Lecture 9: Procedures & Functions

CS 540

George Mason University

Procedures/Functions

- Control Abstraction
  - call/return semantics, parameters, recursion
- Controlled Namespace
  - Scope (local/non-local), binding, addressing
- External Interface
  - separate compilation, libraries (not dealing with here)

Procedures as Control Abstractions

Relationship between caller and callee is asymmetric

- Control flow (call and return)
- Data flow (call and return): parameters and return values
- Recursion
- Variable addressing

The way this data/control flow is achieved is strictly defined and the given rules must be adhered to by the compiler

Data Structure: Call Graph

A **call graph** is a directed multi-graph where:

- the nodes are the procedures of the program and
- the edges represent calls between these procedures.

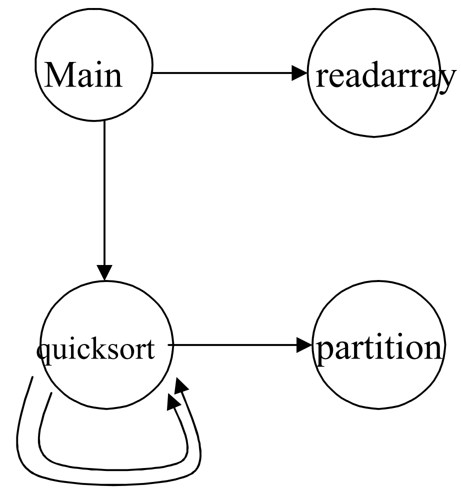
Used in optimization phase.

Acyclic → no recursion in the program

Can be computed **statically**.

Example

```
var a: array [0 .. 10] of integer;
procedure readarray
var i: integer
begin … a[i] … end
function partition(y,z: integer): integer
var i,j,x,v: integer
begin … end
procedure quicksort(m,n: integer)
var i: integer
begin i := partition(m,n); quicksort(m,i-1); quicksort(i+1,n) end
procedure main
begin readarray(); quicksort(1,9); end
```

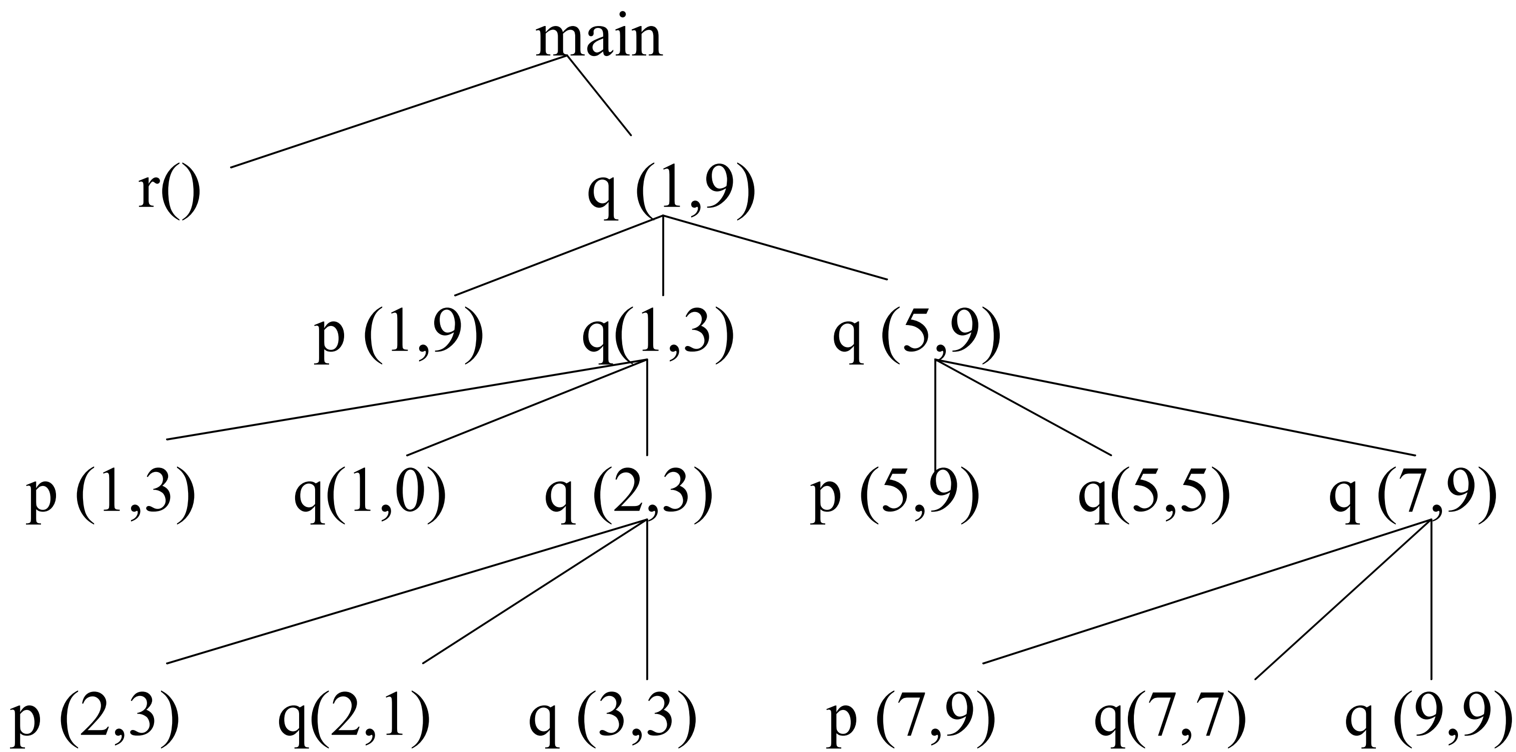


Data Structure: Call Tree

- A **call tree** is a tree where:
  - the nodes are the procedure activations of the program and
  - the edges represent calls between these procedure activations.
- Dynamic – typically different every time the program is run

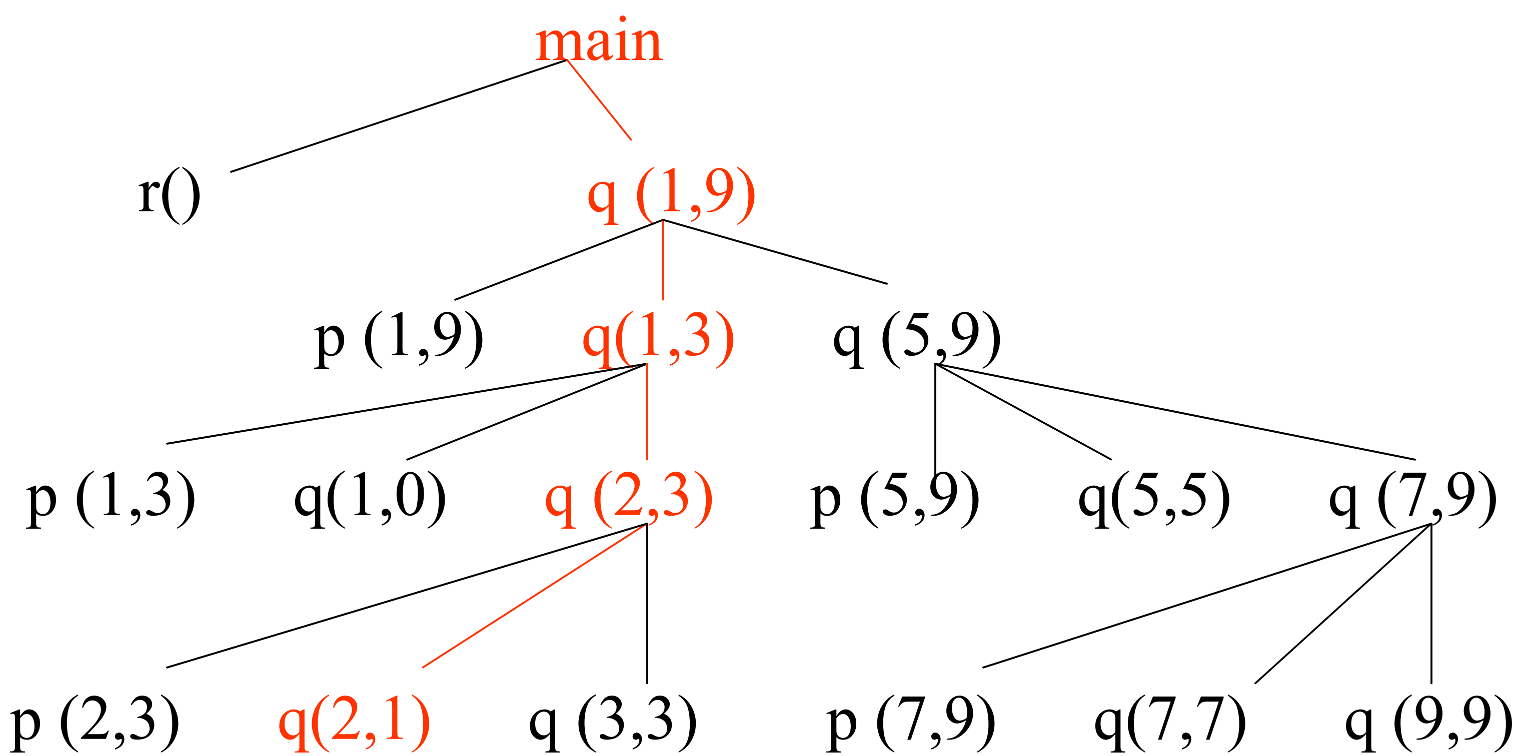
Run-time Control Flow

Call Tree - cannot be computed statically



Run-time Control Flow

Paths in the call tree from root to some node represent a sequence of active calls at runtime



Static Allocation

- Historically, the first approach to solving the run-time control flow problem (Fortran)
- **All** space allocated at compile time → No recursion
  - Code area – machine instructions for each procedure
  - Static area –
    - single data area allocated for each procedure.
      - local vars, parameters, return value, saved registers
    - return address for each procedure.

Static Allocation

Code area

Code generated for A

Code generated for B

Data area for procedure A

return addr

Local data, parameters, return value, registers for A

Data area for procedure B

return addr

Local data, parameters, return value, registers for B

Call/Return processing in Static Allocation

- When A calls B:
  - in A: evaluate and save actual parameters, save any registers and status data needed, save RA, finally update the program counter (PC) to B's code
  - In B: deal with parameters and RA (if needed)
- When the call returns
  - in B: save return value, update PC to value in RA
  - in A: get return value, restore any saved registers or status data

Save options: data areas (A or B), registers

Static Allocation

Call tree:
A

Code area

```
A:
PC → call B
L1:

B:
…
return
```

Activation for procedure A

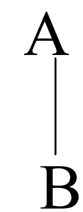
```
Local data,
parameters,
return
value,
registers
for A
```

