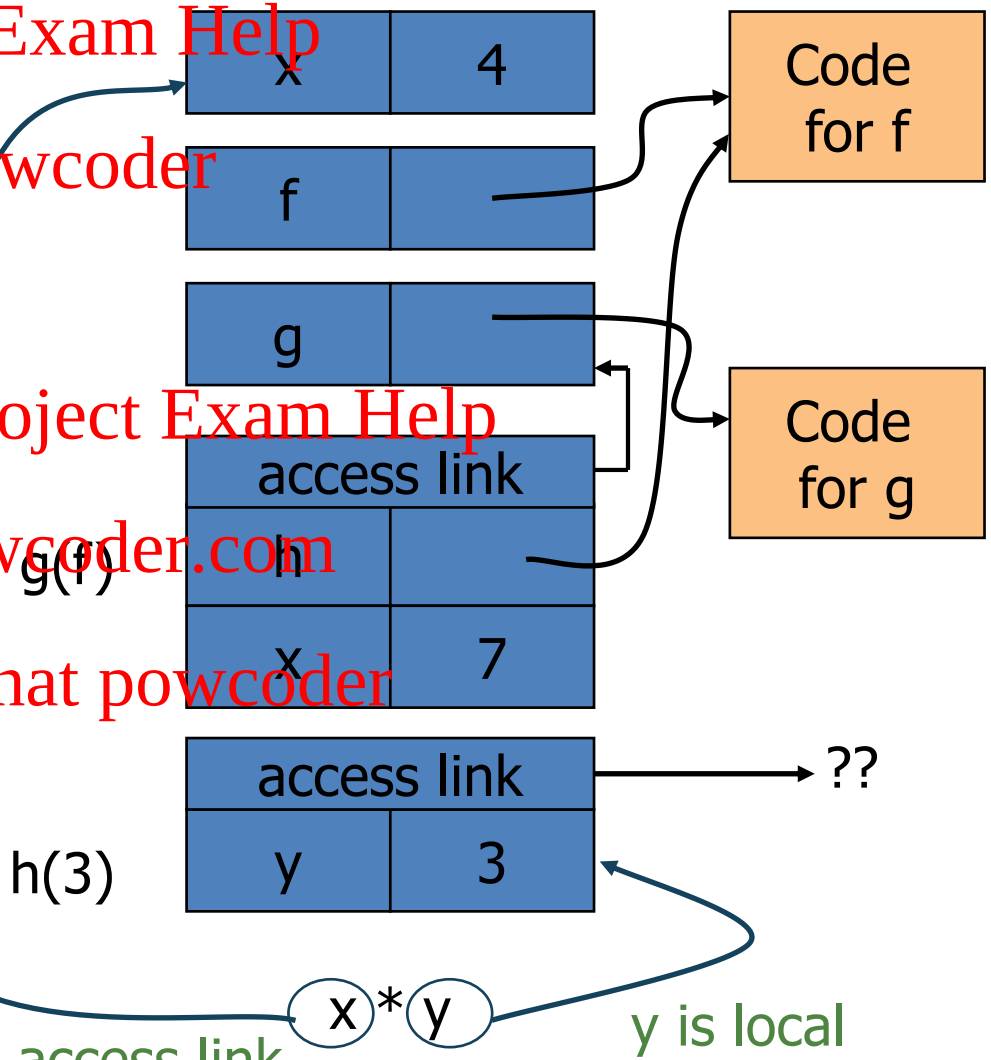


g can call different functions depending on value of h; can't tell from program text what values h will get

How is access link for h(3) set?

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);
} } }
```



Closures

- With first-class functions and static scope, need a *closure* which is a pair:

  - Pointer to function code
  - Pointer to activation record (the environment of the function)
- Function value (when passed as a parameter) is a closure

- 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

- C and C++ do not support closures (because of implementation costs, though objects are like closures because they combine data with code for functions).

Function Argument and Closures

Run-time stack with access links


```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
      (let x = 7
       in
       h(3) + x) in
    g(f)
```

Code for f

Code for g

Function Argument and Closures

Run-time stack with access links


