G53CMP: 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

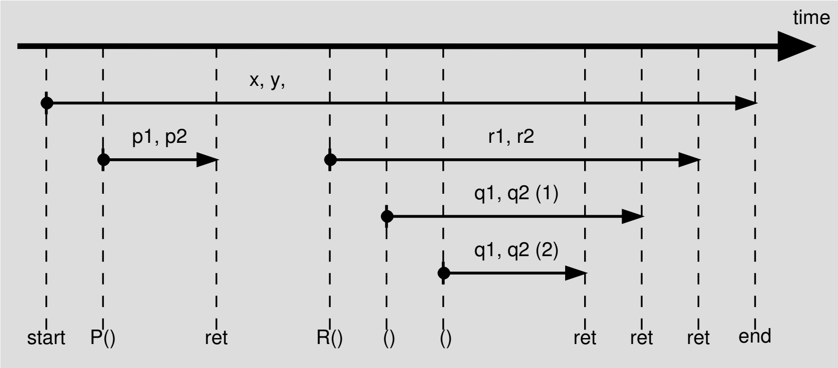
Storage Areas

- ***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: ...
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

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

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 related to dynamic call graph.
- ***Static Link***: Base of underlying frame of function that ***immediately lexically encloses*** this one.
  - "Static" because related to program's static structure.
  - Used to determine addresses of variables of lexically enclosing functions.

Example: Stack Allocation (1)

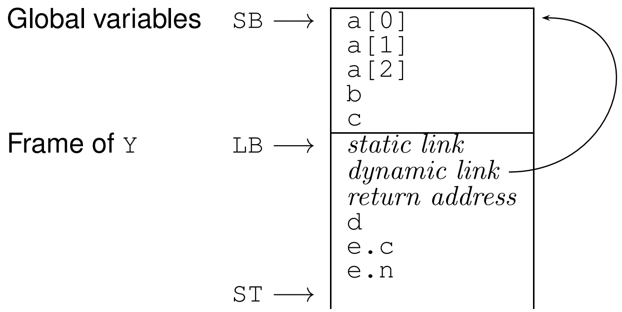
```
let
   var a: Integer[3];
   var b: Boolean;
   var c: Character;

   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)

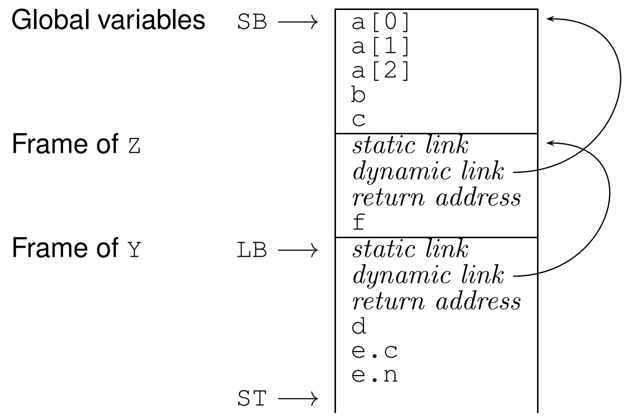
Initially LB = SB; i.e., the global variables constitute the frame of the main program.

Call sequence: main →`Y` (i.e. after main calling `Y`):

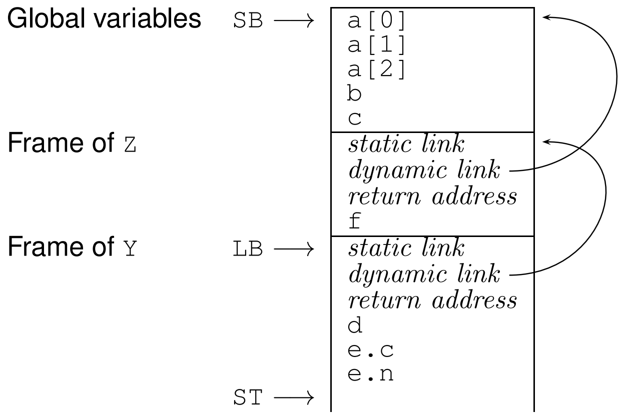


Example: Stack Allocation (3)

Call sequence: main →`Z` →`Y`:



Exercise: Stack Allocation



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.

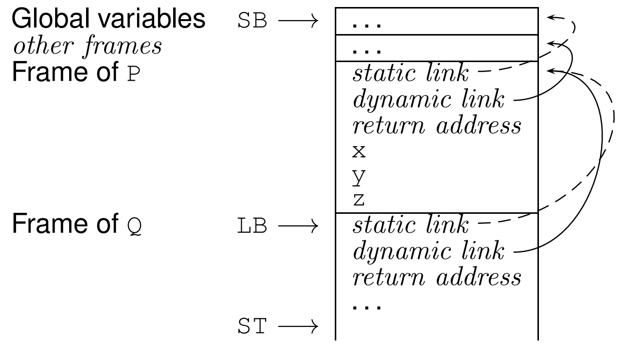
Non-Local Variable Access (4)

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.

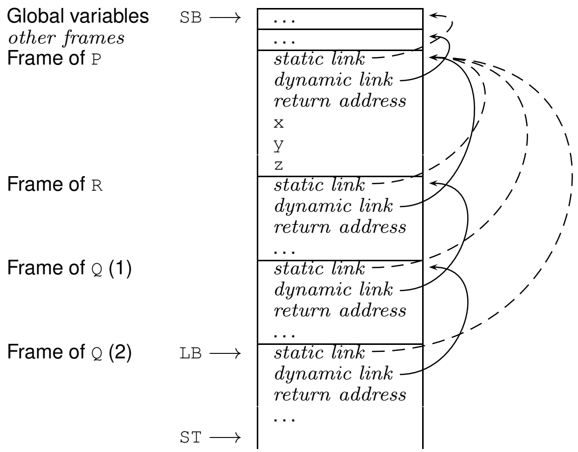
Non-Local Variable Access (5)

Call sequence: main →. . . →P →Q:



Non-Local Variable Access (6)

Call sequence: main →. . . →P →R →Q →Q:



Non-Local Variable Access (7)

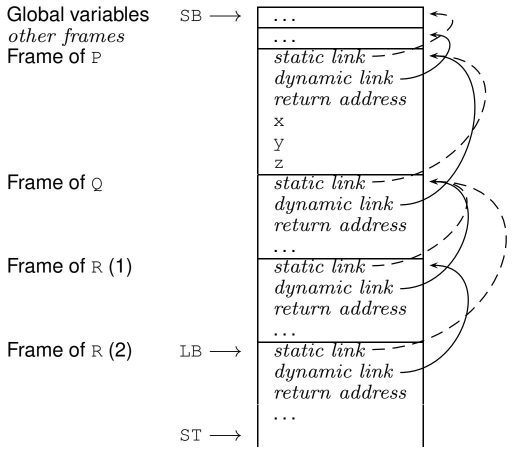
Consider further levels of nesting:

