COMP3048: Lecture 14

Run-Time Organisation I

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This Lecture

One aspect of run-time organisation:
stack-based storage allocation

- Lifetime and storage
- Basic stack allocation:
  - stack frames
  - dynamic links
- Allocation for nested procedures:
  - non-local variable access
  - static links

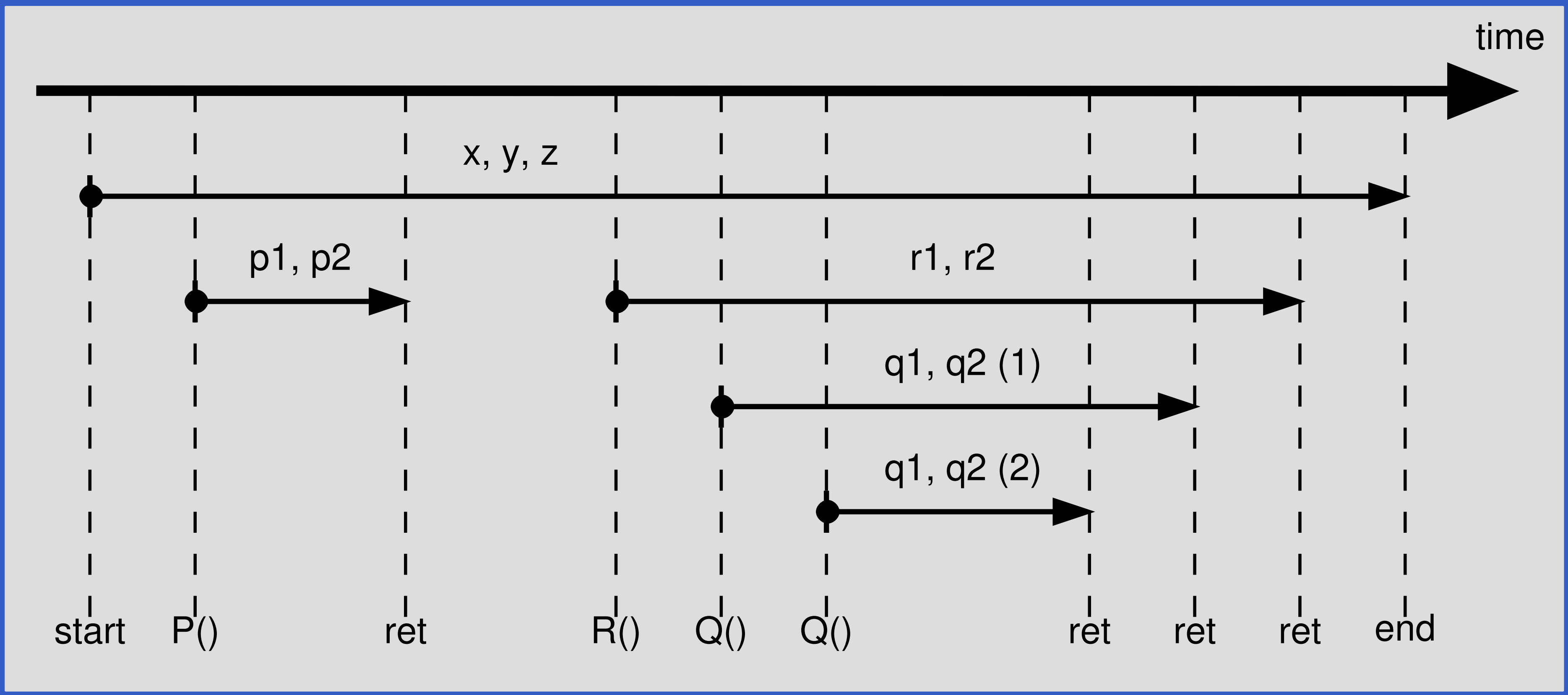
Storage Areas

- ***Static storage***: storage for entities that live throughout an execution.
- ***Stack storage***: storage allocated dynamically, but deallocation must be carried out in the opposite order to allocation.
- ***Heap storage***: region of the memory where entities can be allocated and deallocated dynamically as needed, in any order.