```
let x = 4 in
  let f(y) = x*y in
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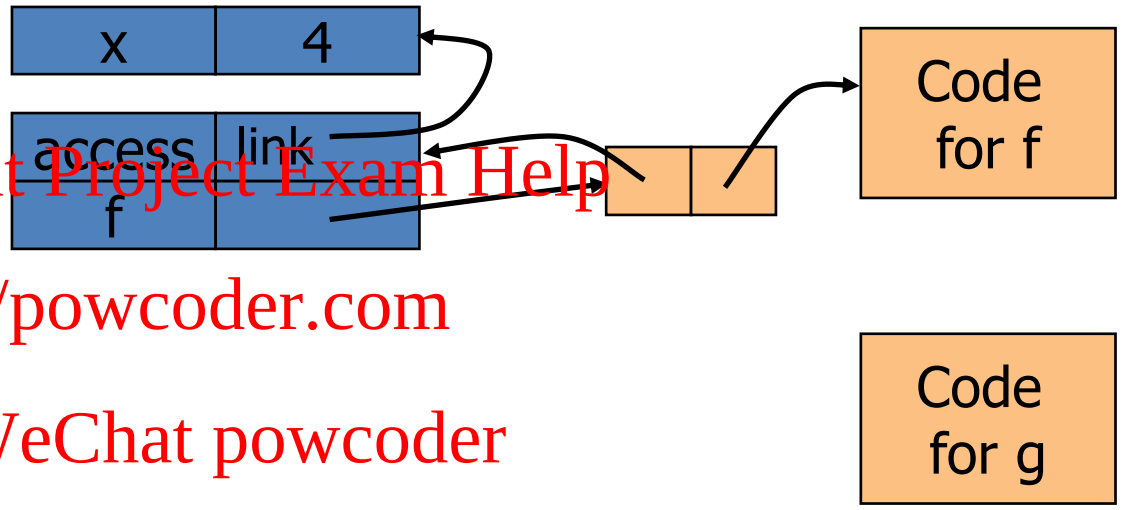
```



Function Argument and Closures

Run-time stack with access links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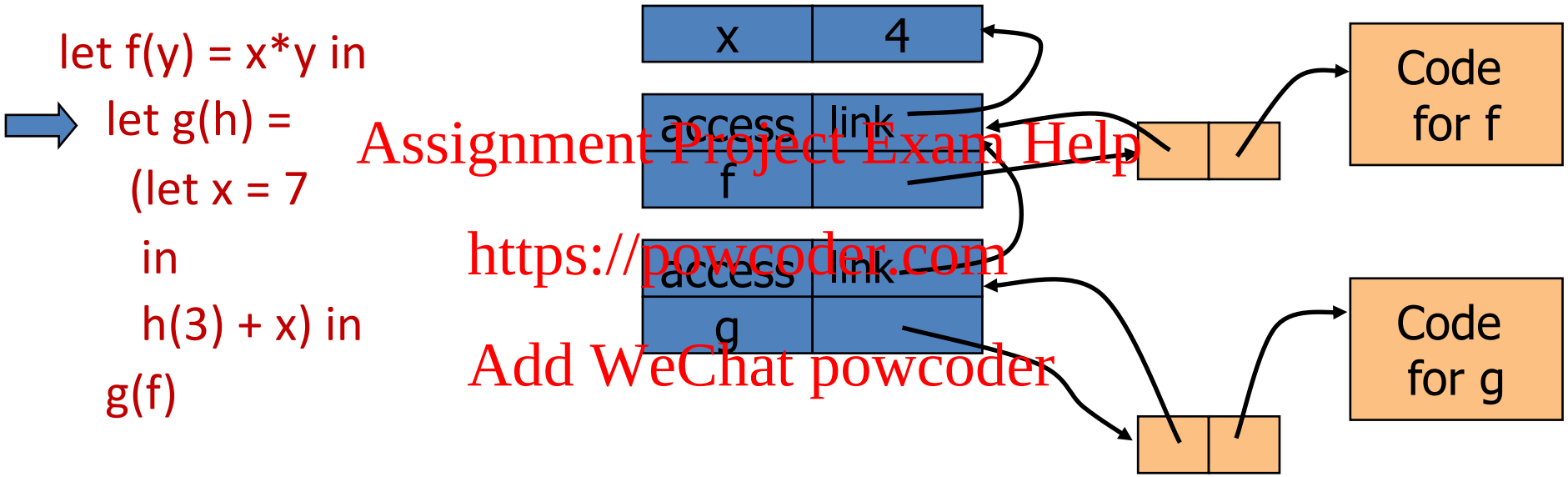
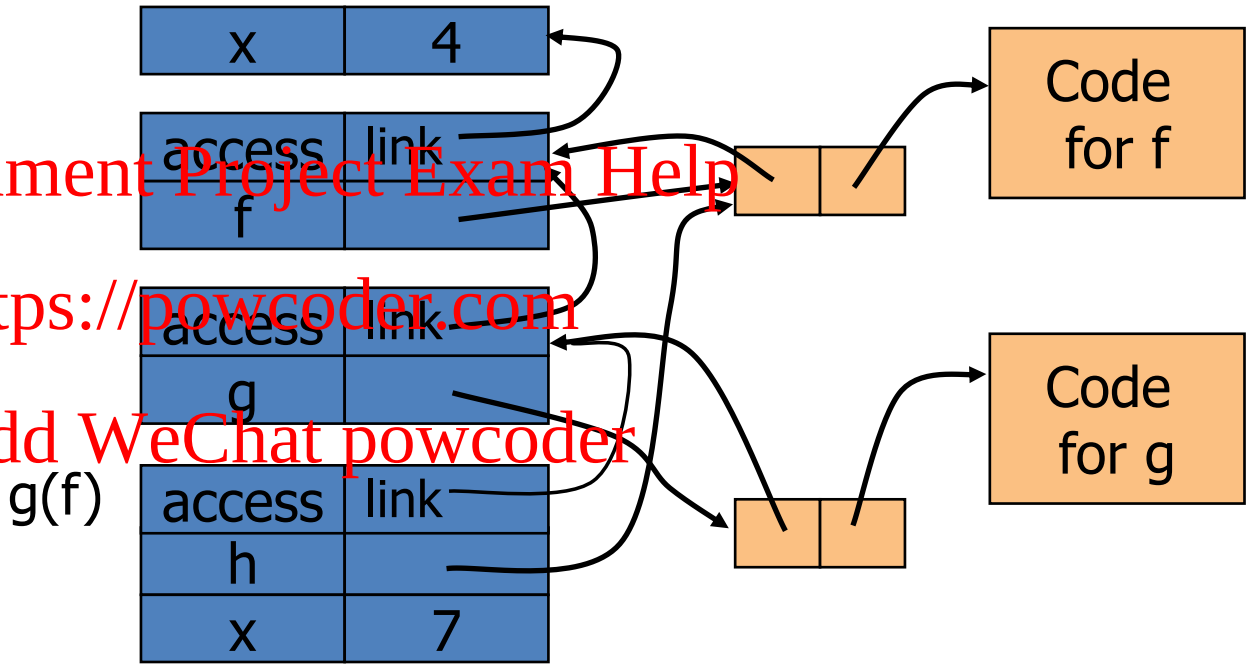
```



Function Argument and Closures

Run-time stack with access links


```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
      (let x = 7
       in
       h(3) + x) in
⇨   g(f)
```