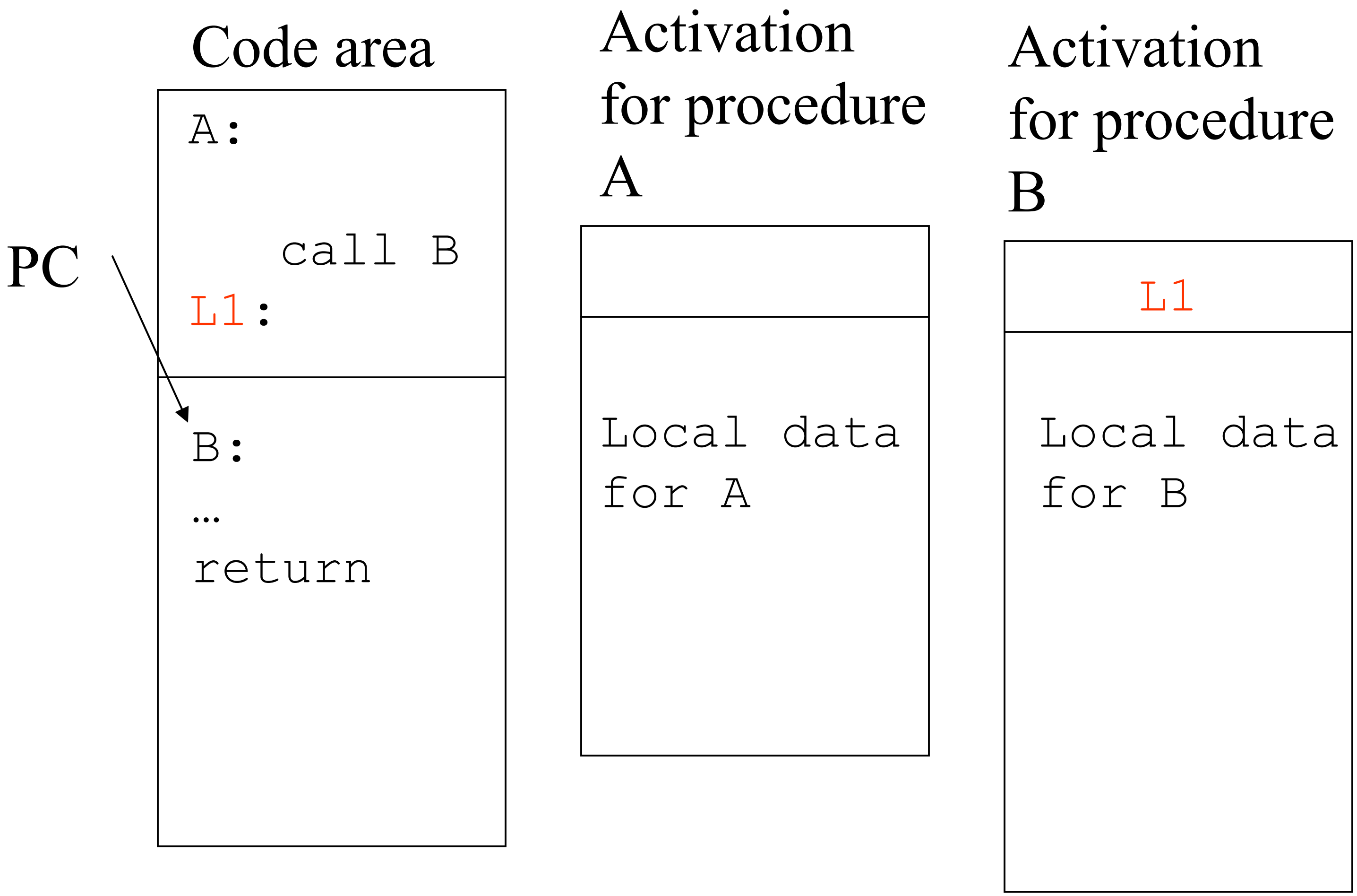
Activation for procedure B

```
Local data,
parameters,
return
value,
registers
for B
```

Static Allocation

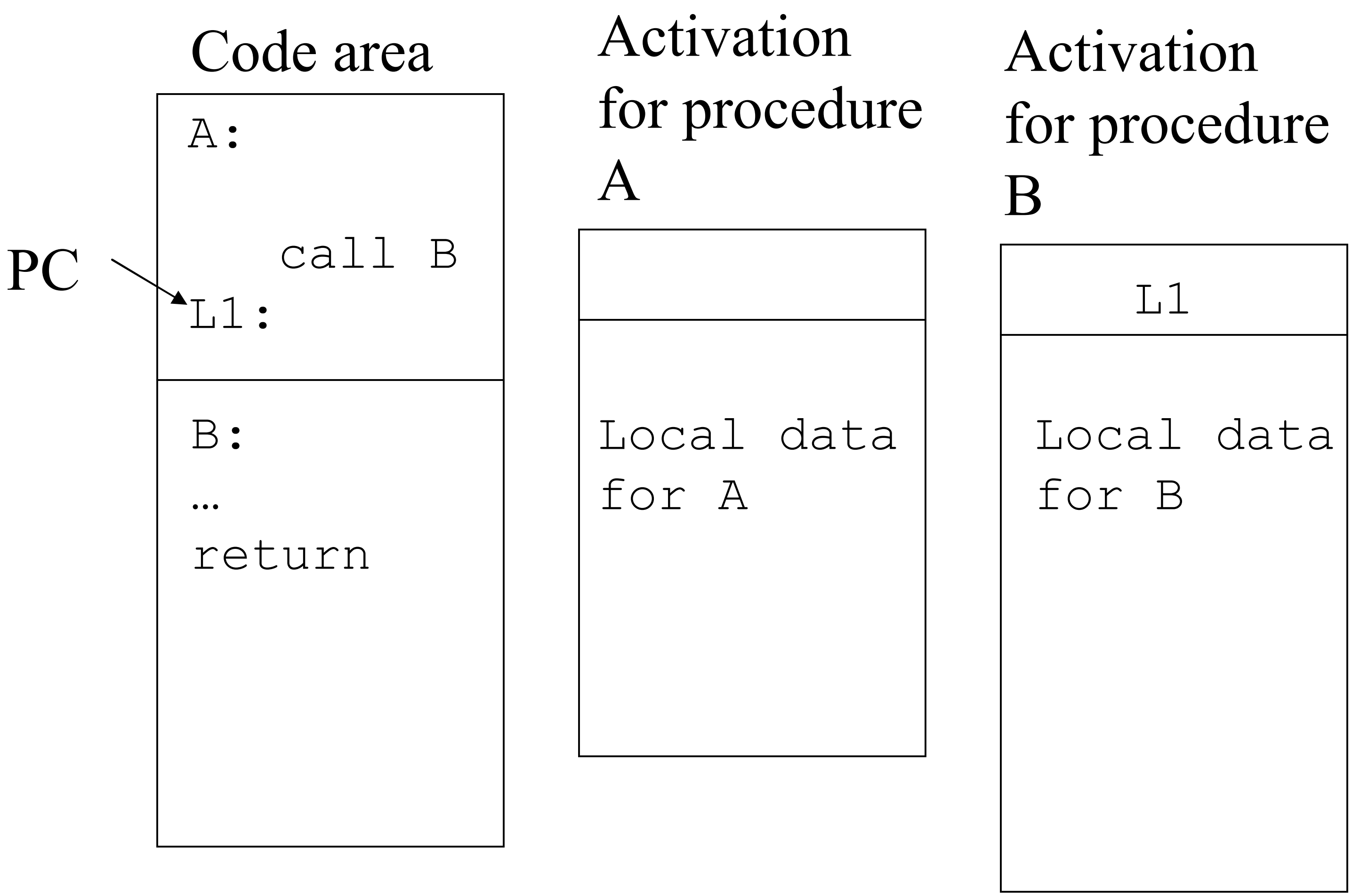
Call tree:





Static Allocation

Call tree:
A



Managing Control Flow: Spim

1. Set aside extra space for return address and local info for each function.

```
FN_RA:          .word   0
FN_Regs:        .space  48
      # save 8 $t + 4 $a registers
FN_Params:      .word …
```

Managing Control Flow: Spim

2. Add code at the point of the call:

```
sw $t0, FN1_Regs
sw $t1, FN1_Regs+4 …
move $a0, $t …
jal function
lw $t0, FN1_Regs
lw $t1, FN1_Regs +4 …
move $tx,$v0
```

Save and restore local registers in use

Pass in parameters and get the return value

jal – save the address of the next statement in $ra and then jump to the given label

Managing Control Flow: Spim

3. Add code in the called function
   - Prologue:

```
sw $ra, FN2_RA
sw $a0, FN2_Param1 …
```

jal put return address in $ra

   - Epilogue

move $v0,$t$_y$

lw t_x$, FN2_RA

jr t_x$

If there is a return value…

result := f(a,bb);

```
   .data
main_Regs: .word 0,0,0,0,0,0,0,0
main_RA:    .word 0
   .text
   lw $t0,a
   move $a0,$t0
   lw $t0,bb
   move $a1,$t0
   sw $t0,main_Regs
   sw $t1,main_Regs+4
   sw $t2,main_Regs+8
   …
```

```
jal label_f
lw $t0,main_Regs
lw $t1,main_Regs+4
lw $t2,main_Regs+8
move $t0,$v0
sw $t0,result
```

int f(int x, int y) {… return max; }

```
   .data
f_RA: .word 0 # return addr
   .text
label_f:
   sw $ra,F_RA
   .data
x:    .word 0   # param 1
   .text
   sw $a0,x
   .data
y:    .word 0   # param 2
   .text
   sw $a1,y
```

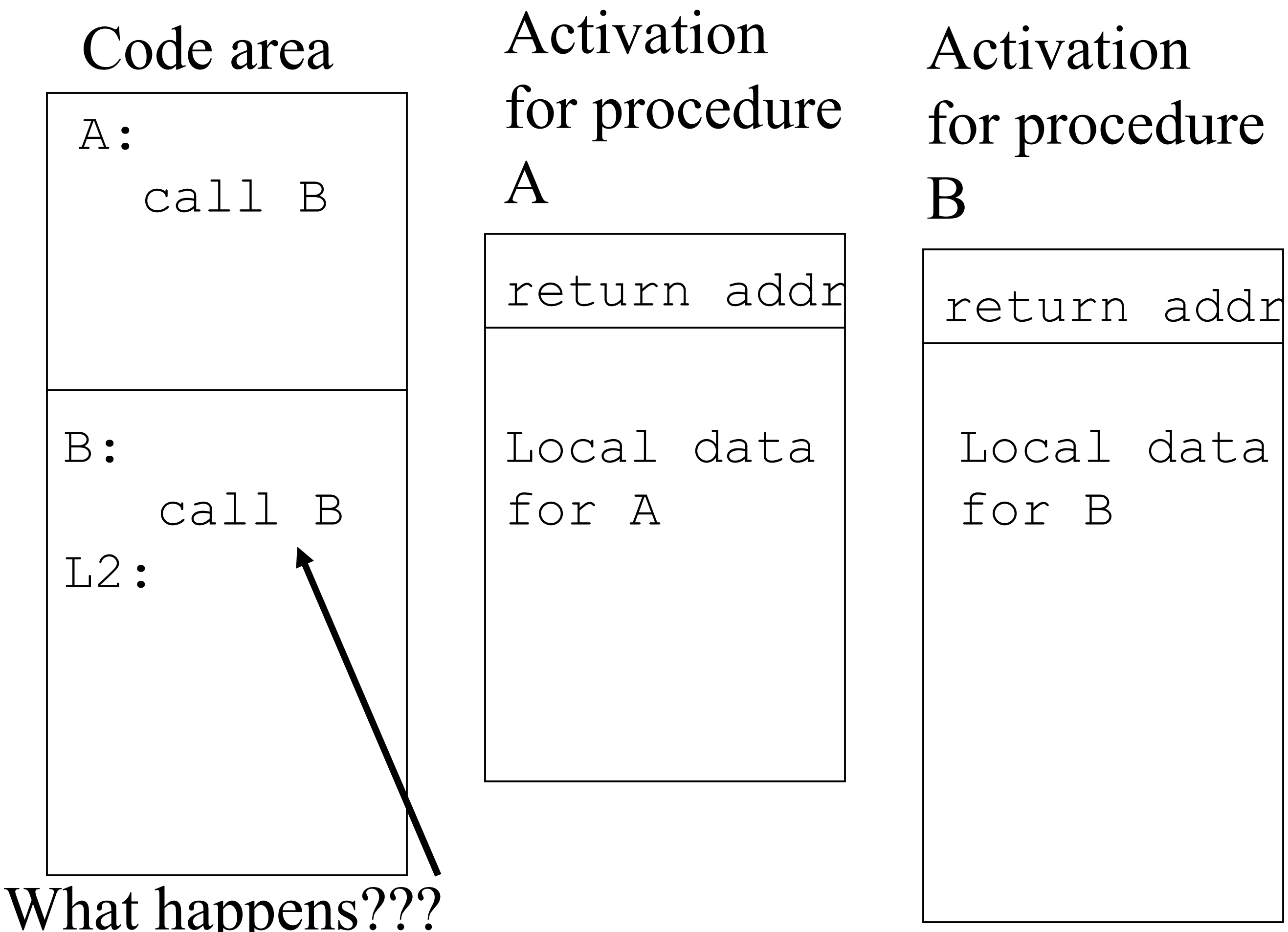
body of f

```
lw $v0,max  # return val
lw $t0,f_RA
jr $t0
```