Example: Lifetime (1)

```
var x, y, z: ...
proc P()
    var p1, p2: ...
    begin ... end
proc Q()
    var q1, q2: ...
    begin ... if ... Q(); ... end
proc R()
    var r1, r2: ...
    begin ... Q() ... end
begin ... P() ... R() ... end
```

Example: Lifetime (2)



Example: Lifetime (3)

```
private static Integer foo(int i) {
    Integer n = new Integer(i);
    return n;
}
```

- The lifetimes of `i` and `n` coincides with the invocation of `foo`.
- The lifetime of the integer ***object*** created by `new` starts when `new` is executed and ends when there are no more references to it.
- The integer object thus ***survives*** the invocation of `foo`.

Storage Allocation (1)

- ***Global variables*** exist throughout the program's run-time.
- Where to store such variables can thus be decided ***statically***, at compile (or link) time, once and for all.

Example:

```
private static String [] tokenTable = ...
```

Storage Allocation (2)

- ***Arguments*** and ***local variables*** exist only during a function (or procedure or method) invocation:
  - Function calls are properly nested.
  - In case of ***recursion***, a function may be ***re-entered*** any number of times.
  - Each function activation needs a private set of arguments and local variables.
- These observations suggest that storage for arguments and local variables should be allocated on a ***stack***.

Storage Allocation (3)

- When the lifetime does not coincide with procedure/function invocations, ***heap allocation*** is needed. E.g. for:
  - objects in object-oriented languages
  - function closures in languages supporting functions as first class entities
  - storage allocated by procedures like `malloc` in C.
- Such storage either ***explicitly deallocated*** when no longer needed, or ***automatically reclaimed*** by a garbage collector.

Stack Frames

One ***stack frame*** or ***activation record*** for each currently active function/procedure/method.

Contents:

- Arguments
- Bookkeeping information; e.g.
  - Return address
  - Dynamic link
  - Static link
- Local variables
- Temporary workspace

Defining the Stack

The stack is usually defined by a handful of registers, dictated by the CPU architecture and/or convention. For example:

- ***SB***: Stack Base
- ***ST***: Stack Top
- ***LB***: Local Base

The names vary. Stack Pointer (SP) and Frame Pointer (FP) are often used instead of ST and LB, respectively.

Typical Stack Frame Layout

address	contents
`LB` $-$ *argOffset*	arguments
...	...
`LB`	static link
`LB + 1`	dynamic link
`LB + 2`	return address
`LB + 3`	local variables
...	...
`LB` + *tempOffset*	temporary storage

where

$$\begin{aligned} argOffset &= \mathrm{size}(arguments) \\ tempOffset &= 3 + \mathrm{size}(local\ variables) \end{aligned}$$

TAM uses this convention. (Word (e.g. 4 bytes) addressing assumed, offsets in ***words***.)

Example: A function f

(Not quite current MiniTriangle, but language could easily be extended in this way.)

```
var n: Integer;
...
fun f(x,y: Integer): Integer =
    let
        z: Integer
    in begin
        z := x * x + y * y;
        return n * z
    end
```

Example: Calling `f`

Call sequence for `f(3,7) * 8`:

```
2015    LOADL 3      ;  1st arg. (x)
2016    LOADL 7      ;  2nd arg. (y)
2017    CALL  f
2018    LOADL 8
2019    MUL
```

Address of each instruction explicitly indicated to the left. Address of `f` here given symbolically by a label. Corresponds to the address where the code for `f` starts, say 2082.

Example: Stack layout on entry to `f`

On entry to `f`; caller's `ST` = `f`'s `LB`:

address	contents
...	...
`SB + 42`	`n`: n
...	...
`LB - 2`	`x`: 3
`LB - 1`	`y`: 7
`LB`	static link
`LB + 1`	dynamic link
`LB + 2`	return address $= 2018$

Ret. addr. $=$ old program counter (PC) $=$ addr. of instruction immediately after the call instruction.
New PC $=$ address of first instruction of `f` $=$ 2082.