Function Argument and Closures

Run-time stack with access links


```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
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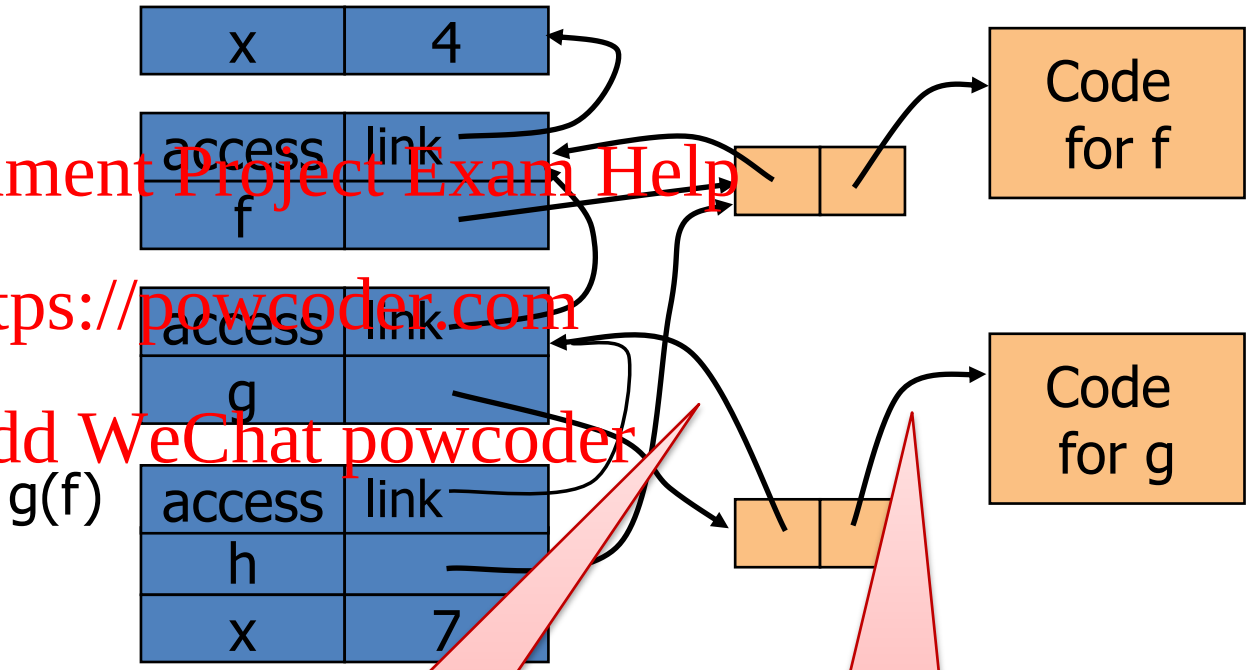
       in
       h(3 + x) in
    g(f)
```



g(f) called from block where g is local.

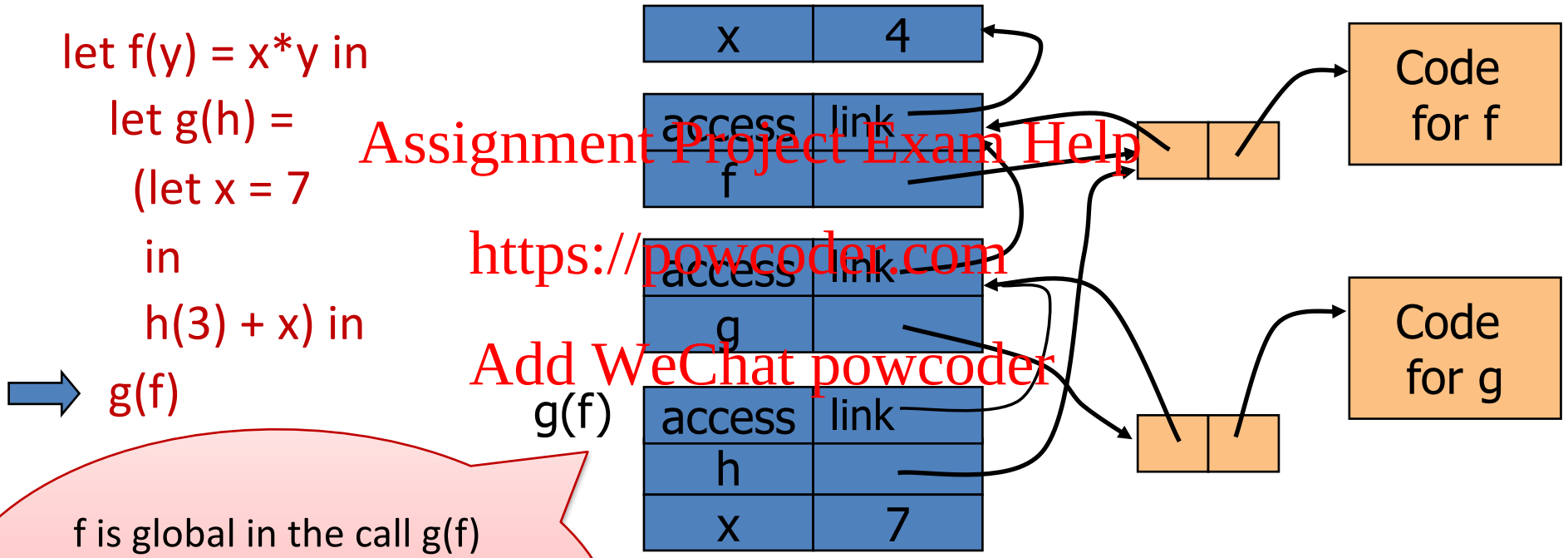
set access link from first element of closure

Follow code pointer for code to execute

Function Argument and Closures

Run-time stack with access links


```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
      (let x = 7
       in
       h(3) + x) in
    g(f)
```



f is global in the call g(f) so is accessed via an access link; f is passed as actual parameter for formal parameter h