Runtime Addressing in Static Allocation

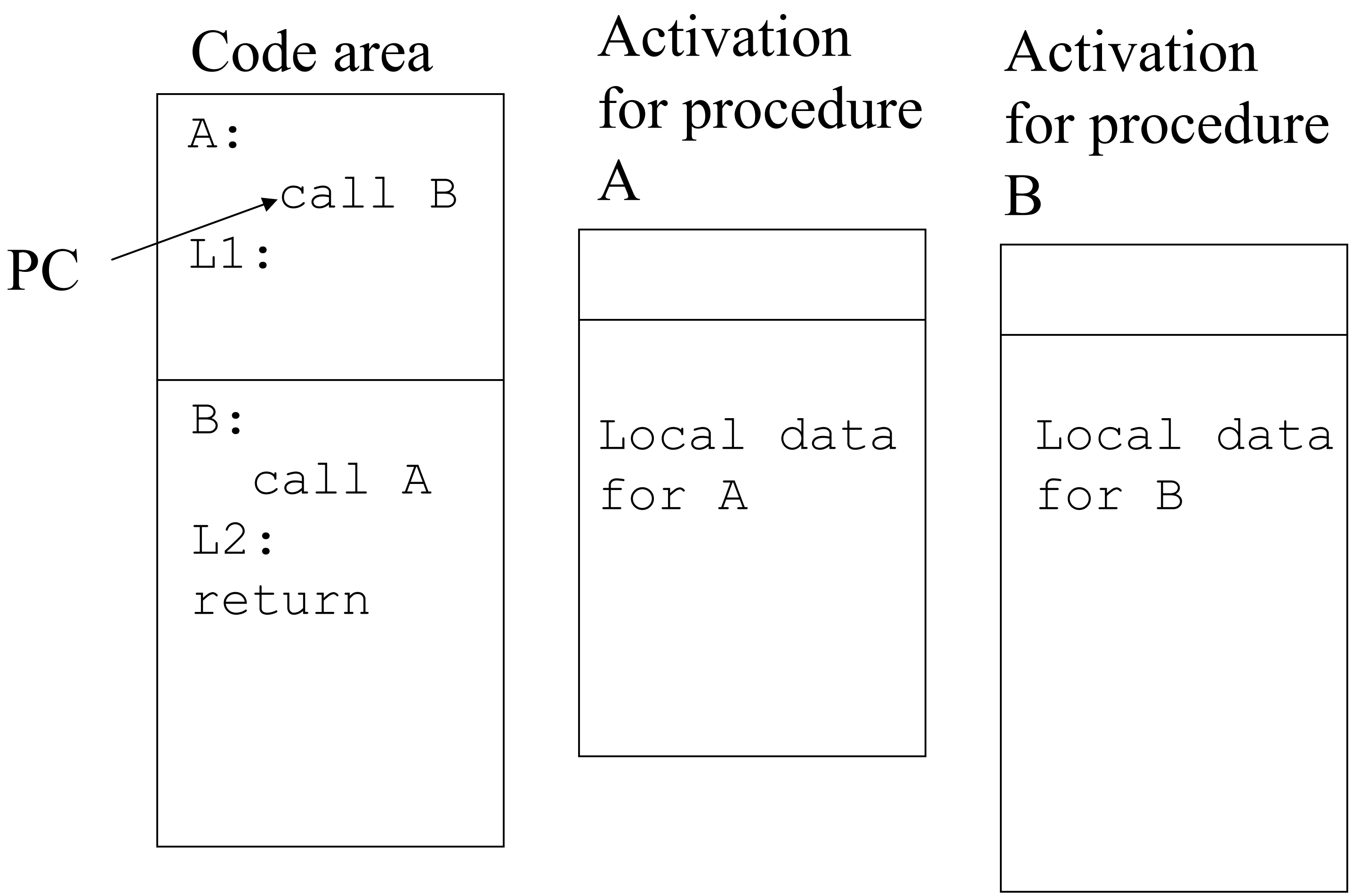
- Variable addresses hard-coded, usually as offset from data area where variable is declared.
  - addr(x) = start of x's local scope + x's offset
- In Spim, we are going to save the local variable using a label and when needed, we can use **`lw`** to get the value (or **`la`** to get the address).

Static Allocation: Recursion?

