Tiger Runtime Environments

- ***Compile-time environments*** *are just symbol tables; they are used to assist static semantic analysis, code generation and code optimization.*
- ***Run-time environments*** *are about how to map each runtime value into the memory? more specifically, here are the main issues*

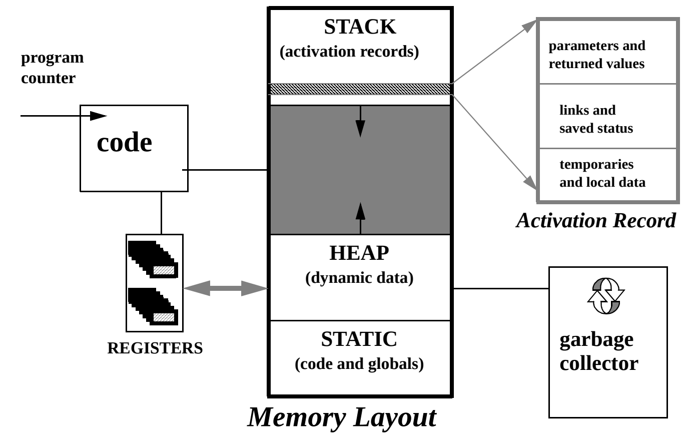
  how to implement procedure (or function) call ?   --- stack frames
  (activation records, access to non-local variables, parameter passing,...)

  what are the data representations ?
  (primitive data type, records, arrays, dynamic data structure, ...)

  what are the memory layout (i.e., storage organization) ?
  (where to put the static data, code segments, stack, heap?)

  how to do the memory allocation and de-allocation ?
  (malloc-free package, garbage collection, ...)

Typical Runtime Layout

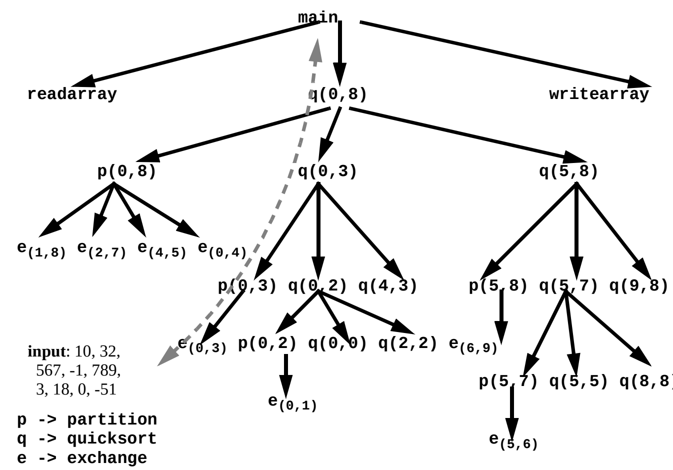


Example: Nested Functions

```
let type intArray = array of int
    var a := intArray [9] of 0
    function readarray () = ...
    function writearray () = ...
    function exchange(x : int, y : int) =
       let var z := a[x] in a[x] := a[y]; a[y] := z end

    function quicksort(m : int, n : int) =
       let function partition(y : int, z : int) : int =
              let var i := y          var j := z + 1
               in (while (i < j) do
                     (i := i+1; while a[i] < a[y] do i := i+1;
                      j := j-1; while a[j] > a[y] do j := j-1;
                      if i < j then exchange(i,j));
                   exchange(y,j); j)
              end

        in if n > m then (let var i := partition(m,n)
                           in quicksort(m, i-1);
                              quicksort(i+1, n)
                          end)
       end
 in readarray(); quicksort(0,8); writearray()
end
```

input: 10, 32, 567, -1, 789, 3, 18, 0, -51

Activation Trees



Activations

- *Each function (or procedure)* ***declaration*** *associates a* ***name*** *with a function body --------- this binding is done at compile time.*
- *An* ***activation*** *is created during runtime execution when the function (or procedure) is invoked. The* ***lifetime*** *of an activation is the time between execution of the 1st operation of the body and through the last operation.*
- *Activations are either* ***nested*** *or* ***non-overlapping.*** *If two activations are* ***nested****, then one must be the descendant of another. If two activations are non-overlapping, then they must be the siblings.*
- *A function* `f` *is* ***recursive*** *if more than 2 activations of* `f` *is nested.*
- *Program execution is just* ***depth-first traversal*** *of activation tree !*

How to implement depth-first traversal ?