Function Argument and Closures

Run-time stack with access links


```
let x = 4 in
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    let g(h) =
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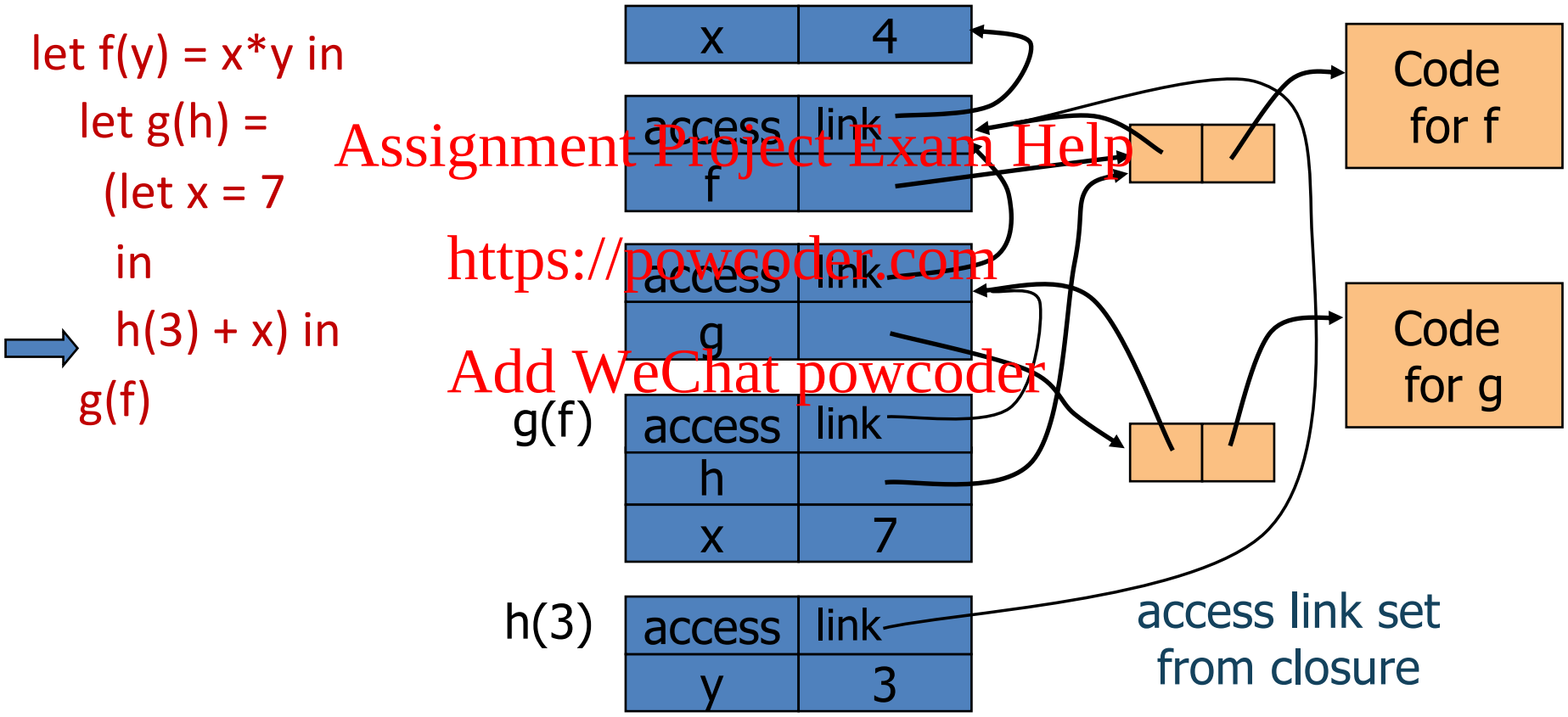
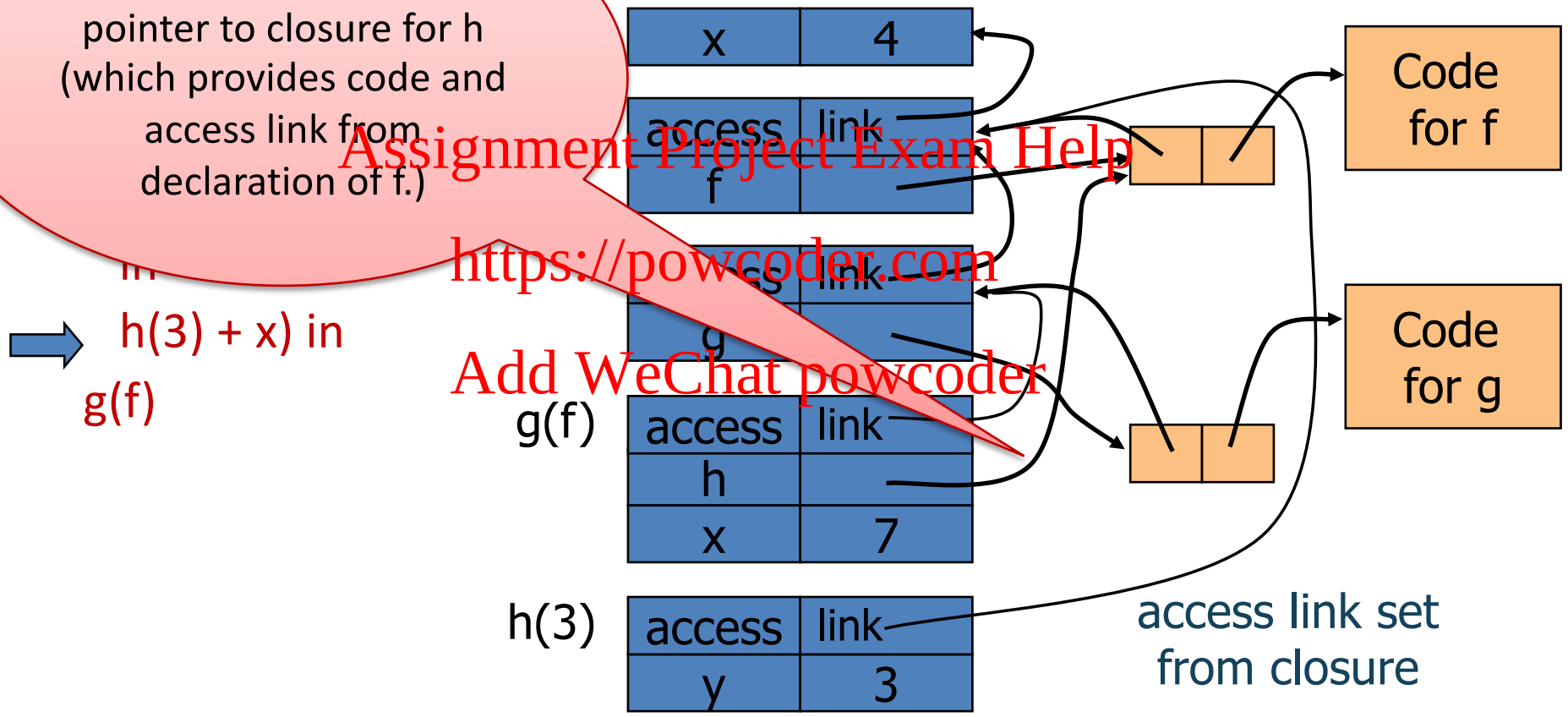


Function Argument and Closures

Run-time stack with access links

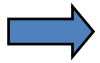
To execute h(3), follow pointer to closure for h (which provides code and access link from declaration of f.)

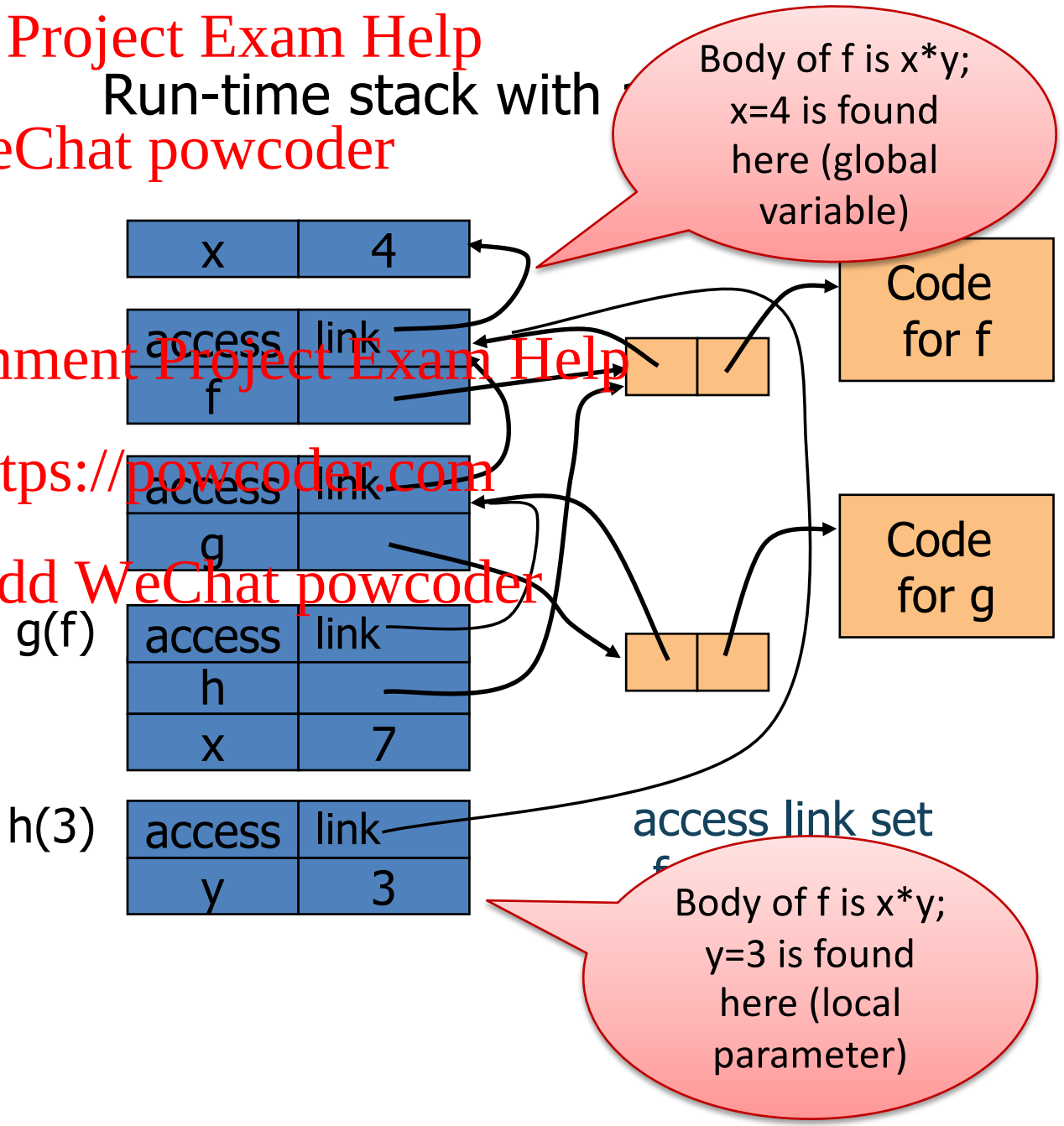


Function Argument and Closures

Run-time stack with