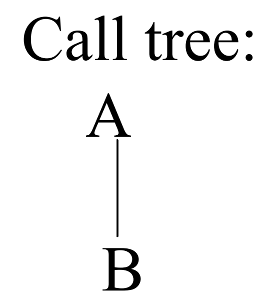


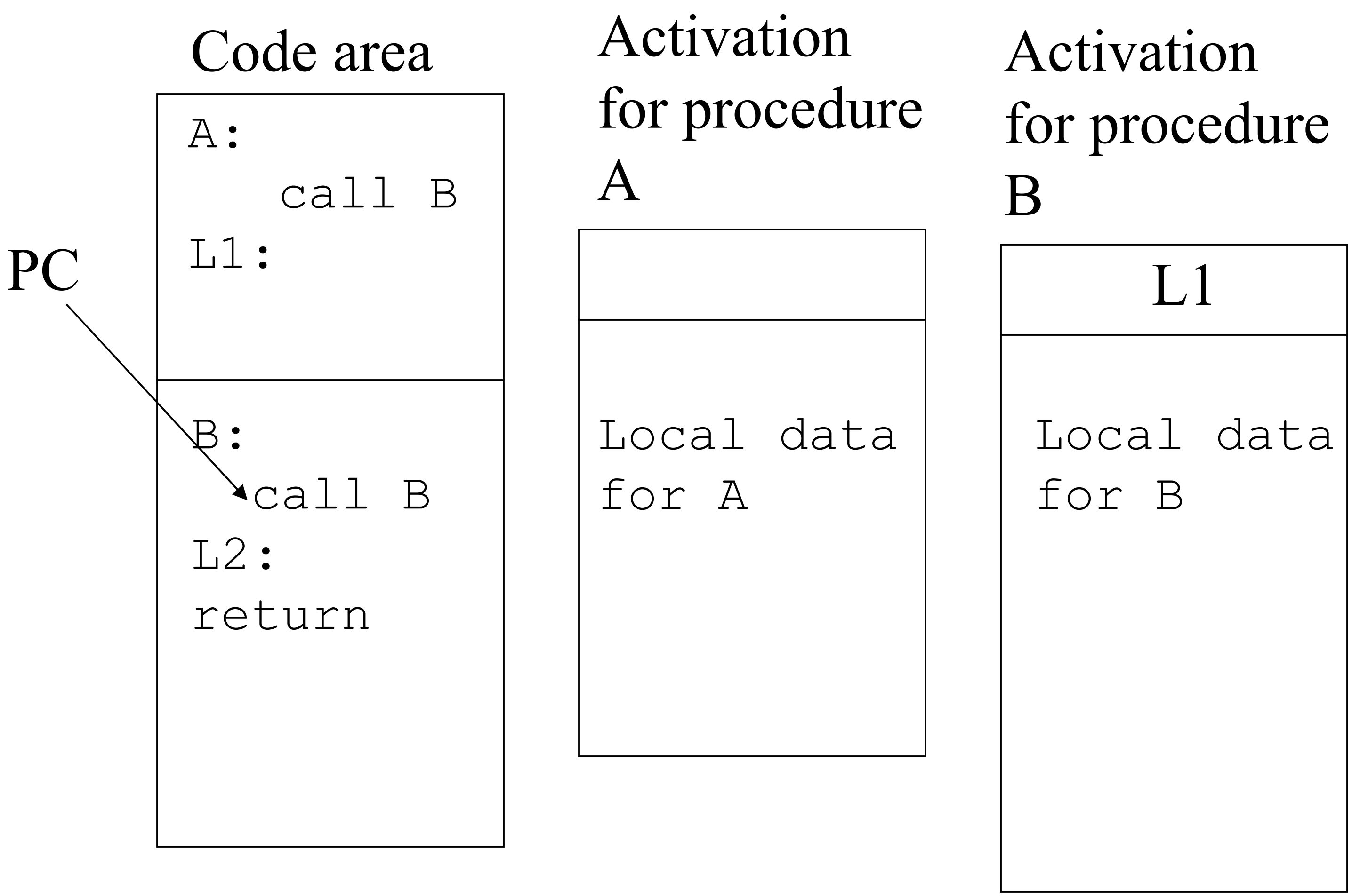
Static Allocation

Call tree:
A

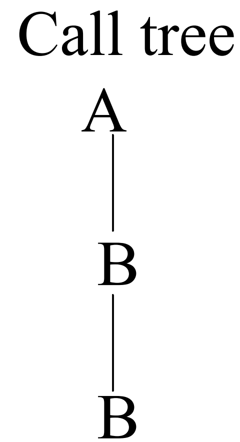


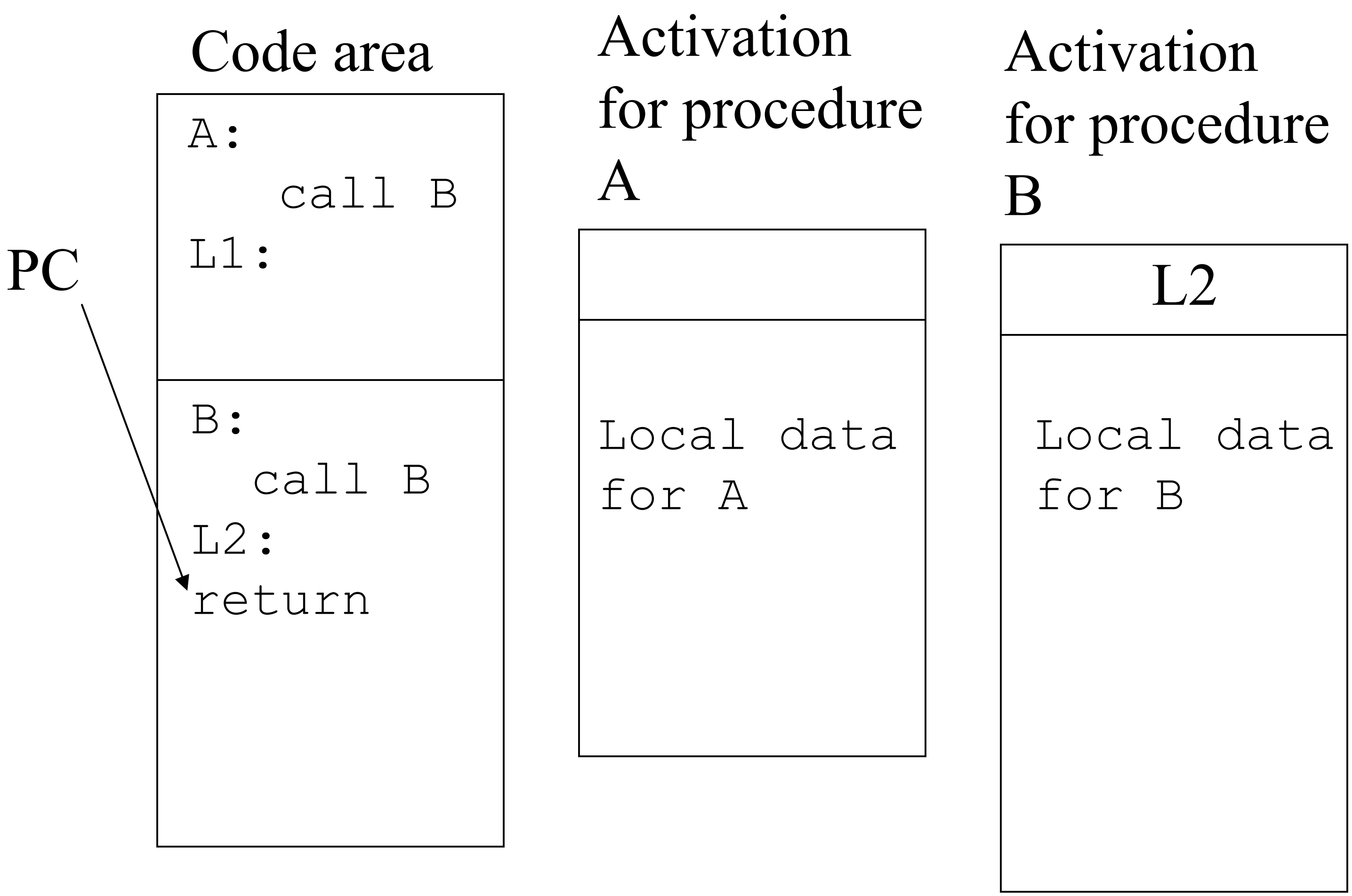
Static Allocation





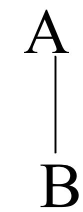
Static Allocation

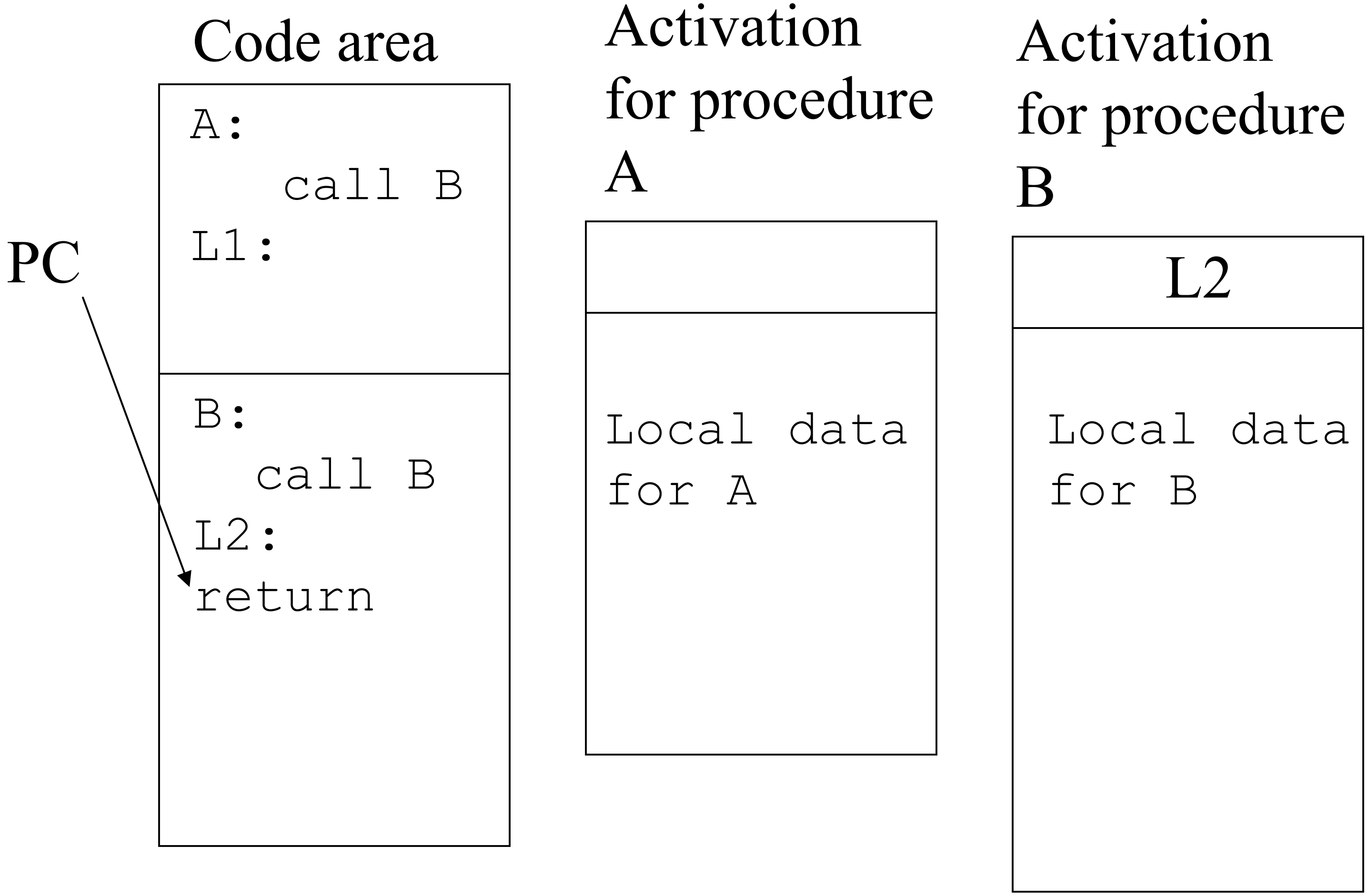




Static Allocation

Call tree:



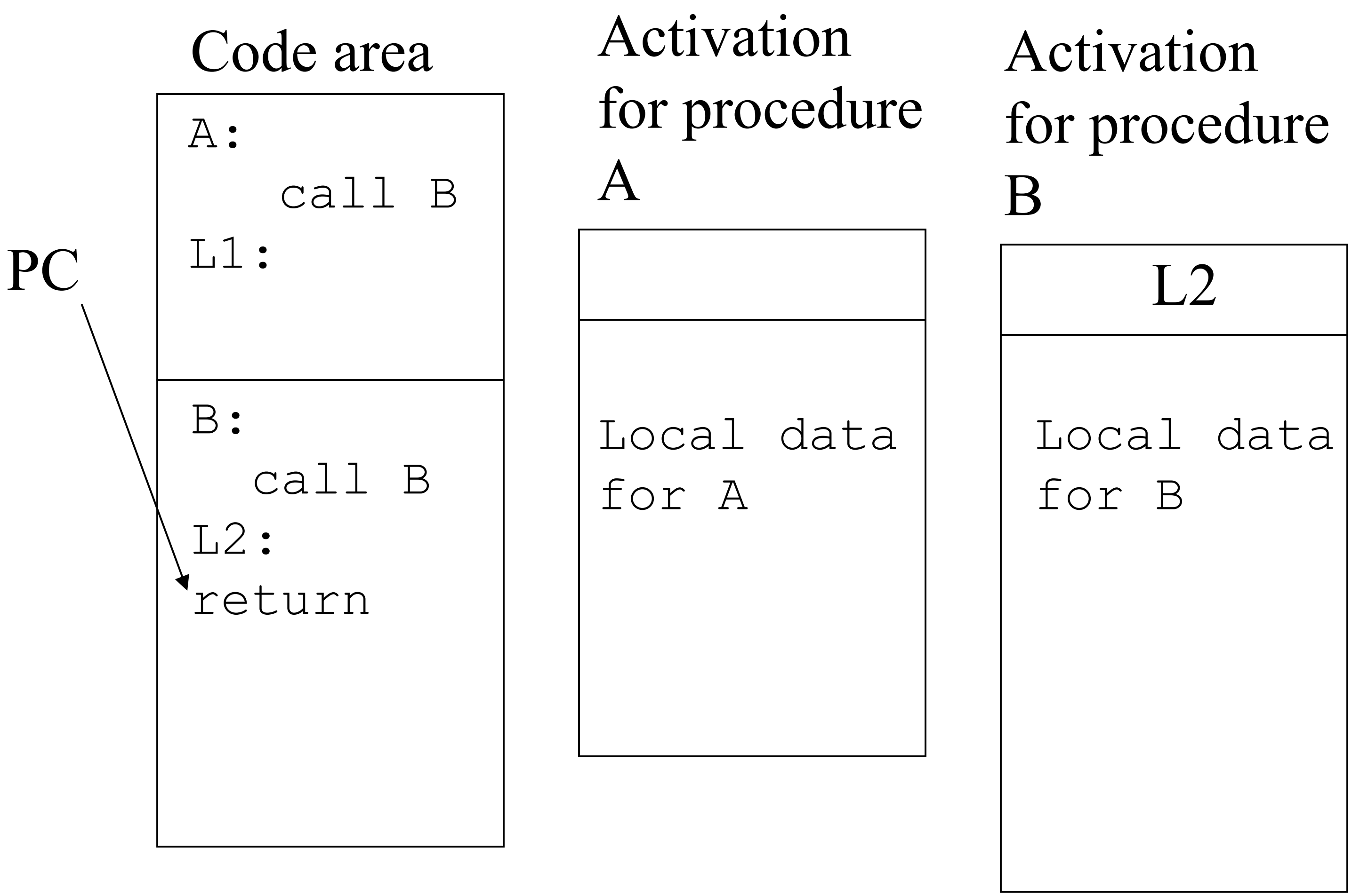


Static Allocation

Call tree:

A

B



We've lost the L1 label so we can't get back to A

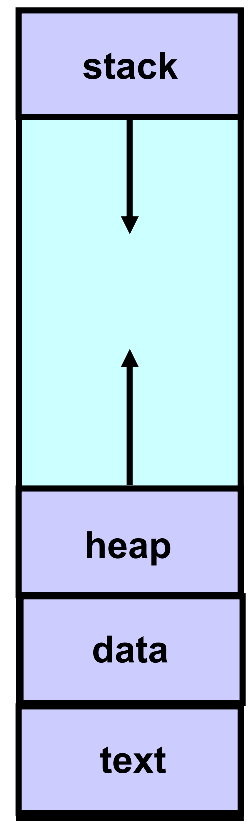
Stack Allocation

Need a different approach to handle recursion.

- Code area – machine code for procedures
- Static data – often not associated with procedures
- Stack – runtime information
  - Activation records – allocated at call time onto a runtime stack. Holds return addresses, local information
  - Dynamic – can grow and shrink

Process Address Space

- Each process has its own *address space*:
  - Text section (text segment) contains the executable code
  - Data section (data segment) contains the global variables
  - Stack contains temporary data (local variables, return addresses..)
  - Heap, which contains memory that is dynamically allocated at run-time.



Activation Records (frame)

Information needed by a single instance of a procedure.

- Local data
  - Parameter storage
  - Return value storage
- Saved registers
- Control links for stack
- Return address

Activation Records

Different procedures/functions will have different size activation records.

Activation record size can be determined at compile time.

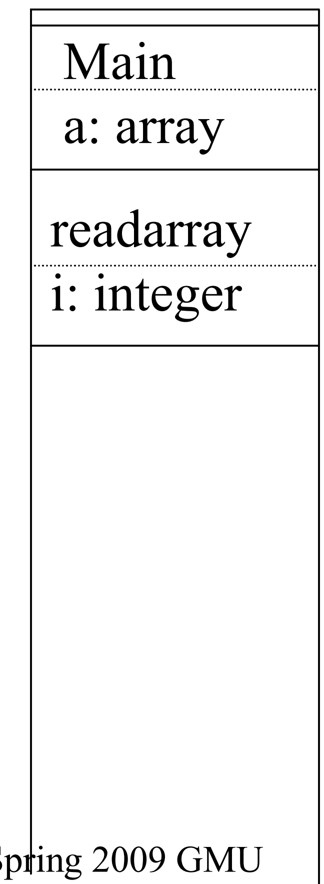
At call time, we push a new activation on the runtime stack.

At call termination time, we pop the activation off the stack.