Example: TAM Code for `f`

TAM-code for the function `f` (at address 2082):

```
LOADL 0                     ADD
LOAD   [LB - 2]; x          STORE    [LB + 3] ; z
LOAD   [LB - 2]; x          LOAD     [SB + 42]; n
MUL                         LOAD     [LB + 3] ; z
LOAD   [LB - 1]; y          MUL
LOAD   [LB - 1]; y          POP      1 1
MUL                         RETURN   1 2
```

`RETURN` replaces activation record (frame) of `f` by result, restores LB, and jumps to ret. addr. (2018).

Note: all variable offsets are ***static***.

Dynamic and Static Links

- ***Dynamic Link***: Value to which `LB` (Local Base) is restored by `RETURN` when exiting procedure; i.e. addr. of ***caller's frame*** = old `LB`:
  - "Dynamic" because depends on where function was called from.
- ***Static Link***: Base of underlying frame of function that ***immediately lexically encloses*** this one.
  - "Static" because depends on the program's structure and not on its execution.
  - Used to determine addresses of variables of lexically enclosing functions.

Example: Stack Allocation (1)

```
let
   var a: Integer[3];
   var b: Boolean;
   var c: Character;

   proc Y ()
      let
         var d: Integer;
         var e: record c: Character, n: Integer end
      in
         ...;
   proc Z ()
      let
         var f: Integer
      in
         begin ...; Y(); ... end
in
   begin ...; Y(); ...; Z(); ... end
```

Example: Stack Allocation (2)

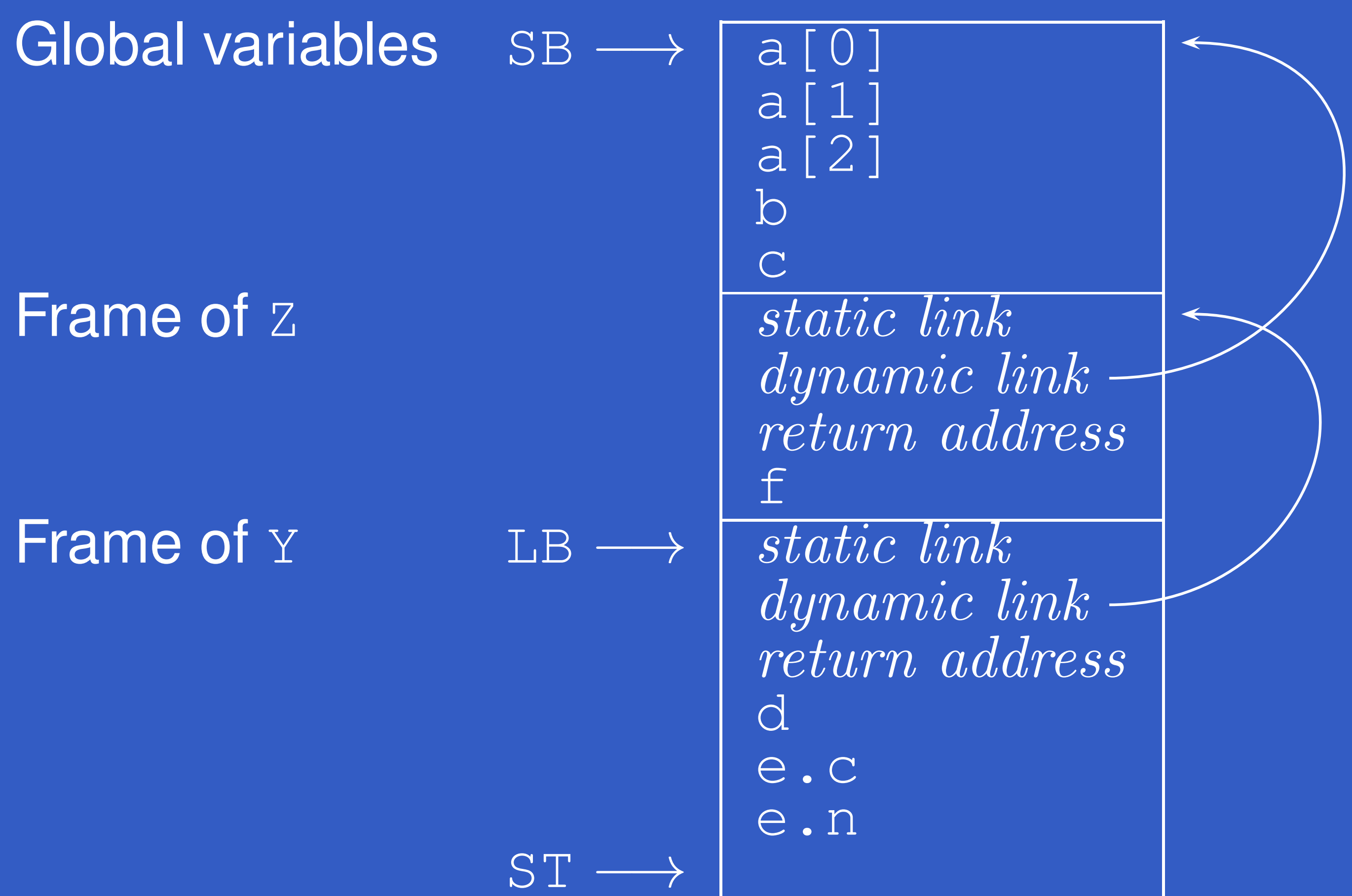
Initially LB = SB; i.e., the global variables constitute the frame of the main program.