```
let x = 4 in
  let f(y) = x*y in
    let g(h) =
      (let x = 7
       in
       h(3) + x) in
    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 activation records to find global variables
  - Still deallocate activation records using stack order

Return Function as Result

- Language Feature
  - Functions that return "new" functions
  - Need to maintain environment of function
- Example

  let compose f g. = (fun x -> g(f x))

- Function "Created" Dynamically
  - expression with free variables

    values are determined at run time
  - function value is closure = ⟨env, code⟩
  - The code pointer of this closure points to compiled code for "get function parameter x and then compute g(f(x))".

Example: Return a Function with Private State


```
let mk_counter (init : int) =
    (let count = ref init in
     let counter (inc : int) =
       (count := !count + inc; !count)
     in
     counter)
in
let c = mk_counter(1) in
c(2) + c(2)
```


- The function counter is returned; the code for mk_counter builds it.
- Note that there is a parameter inc and a global variable count in the returned function.

Example: Return a Function with Private State


```
let mk_counter (init : int) =
    (let count = ref init in
     let counter (inc : int) =
       (count := !count + inc; !count)
     in
     counter)
in
let c = mk_counter(1) in
c(2) + c(2)
```


- Function to "make counter" returns a closure
- How is correct value of count determined in c(2) ?

Function Results and Closures

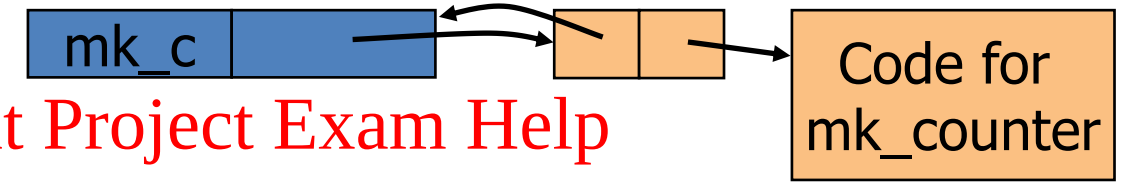

```
let mk_counter (init:int) =
  (let count = ref init in
       let counter (inc : int) = (count := !count + inc; !count)
       in  counter)
   in
let c = mk_counter(1) in
c(2) + c(2)
```


Code for mk_counter

Code for counter

Function Results and Closures

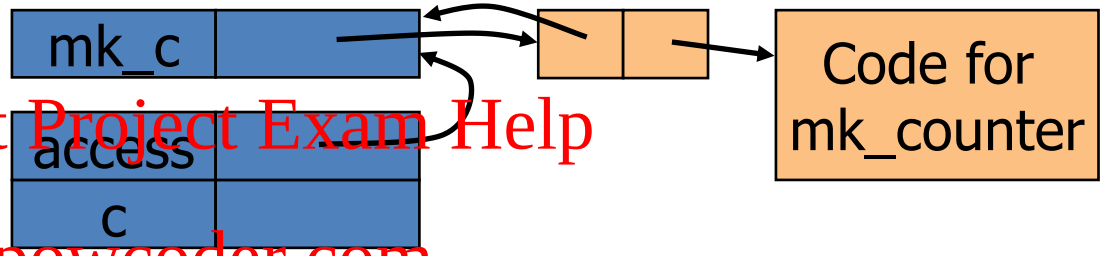

```
let mk_counter (init:int) =
  (let count = ref init in
       let counter (inc : int) = (count := !count + inc; !count)
       in  counter)
   in
let c = mk_counter(1) in
c(2) + c(2)
```



Code for
counter

Function Results and Closures


```
let mk_counter (init:int) =
  (let count = ref init in
       let counter (inc : int) = (count := !count + inc; !count)
       in  counter)
   in
let c = mk_counter(1) in
c(2) + c(2)
```



Code for
counter

Function Results and Closures


```
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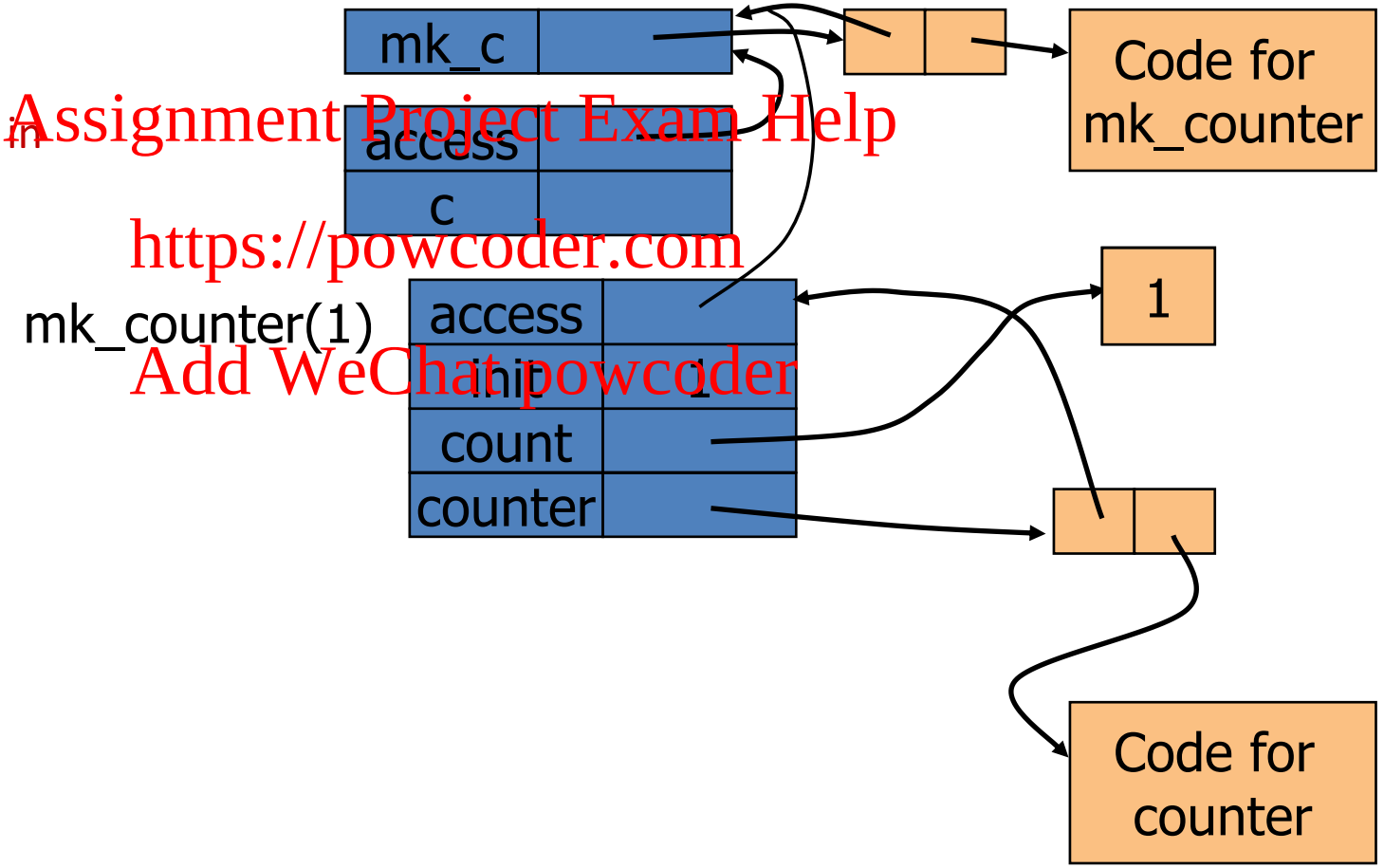
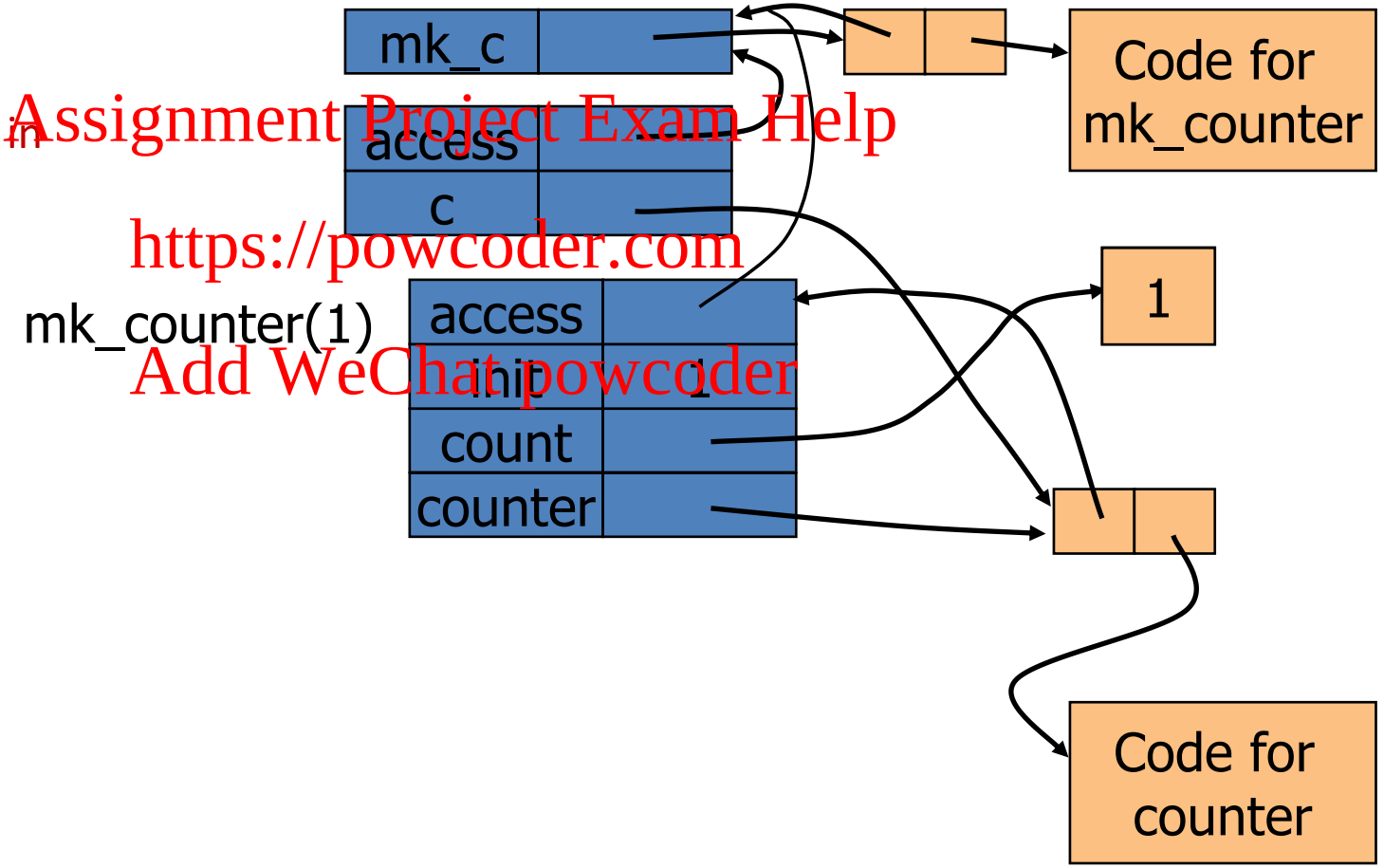
  (let count = ref init in
       let counter (inc : int) = (count := !count + inc; !count)
       in  counter)
   in
let c = mk_counter(1) in
c(2) + c(2)
```