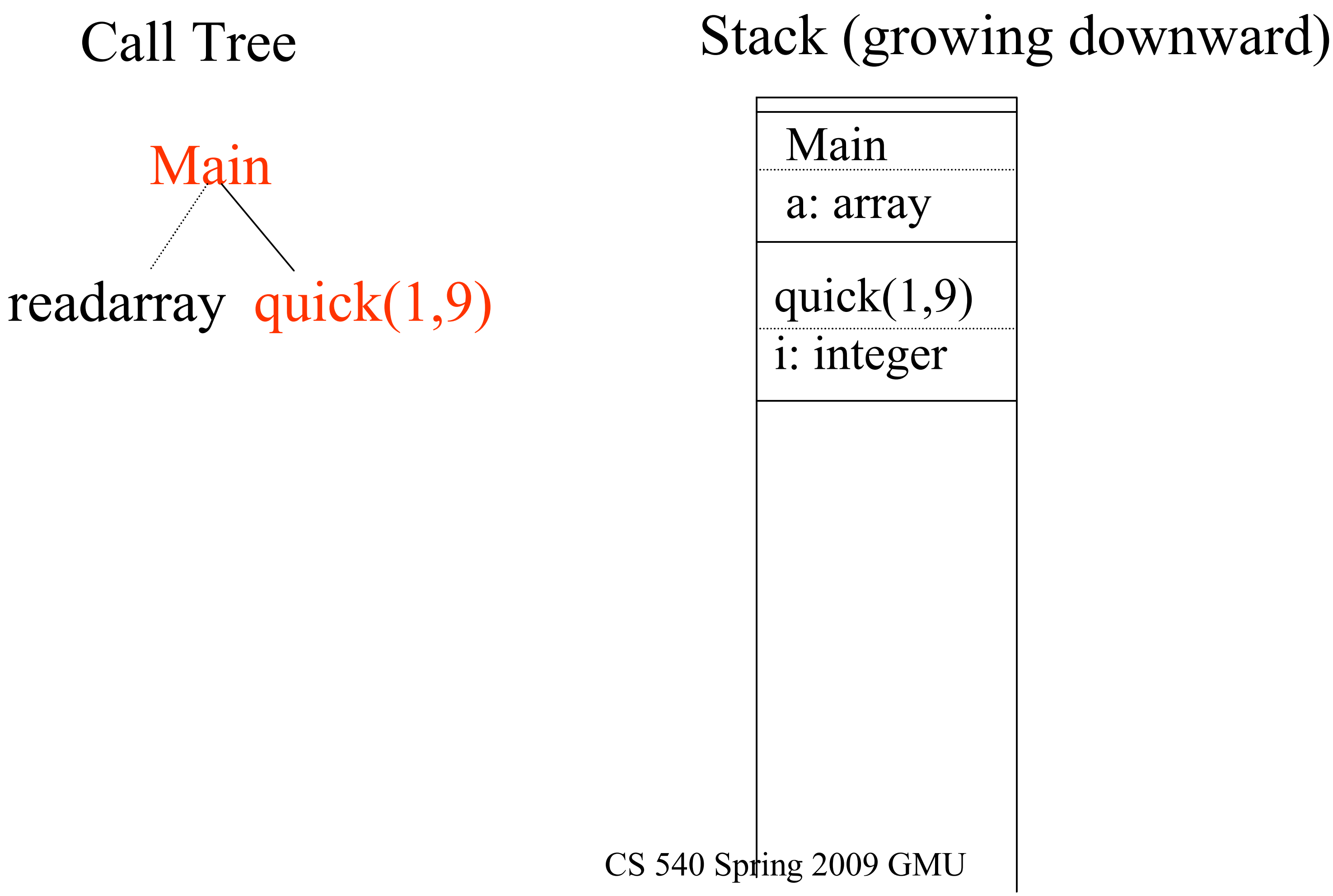
Stack Allocation - 1

Call Tree

Stack (growing downward)

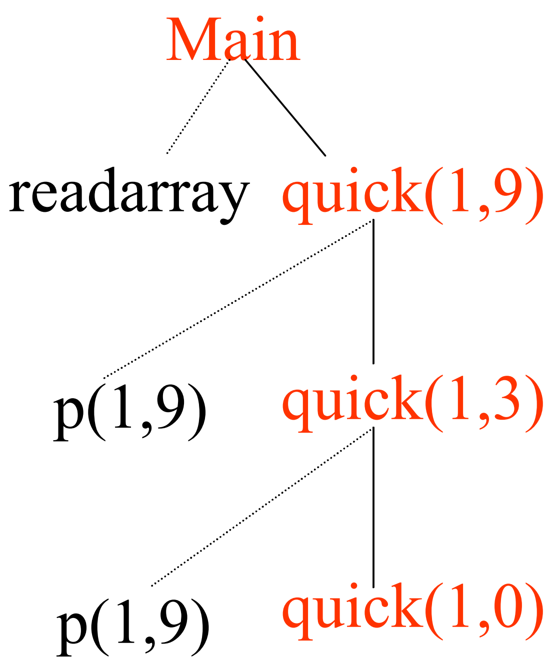


Stack Allocation - 2

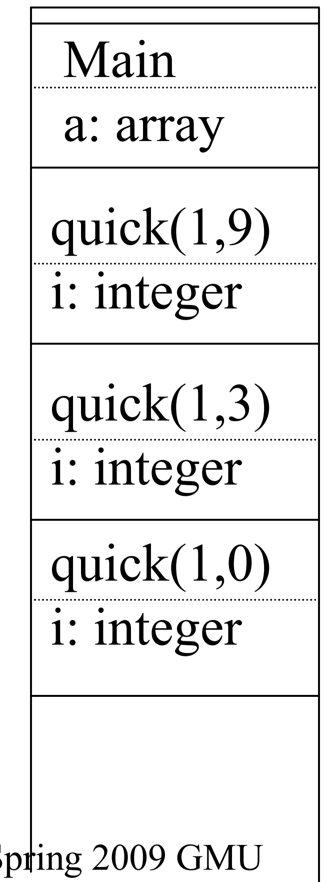


Stack Allocation - 3

Call Tree



Stack (growing downward)



Call Processing: Caller

- **Create new (callee) activation record on stack.**
- Evaluate actual parameters and place them on stack (or register).
- Save registers and other status data
- Store a return address, **dynamic link (= current stack pointer),** and **static link information** into callee activation then
- **Make stack pointer (SP) point at new activation**.
- Update the program counter (PC) to the code area for the called procedure.

Added at the point of the call

Call Processing: Callee

- Initialize local data, including moving parameters (if needed)
- Save return address if needed
- Stack maintenance
- Begin local execution

Added at the start of the function

Return Processing: Callee

- Place return value (if any) in activation.
- Stack maintenance
- Restore PC (from saved RA).

Added at the ‘return’ point(s) of the function

Return Processing: Caller

- Restore the stack pointer
- Restore registers and status
- Copy the return value (if any) from activation
- Continue local execution

Added after the point of the call

Spim Example: Activation

Offset	Data	Size
0	Return address	4
4	old frame ptr	4
8	$t registers	32
40	$a registers	16
56	local vars	?
…		

Spim Example

Assume a function f with two integer parameters named x and y that are passed by value. f returns a single integer. Also in function f are two local variables a and b.

Function f's prolog :

```
sw $ra,0($sp)  # save return address
sw $a0,56($sp) # parameter x
sw $a1,60($sp) # parameter y
```

NOTE: local variables a and b can be stored at offsets 64 and 68 respectively.

- Function f's epilog:

```
move $v0,$t1
lw $t1,0($sp)
jr $t1
```

At f(a,b)

```
# saving registers
sw $t0,8($sp)
sw $t1,12($sp)
. . .
sw $a0,40($sp)
…
# get actual parameters
lw $a0,a_global
lw $a1,b_global
#stack maintenance
sw $fp,4($sp)
subu $sp,$sp,104
```

```
addiu $fp,$sp,100 # set frame ptr
jal outputnums
move $t0,$v0  # grab return value
addiu $sp,$sp,104 # reset sp
lw $fp,4($sp) # reset frame pointer
lw $t0,8($sp) # restoring registers
lw $t1,12($sp)
. . .
lw $a0,40($sp)
…
```

http://cs.gmu.edu/~white/CS540/Slides/Semantic/runtime.html

Runtime Addressing

- Given a variable reference in the code, how can we find the correct instance of that variable?
- Things are trickier – variables can live on the stack.
- Tied to issues of scope

Types of Scoping

- Static – scope of a variable determined from the source code. Scope A is enclosed in scope B if A's source code is nested inside B's source code.
- Dynamic – current call tree determines the relevant declaration of a variable use.

Static Scoping: Most Closely Nested Rule

The scope of a particular declaration is given by the most closely nested rule

- The scope of a variable declared in block B, includes B.
- If x is not declared in block B, then an occurrence of x in B is in the scope of a declaration of x in some enclosing block A, such that A has a declaration of x and A is more closely nested around B than any other block with a declaration of x.

Example Program

```
Program main;
  a,b,c: real;
  procedure sub1(a: real);
    d: int;
    procedure sub2(c: int);
        d: real;
    body of sub2
    procedure sub3(a:int)
      body of sub3
 body of sub1
body of main
```

Example Program: Static

```
Program main;
  a,b,c: real;
  procedure sub1(a: real);
    d: int;
    procedure sub2(c: int);
        d: real;
    body of sub2
    procedure sub3(a:int)
      body of sub3
  body of sub1
body of main
```

What is visible at this point (globally)?

Example Program: Static

```
Program main;
  a,b,c: real;
  procedure sub1(a: real);
    d: int;
    procedure sub2(c: int);
      d: real;
    body of sub2
    procedure sub3(a:int)
      body of sub3
  body of sub1
body of main
```

What is visible at this point (sub1)?

Example Program: Static

```
Program main;
   a,b,c: real;
   procedure sub1(a: real);
      d: int;
      procedure sub2(c: int);
            d: real;
      body of sub2
      procedure sub3(a:int)
         body of sub3
   body of sub1
body of main
```

What is visible at this point (sub3)?

Example Program: Static

```
Program main;
  a,b,c: real;
  procedure sub1(a: real);
    d: int;
    procedure sub2(c: int);
        d: real;
    body of sub2
    procedure sub3(a:int)
      body of sub3
  body of sub1
body of main
```

What is visible at this point (sub2)?

Variables from Example

Procedure	Enclosing	Local:addr = offset	Non-local: addr =(scope,offset)
main	-	a:0,b:1,c:2	-
sub1	main	a:0,d:1	b:(main,1),c:(main,2)
sub2	sub1	c:0,d:1	b:(main,1) a:(sub1,0)
sub3	sub1	a:0	b:(main,1),c:(main,2) d:(sub1,1)

Control Links in Stack Allocation

- Dynamic – points to caller's activation (old frame pointer)
- Static (access) link – points to enclosing scope

Static Chain Maintenance

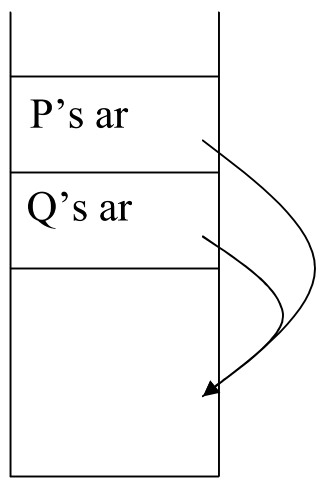
- How to set the static link?
  - Let P_{sd} be the static_depth of P, and Q_{sd} be the static_depth of Q
  - Assume Q calls P
  - There are three possible cases:

1. $Q_{sd} = P_{sd}$
2. $Q_{sd} < P_{sd}$
3. $Q_{sd} > P_{sd}$

Static Chain Maintenance: Q calls P

$Q_{sd} = P_{sd}$ - They are at same static depth

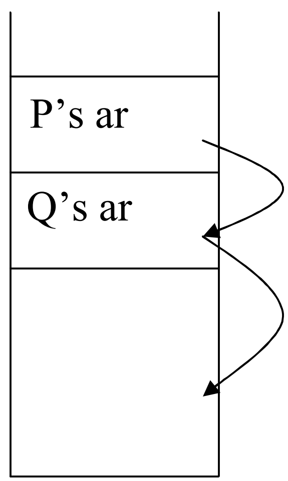
P's static link should be the same as Q's since they must occur in same enclosing scope – Q copies its link to P



Static Chain Maintenance: Q calls P

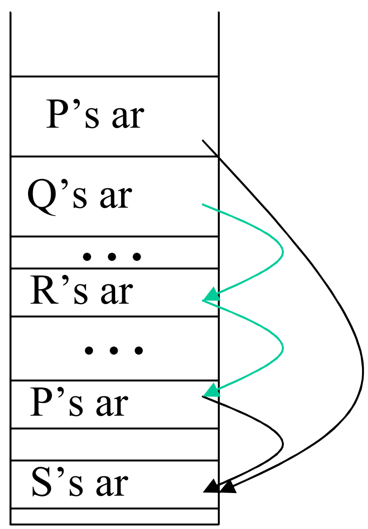
$Q_{sd} < P_{sd}$ - P must be enclosed directly in Q

P's static link should point at Q's activation

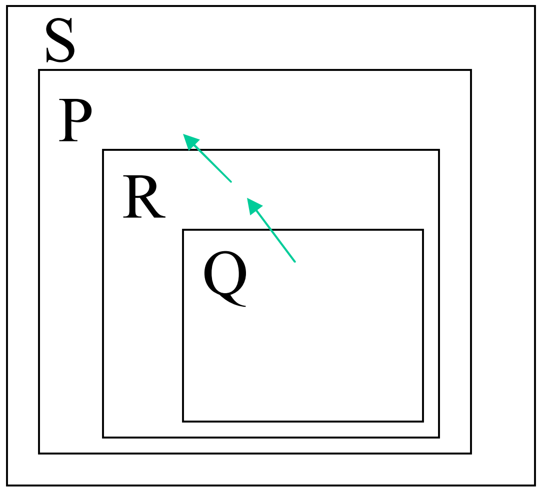


Static Chain Maintenance: Q calls P

$Q_{sd} > P_{sd}$ - Q is *n* levels down in the nesting – must follow Q's static chain *n* levels and copy that pointer