Call sequence: main $\longrightarrow$`Y` (i.e. after main calling `Y`):

Global variables	`SB` $\longrightarrow$	`a[0]`
		`a[1]`
		`a[2]`
		`b`
		`c`
Frame of `Y`	`LB` $\longrightarrow$	*static link*
		dynamic link
		return address
		`d`
		`e.c`
		`e.n`
	`ST` $\longrightarrow$	

Example: Stack Allocation (3)

Call sequence: main $\rightarrow$ `Z` $\rightarrow$ `Y`:



Exercise: Stack Allocation

Global variables	SB $\longrightarrow$	`a[0]`
		`a[1]`
		`a[2]`
		`b`
		`c`
Frame of `Z`		*static link*
		dynamic link
		return address
		`f`
Frame of `Y`	LB $\longrightarrow$	*static link*
		dynamic link
		return address
		`d`
		`e.c`
		`e.n`
	ST $\longrightarrow$	

In `Y`, what is the address of: `b`? `e.c`? `f`?

Non-Local Variable Access (1)

Consider ***nested*** procedures:

```
proc P()
    var x, y, z: Integer
    proc Q()
        ...
        begin ... if ... Q() ... end
    proc R()
        ...
        begin ... Q() ... end
    begin ... Q() ... R() ... end
```

`P`'s variables are in scope also in `Q` and `R`.
But how to access them from `Q` or `R`?
Neither global, nor local!
Belong to the ***lexically enclosing procedure***.

Non-Local Variable Access (2)

In particular:

- We cannot access `x`, `y`, `z` relative to the stack base (`SB`) since we cannot (in general) statically know if `P` was called directly from the main program or indirectly via one or more other procedures.
- I.e., there could be arbitrarily many stack frames ***below*** `P`'s frame.

Non-Local Variable Access (3)

- We cannot access `x`, `y`, `z` relative to the local base (`LB`) since we cannot (in general) statically know if e.g. `Q` was called directly from `P`, or indirectly via `R` and/or recursively via itself.
- I.e., there could be arbitrarily many stack frames ***between*** `Q`'s and `P`'s frames.