```
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 →. . . →P →Q →R →R:



Example: Call with Static Link

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 callee'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
```


Example: Non-local Access

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
```


Code Generation (1)

```
evaluate majl env (ExpVar {evVar = itms}) =
    case lookupISV itms env of
        ISVDisp d ->
            address majl vl d
        ISVLbl l -> do
            staticLink majl vl
            emit (LOADCA l)
    where
        vl = majScopeLvl (itmsLvl itms)
```

Note: A label represents a procedure or function; what is pushed onto stack is effectively the corresponding ***closure*** (see later slide).

Code Generation (2)

```
address :: Int -> Int -> MTInt -> TAMCG ()
address cl vl d
    | vl == topMajScopeLvl =
        emit (LOADA (SB d))
    | cl == vl =
        emit (LOADA (LB d))
    | cl > vl  = do
        emit (LOAD (LB sld))
        emitN (cl - vl - 1) (LOADI sld)
        emit (LOADL d)
        emit ADD
    | otherwise = error "Bug: Not in scope!"
```

Variable Scope Level (vl)

Current Scope Level (cl)

Code Generation (3)

```
staticLink :: Int -> Int -> TAMCG ()
staticLink crl cel
    | cel == topMajScopeLvl =
        emit (LOADL 0)
    | crl == cel =
        emit (LOADA (LB 0))
    | crl > cel  = do
        emit (LOAD (LB sld))
        emitN (crl - cel - 1) (LOADI sld)
    | otherwise =
        error "Bug: Not in scope!"
```

Callee Scope Level (cel)

Caller Scope Level (crl)

Closures (1)

A ***closure***:

- Code for function or procedure; and
- Bindings for all its free variables.

Under the present scheme:

- Code: Address of function or procedure;
- Bindings: Chain of stack-allocated activation records linked by the static links.

Works only when closure does not survive the activation of the function/procedure where it was created. ***Cannot*** support first-class functions/procedures!

Closures (2)

- Functions/procedures are ***first class*** if they can be handled just like any other values; e.g.
  - bound to variables
  - passed as arguments
  - ***returned*** as results.
- Supporting first-class functions/procedures requires closures to be ***heap-allocated***:
  - Code still just address of function or procedure.
  - Static link replaced by (pointer(s) to) heap-allocated activation record(s).

Closures (3)

- As an optimisation, one could imagine combined schemes: stack allocation and static links might be used when known that a closure will never survive activation of enclosing function/procedure.