Suppose n is 2



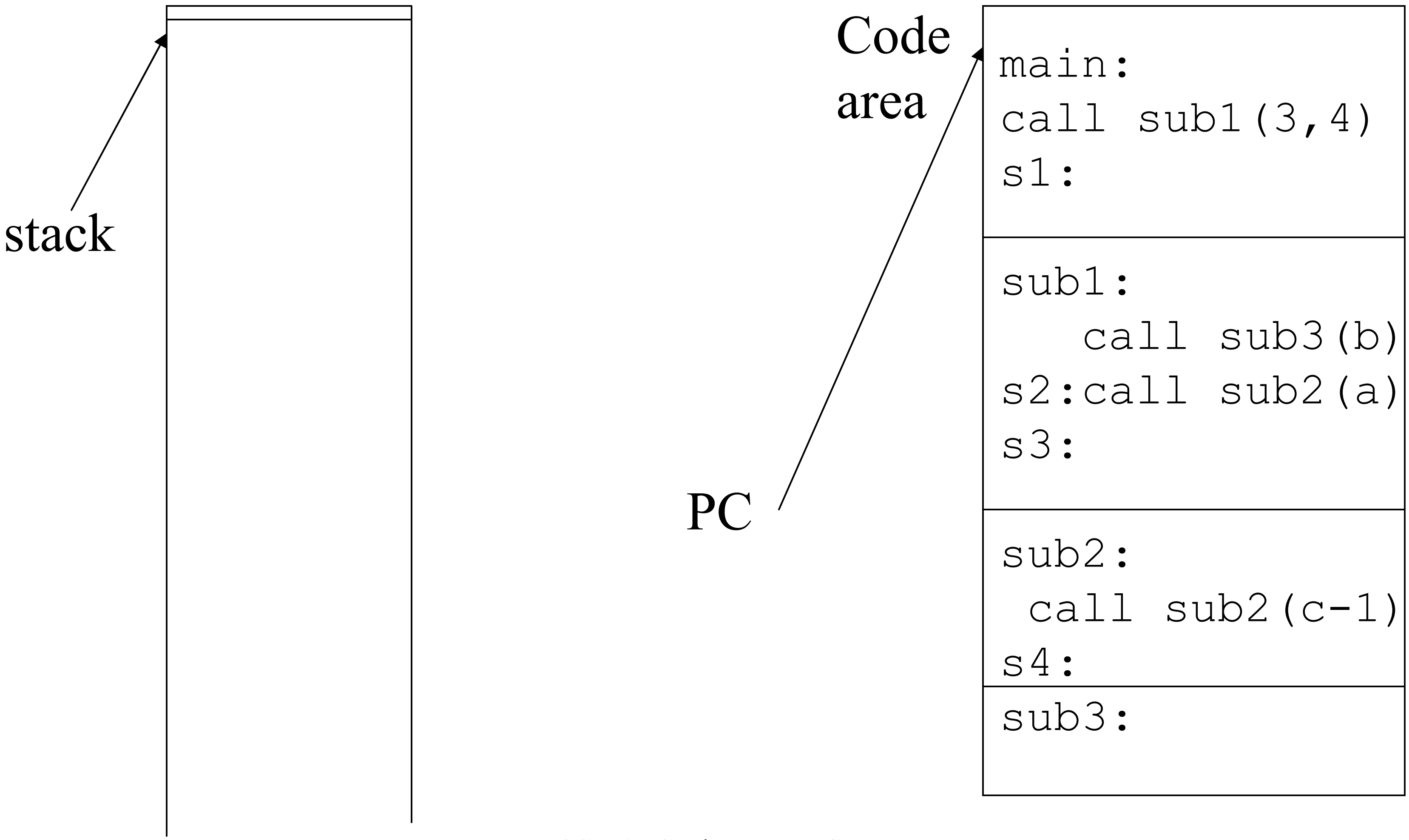
Runtime Addressing in Stack Allocation

- At runtime, we can't know where the relevant activation record holding the variable exists on the stack
- Use static (access) links to enable quick location
  - addr(x) = # static links + x's offset
  - Local: (0,offset)
  - Immediately enclosing scope: (1,offset)

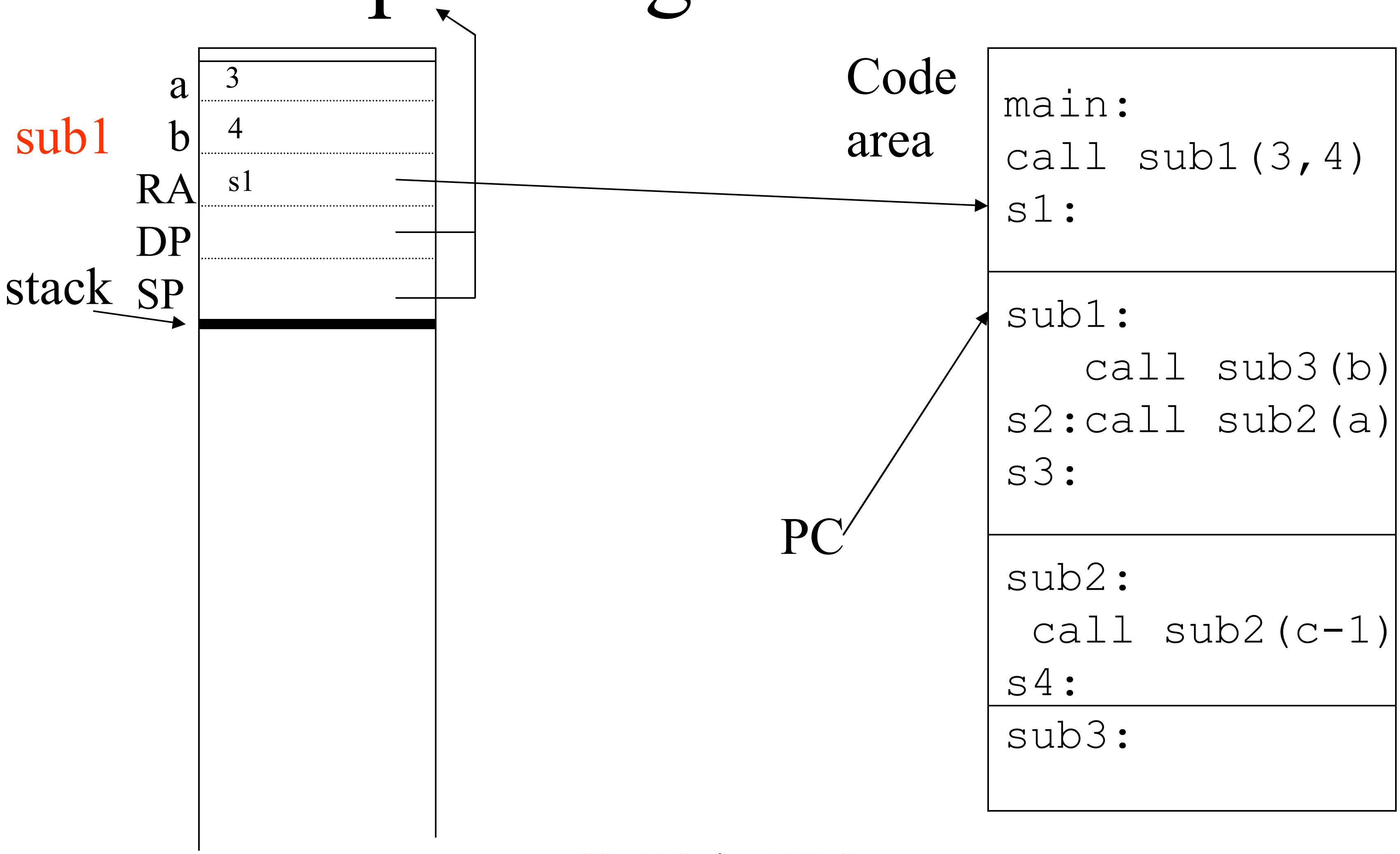
Example Program

```
Program main;
  procedure sub1(a: int,b:int);
    procedure sub2(c: int);
      if c > 0 call sub2(c-1)
    procedure sub3()
      body of sub3
  call sub3(b);  call sub2(a);
call sub1(3,4);
```