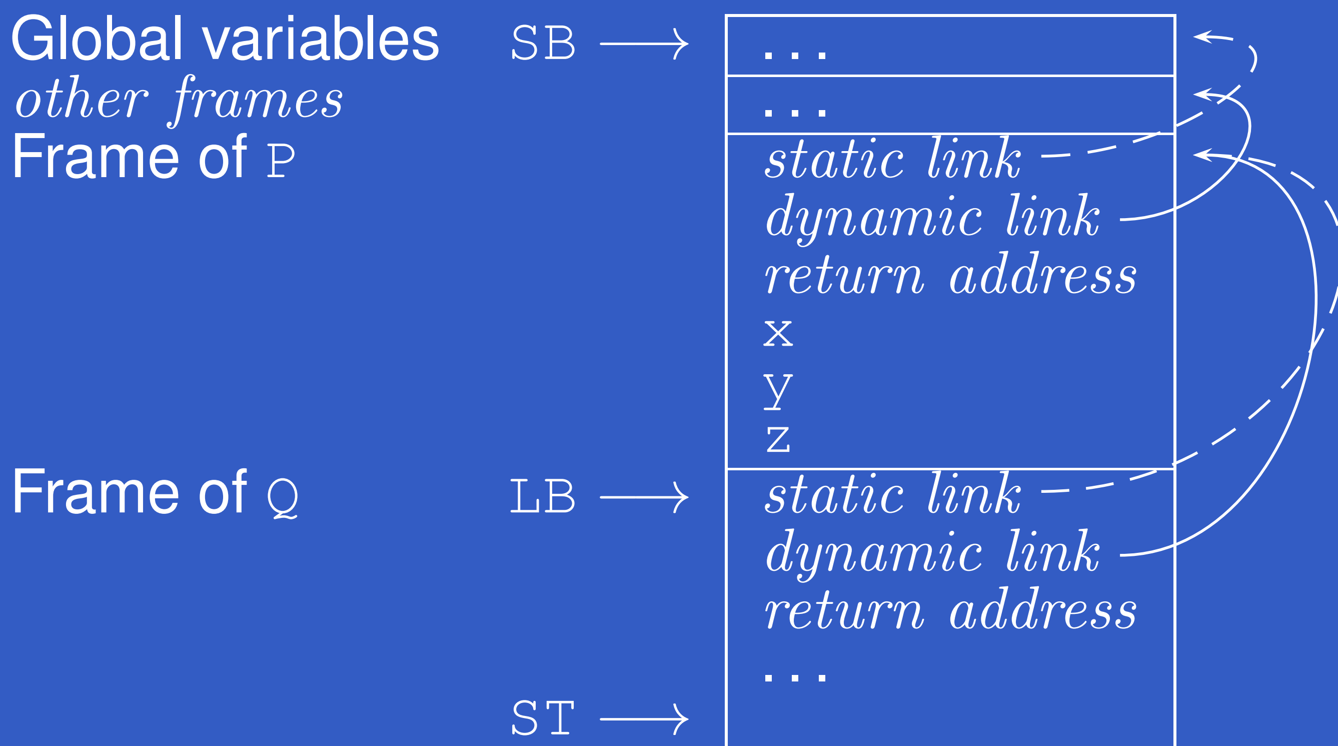
Non-Local Variable Access (4)

Answer:

- The ***Static Links*** in `Q`'s and `R`'s frames are set to point to `P`'s frame on each activation.
- The static link in `P`'s frame is set to point to the frame of ***its*** closest lexically enclosing procedure, and so on.
- Thus, by following the chain of static links, one can access variables at any level of a nested scope.