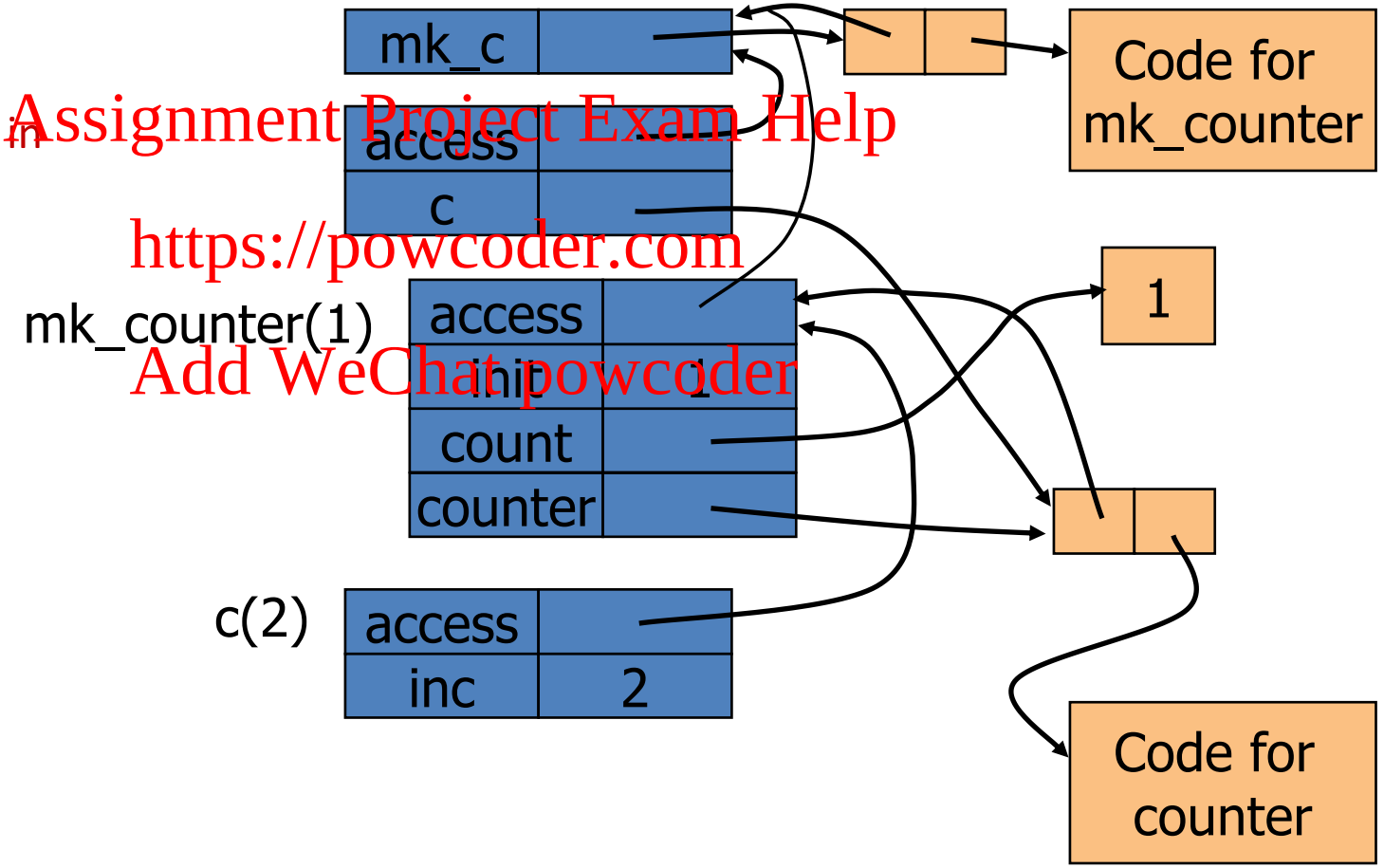
Function Results and Closures


```
let mk_counter (init:int) =
  (let count = ref init in
       let counter (inc : int) = (count := !count + inc; !count)
       in  counter)
   in
let c = mk_counter(1) in
c(2) + c(2)
```