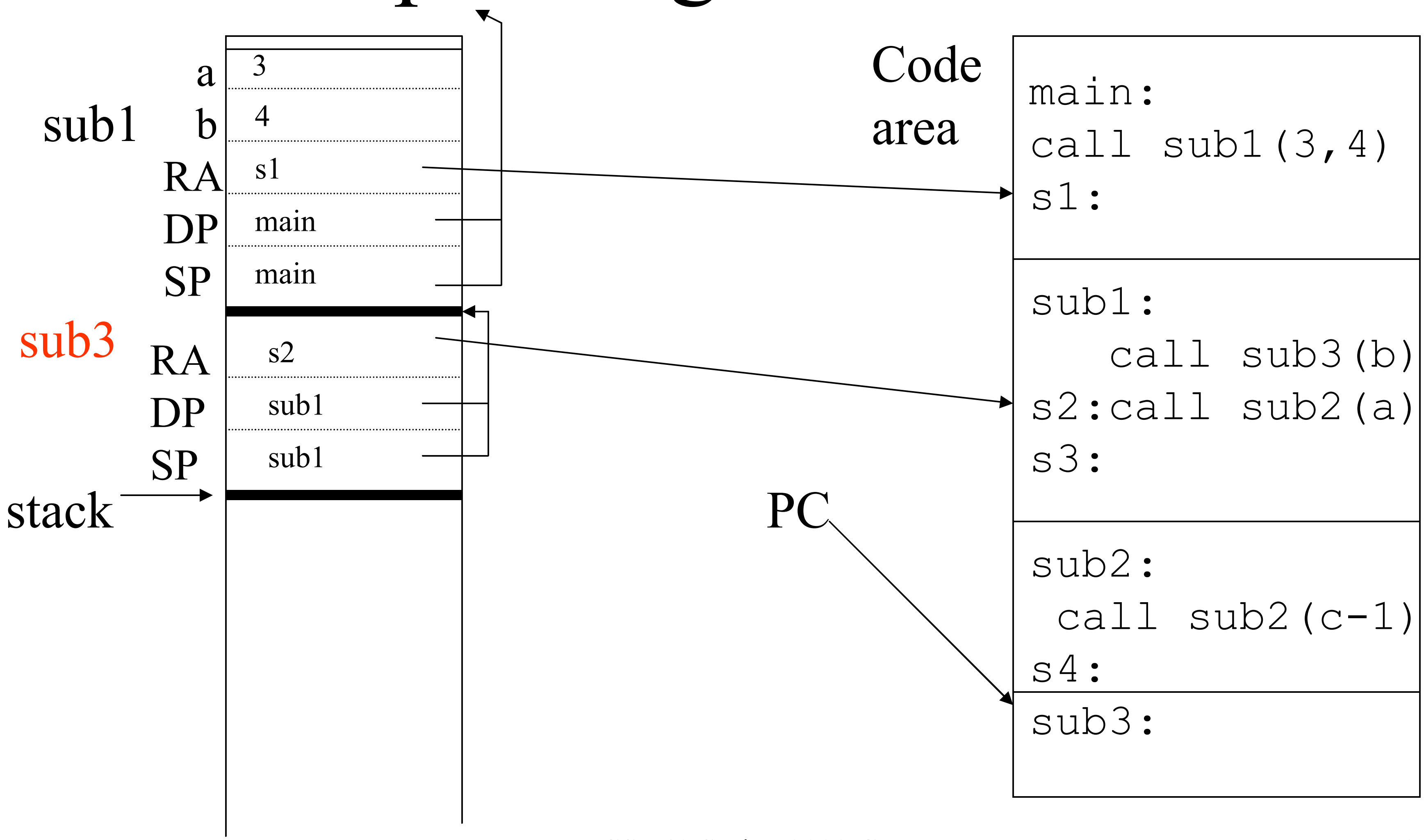
Example Program at runtime 1



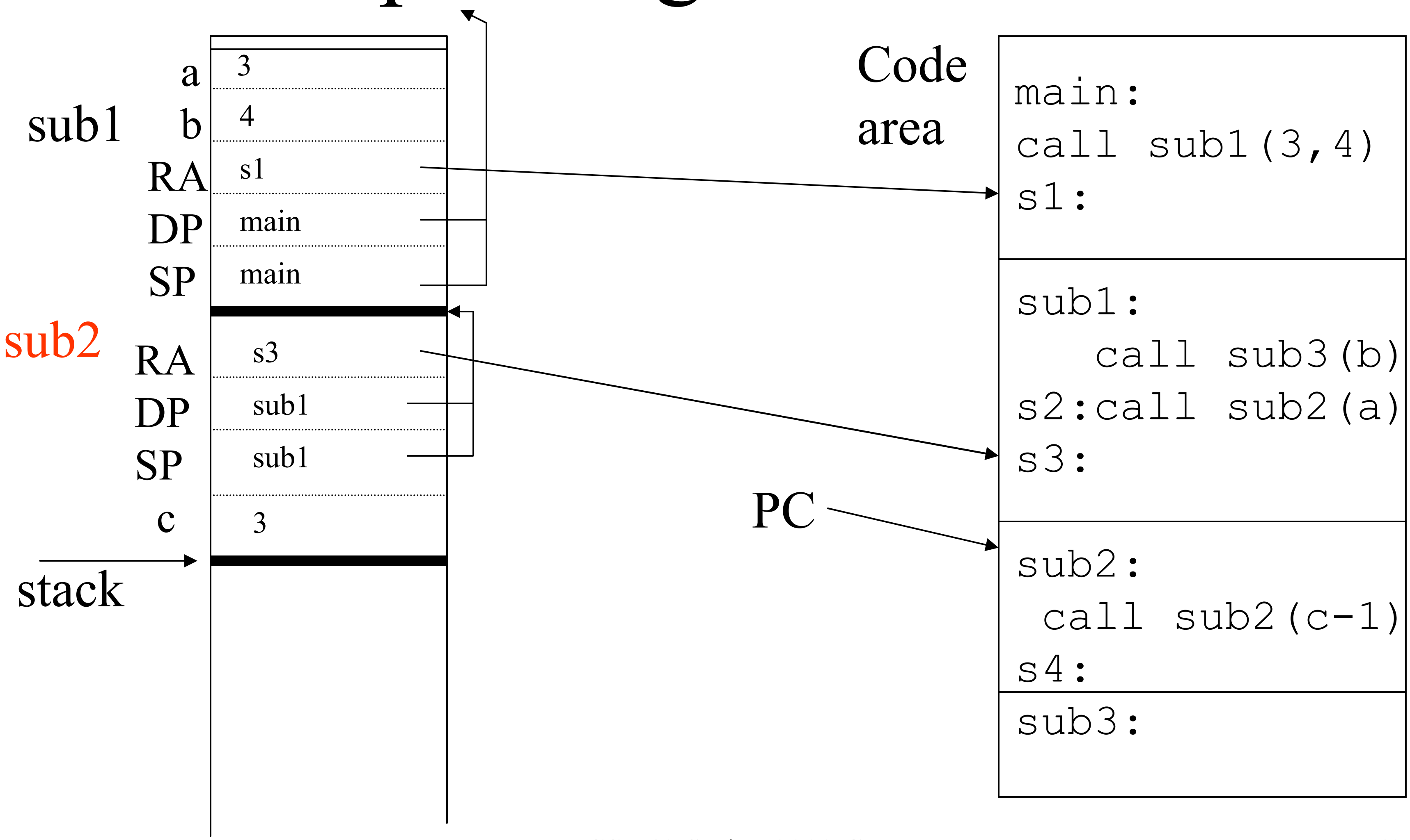
Example Program at runtime 2



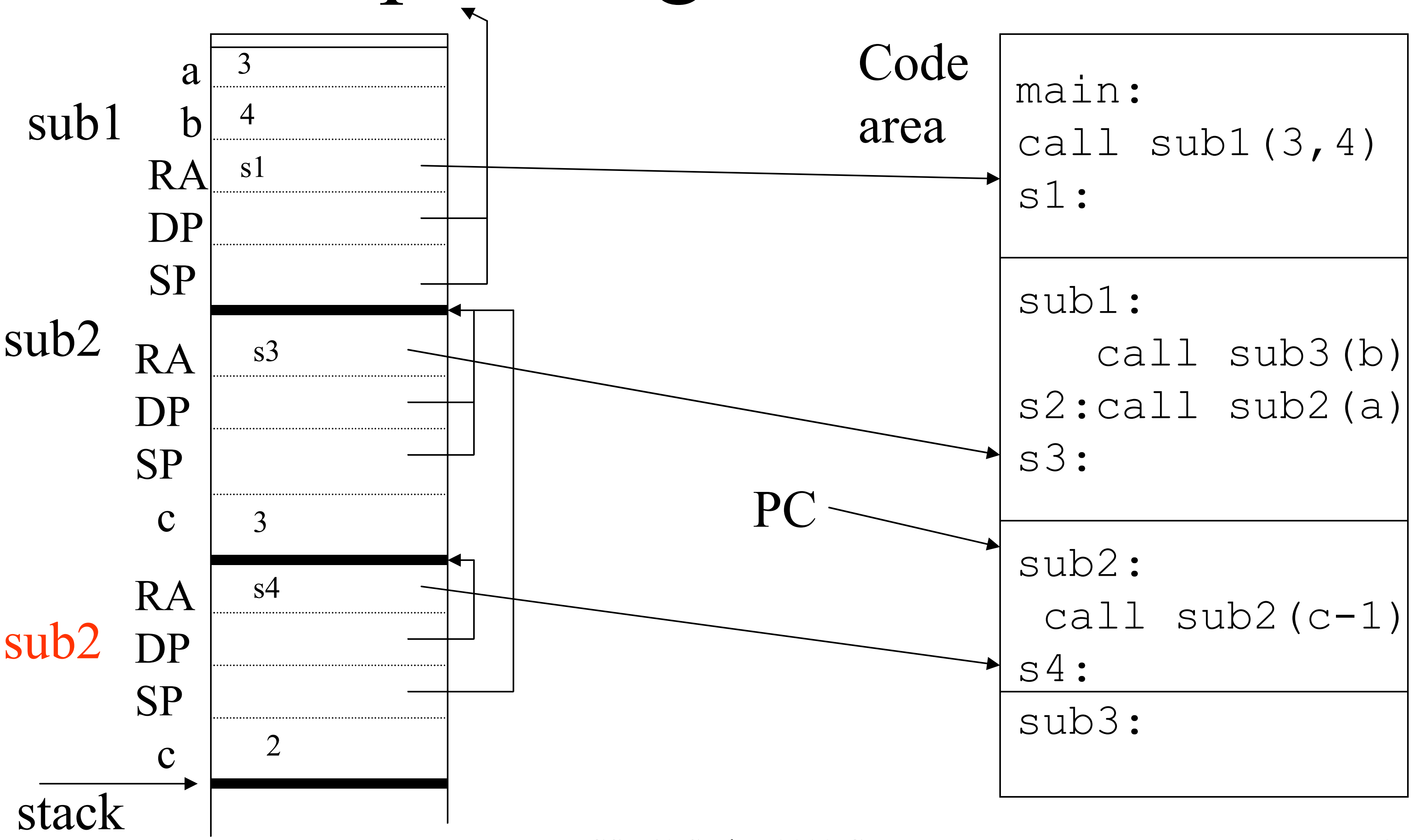
Example Program at runtime 3



Example Program at runtime 4



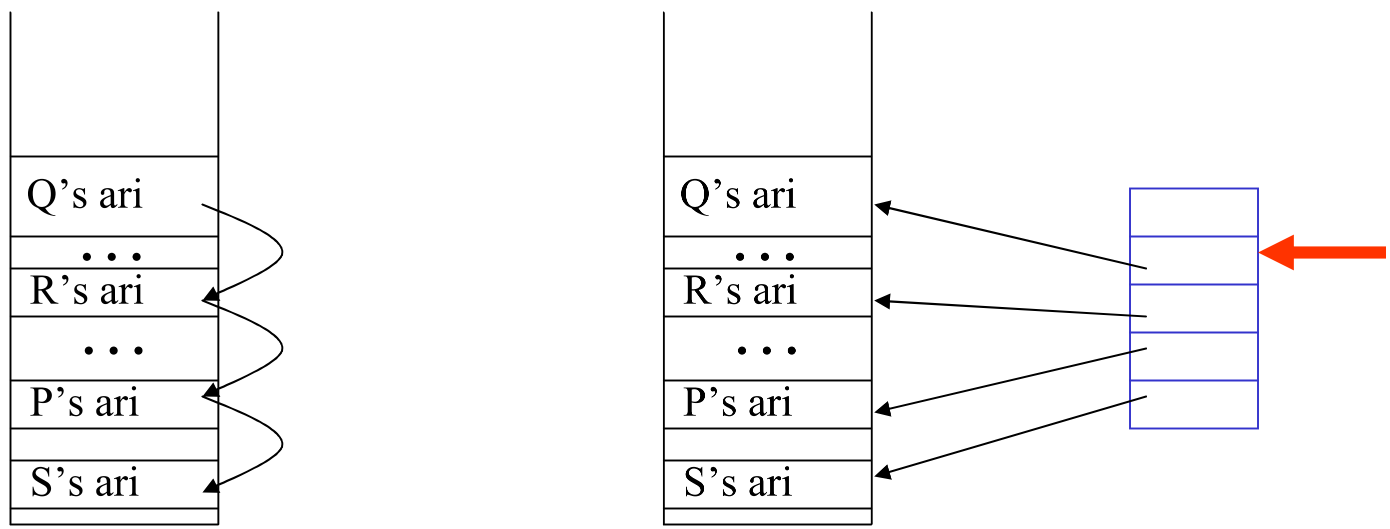
Example Program at runtime 5



Display

Alternate representation for access information.

- The current static chain kept in an array – entry n points to the activation record at level n in the static chain.