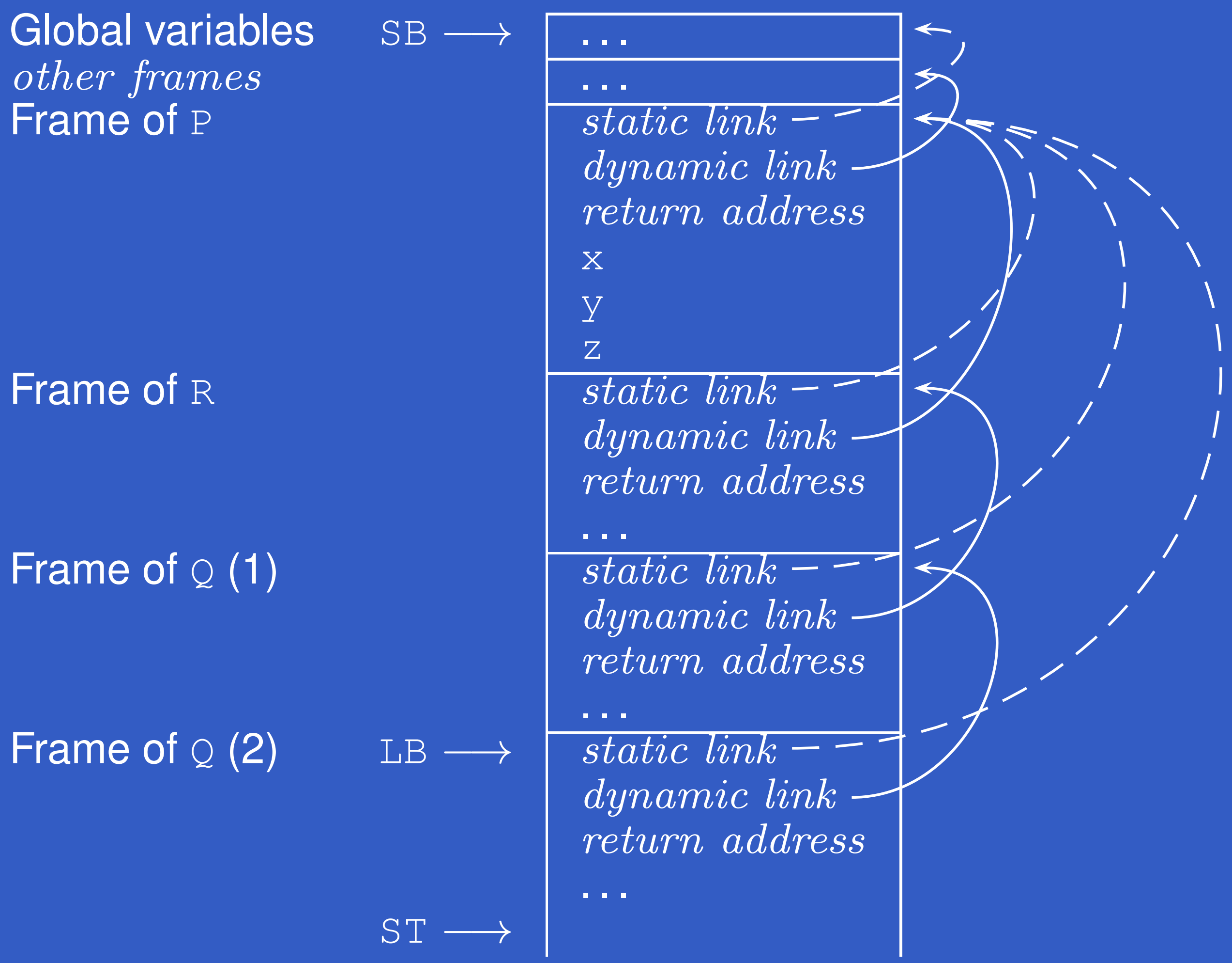
Non-Local Variable Access (5)

Call sequence: main $\rightarrow \ldots \rightarrow$ P $\rightarrow$ Q:



Non-Local Variable Access (6)

Call sequence: main $\rightarrow \ldots \rightarrow$ P $\rightarrow$ R $\rightarrow$ Q $\rightarrow$ Q:



Non-Local Variable Access (7)