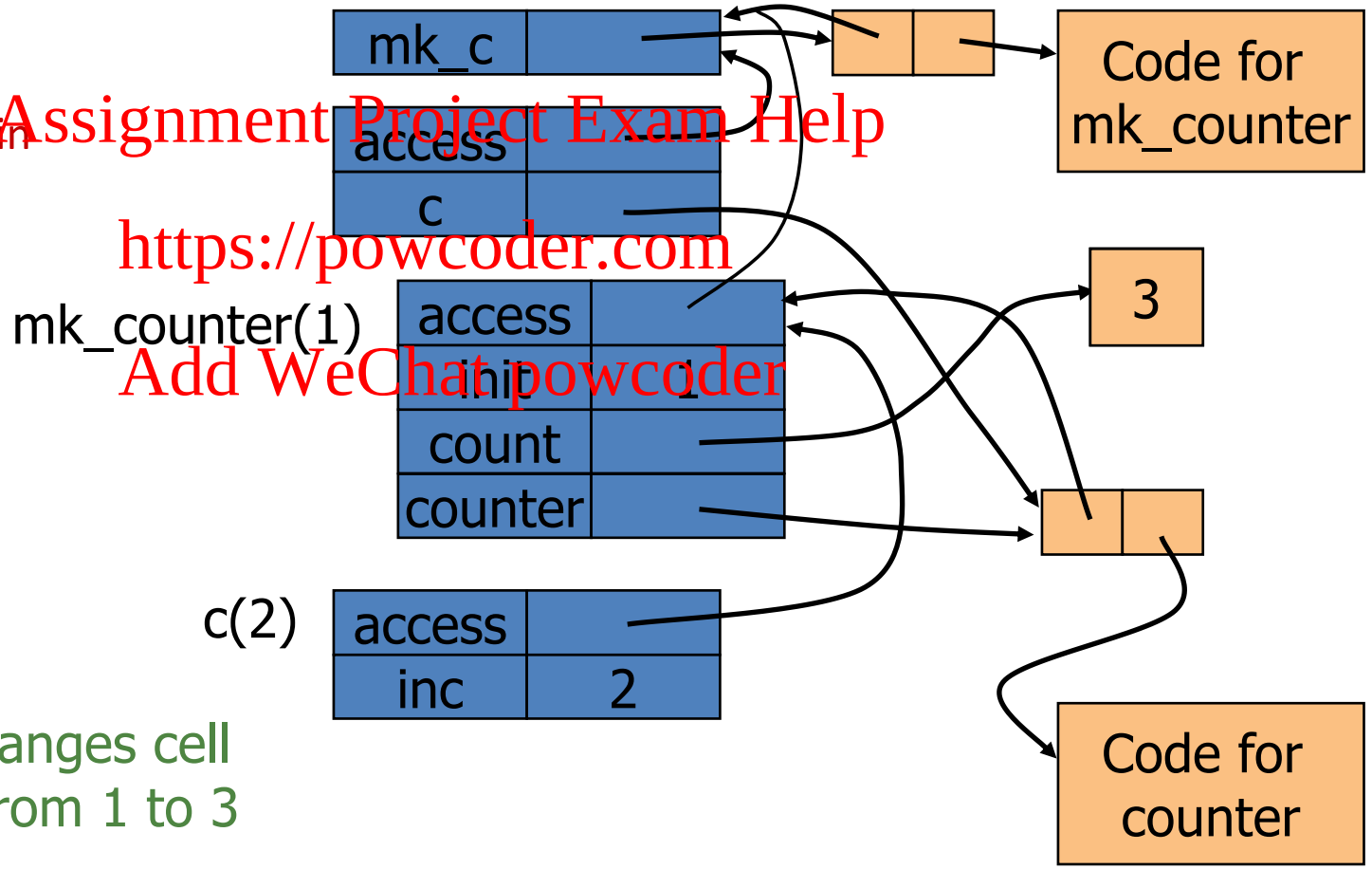
Function Results and Closures


```
let mk_counter (init:int) =
  (let count = ref init in
      let counter (inc : int) = (count := !count + inc; !count)
      in  counter)
   in
let c = mk_counter(1) in
c(2) + c(2)
```

Function Results and Closures


```
let mk_counter (init:int) =
  (let count = ref init in
      let counter (inc : int) = (count := !count + inc; !count)
      in  counter)
   in
let c = mk_counter(1) in
c(2) + c(2)
```

Call changes cell value from 1 to 3

Summary of Example

- Closures are used to set the access pointer when a function returned from a nested scope is called.

- When functions are returned from nested scopes, activation record cannot be popped off the stack.
  - Stack (last-in-first-out) order fails!

- Possible alternative "stack" implementation
  - Forget about explicit deallocation

  - Put activation records on heap

  - Invoke garbage collector as needed
  - May seem inefficient but not necessarily

    May only need to search reachable data

Summary of Scope Issues

- Block-structured languages use stack of activation records
  - Activation records contain parameters, local variables, …
  - 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