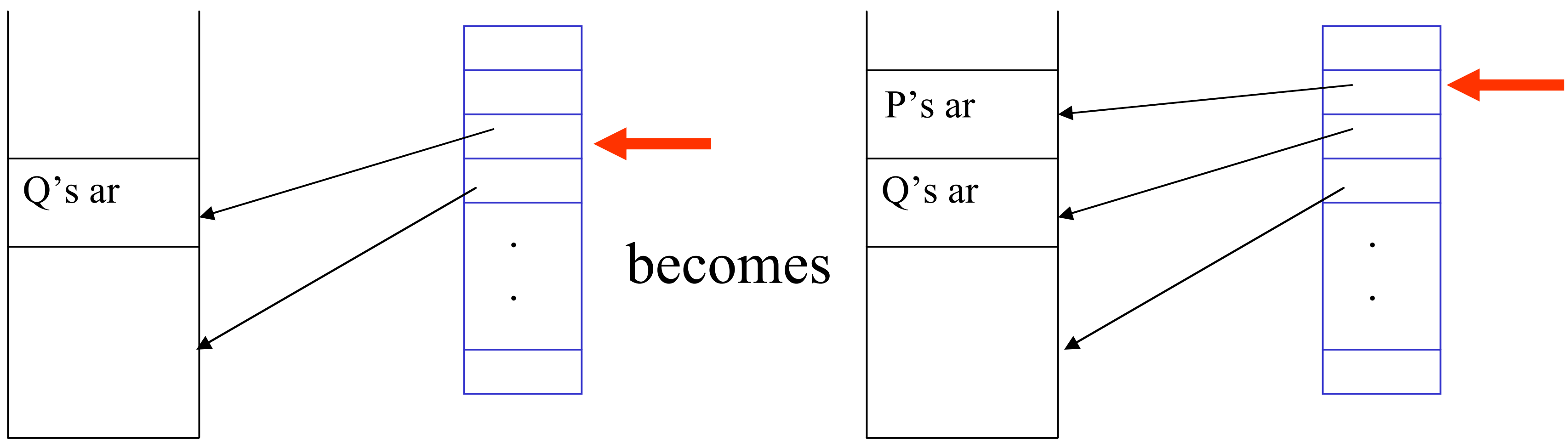


Display Maintenance

For Q calls P …

$Q_{sd} < P_{sd}$ - P must be enclosed directly in Q

If entry n points at Q, entry n+1 points at P



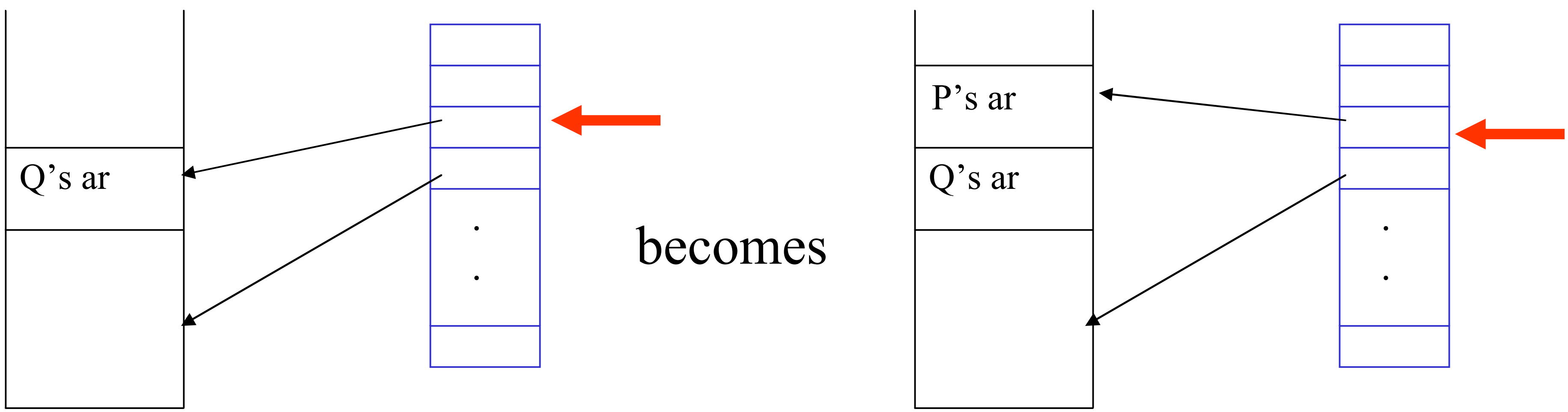
Display Maintenance

For Q calls P …

$Q_{sd} = P_{sd}$ - They are at same static depth

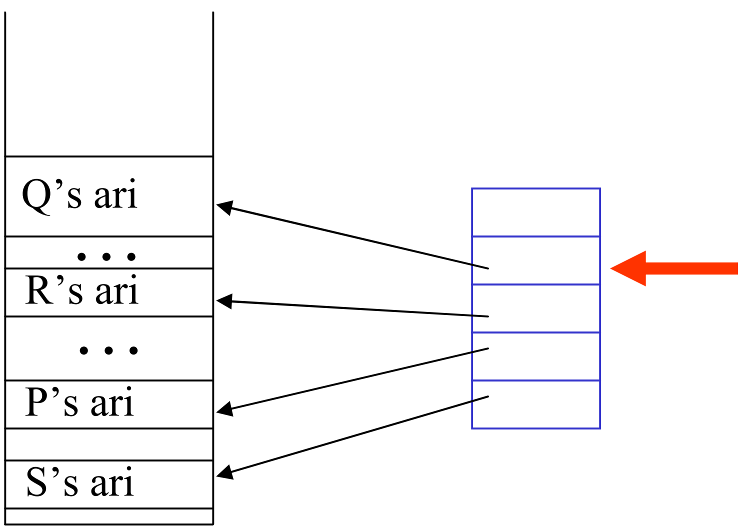
Update entry n to point to P

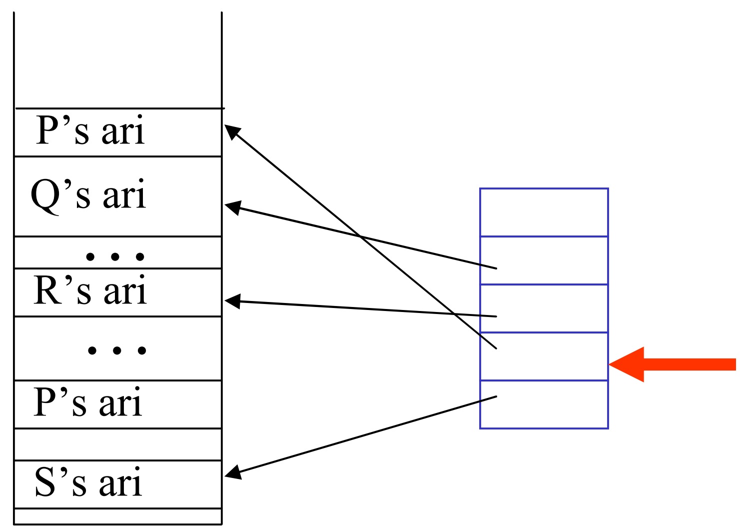
What happens when P ends? Must save the old entry n in P's ar to make things work properly.



Display Maintenance

$Q_{sd} > P_{sd}$ - Q is *n* levels down in the nesting – update that pointer n levels down





Display

- Advantages: faster addressing
- Disadvantages: additional data structure to store and maintain.

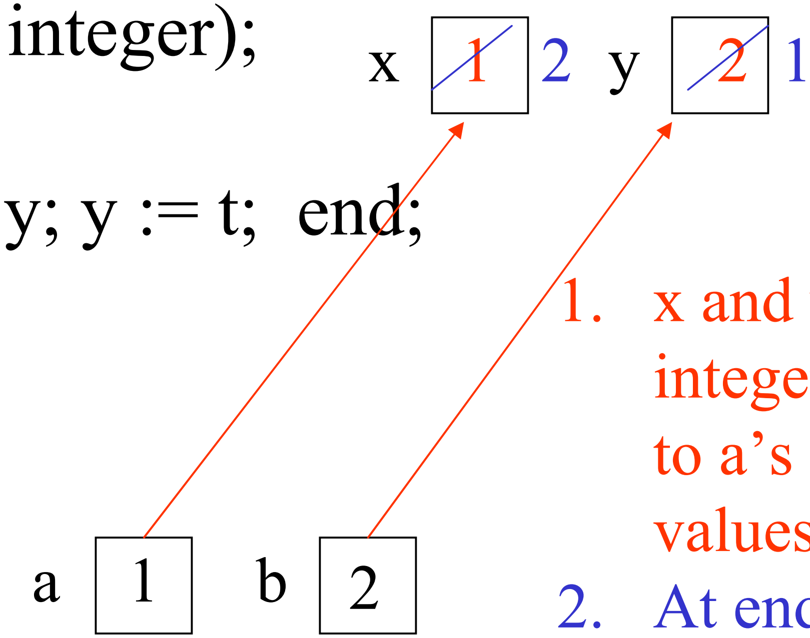
Parameter Passing

Various approaches to passing data into and out of a procedure via parameters

1. **Call-by-value** – data is copied at the callee into activation and any item changes do not affect values in the caller.
2. **Call-by-reference** – pointer to data is placed in the callee activation and any changes made by the callee are indirect references to the actual value in the caller.
3. **Call-by-value-result** (copy-restore) – hybrid of call-by-value and call-by-reference. Data copied at the callee. During the call, changes do not affect the actual parameter. After the call, the actual value is updated.
4. **Call-by-name** – the actual parameter is in-line substituted into the called procedure. This means it is not evaluated until it is used.

Call-by-value

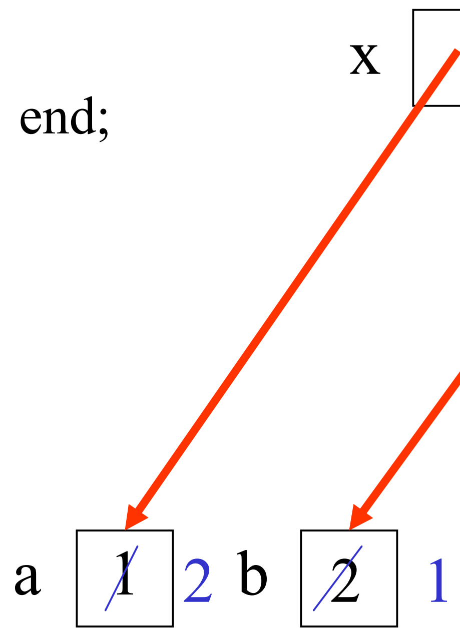
```
var a,b : integer
    procedure s (x,y : integer);
    var t: integer;
    begin  t := x; x := y; y := t;  end;
a := 1;  b := 2;
s (a,b);
write ('a = ',a);
write ('b = ',b);
end.
```



1. x and y are integers initialized to a's and b's values
2. At end of s, x = 2 and y = 1
3. No change to a and b on return

Call-by-reference

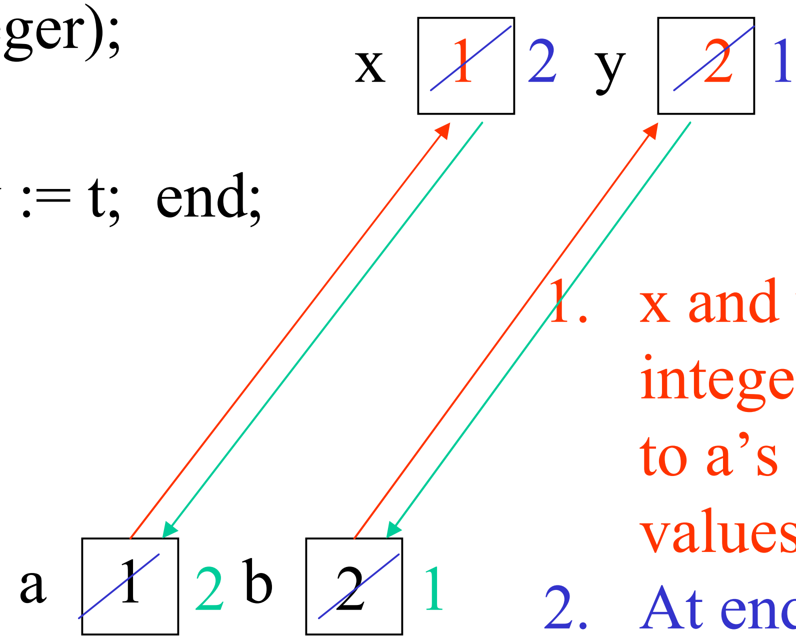
```
var a,b : integer
   procedure s (x,y : integer);
   var t: integer;
   begin  t := x; x := y; y := t;  end;
begin
a := 1;  b := 2;
s (a,b);
write ('a = ',a);
write ('b = ',b);
end.

begin
```



1. Pointers x and y are initialized to a's and b's addresses
2. At end of s, x (and a) = 2 and y (and b) = 1

Call-by-value/result

```
var a,b : integer
   procedure s (x,y : integer);
   var t: integer;
   begin  t := x; x := y; y := t;  end;
begin
a := 1;  b := 2;
s (a,b);
write ('a = ',a);
write ('b = ',b);
end.
```



1. x and y are integers initialized to a’s and b’s values
2. At end of s, x = 2 and y = 1
3. At return, a is given x’s value and b is give y’s value

Call-by-name

```
var a,b : integer
   procedure s (x,y : integer);
   var t: integer;
   begin  t := x; x := y; y := t;  end;
begin
a := 1;  b := 2;
s (a,b);
write ('a = ',a);
write ('b = ',b);
end.
```

```
procedure s
var t: integer;
   begin  t := a; a := b; b := t;  end;
```

a $\boxed{\cancel{1}}$ 2 b $\boxed{\cancel{2}}$ 1

begin

Call-by-value-result vs. Call-by-reference

```
var a: integer
   procedure foo(x: integer);
   begin  a := a + 1; x := x + 1;  end;
begin
a := 1;
foo(a);
write ('a = ',a);
end.
```

	Value-result	reference
write(a)	2	3