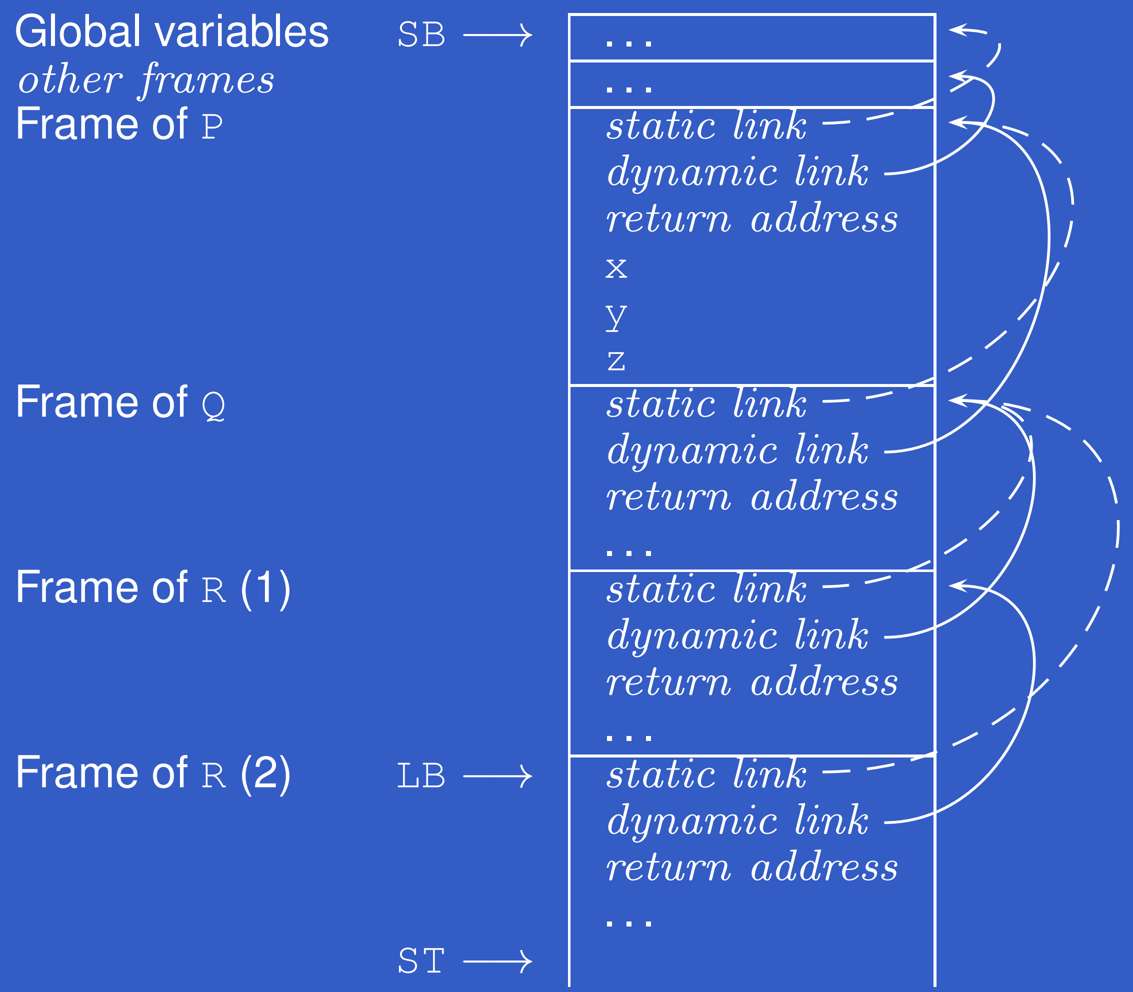
Consider further levels of nesting:

```
proc P()
    var x, y, z: Integer
    proc Q()
        proc R()
            ...
            begin ...if ...  R() ...  end
        ...
        begin ...  R() ...  end
    begin ...  Q() ...  end
```

Note: `Q`’s variables now in scope in `R`.
To access, compute the ***difference between scope levels*** of the accessing procedure/function and the accessed variable (***note: static information***), and follow that many static links.

Non-Local Variable Access (8)

Call sequence: main $\rightarrow \ldots \rightarrow$ P $\rightarrow$ Q $\rightarrow$ R $\rightarrow$ R:



Non-Local Variable Access (9)

TAM code, P calling Q: Q's static link = P's local base, pushed onto stack prior to call:

```
LOADA    [LB + 0]     ; Q's static link
LOADCA   #1_Q         ; Address of Q
CALLI
```

TAM code, R calling iteself recursively: copy of R's static link (as calle's and caller's scope levels are the same) pushed onto stack prior to call:

```
LOAD     [LB + 0]     ; R's static link
LOADCA   #2_R         ; Address of R
CALLI
```

Non-Local Variable Access (10)

Accessing `y` in `P` from within `R`; scope level difference is 2:

```
LOAD    [LB + 0]    ; R's static link
LOADI   0           ; Q's static link
LOADI   4           ; y at offset 4 in P's frame
```