Activation Record

- *An* ***activation record*** *is* ***constructed*** *when a function (or a procedure) is called (activated); it is* ***destroyed*** *when the function returns; the interim is the* ***lifetime*** *of the activation.*
- *The activation record often contains the following:*

  relevant machine state (saved registers, return address)

  space for local data, including temporaries

  space for return value

  space for outgoing arguments

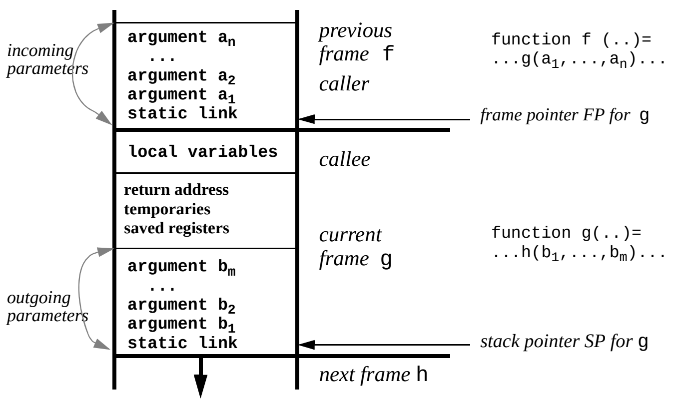
  control link: pointer to caller's activation record (optional)

  static link: pointer to activation for accessing **non-local** data

- ***Main problem****: how to* ***layout*** *the activation record so that the caller and callee can* ***communicate*** *properly ?*

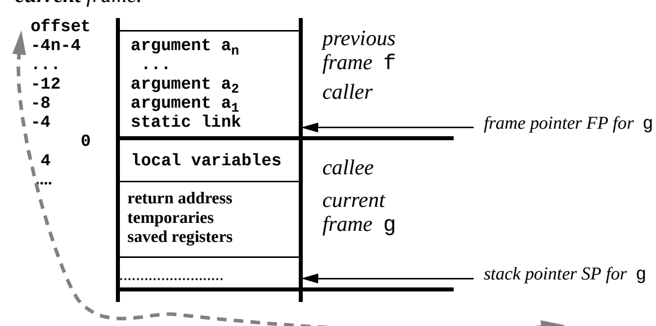
Stack Frames

- *The most common (and standard) way is to allocate activation records on a sequential stack --- using the following* ***standard frame layout.***



Stack Frames (cont'd)

- ***Frame Pointer*** *(FP) is a pointer that points to the start of the* ***current*** *frame;* ***Stack Pointer*** *(SP) --- referring to the top of the stack ---- points to the end of the* ***current*** *frame.*



All `g`*'s arguments and local variables are accessed through FP !*

Typical Calling Sequence

- ***Question**: Suppose function* `f` *calls function* `g(a1,...,an)`, *what will happen at runtime ? how* `f` *and* `g` *communicate ? Assuming FP and SP are in two registers.*
- ***1. Call sequence** (done by the **caller*** `f` *before entering* `g` *)*

  `f` puts arguments `a1,...,an` onto the stack (or in registers)
  `f` puts function `g's` static link onto the stack (or in a register)
  `f` puts the return address of this call to `g` onto the stack (or in a register)
  `f` puts current FP onto the stack (i.e., control link, optional)
  Jump to `g`'s code

- ***2. Entry sequence** (the first thing done after entring the **callee*** `g` *)*

  move SP to FP
  decrement SP by the frame size of `g` (stack grows downwards!!!)
  (optional: save callee-save registers if any)

Typical Calling Sequence (cont'd)

- ***3. Return sequence** (the **callee*** `g` *exits and returns back to* `f` *)*

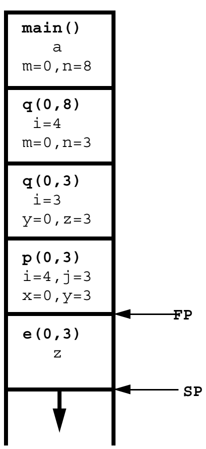
  put the return result into a designated register
  (optional: restore calleesave registers if any)
  fetch the return address to a register (if in register, do nothing)
  fetch the saved FP of `f` back to the FP register
  increment SP by the frame size of `g` (pop off the activation of `g`)
  Return back to `f`

- ***Tiger Specifics** (also true for many other modern compilers)*

  return address is put in a designated register
  only maintain SP at runtime (FP is a "virtual" reg. = SP - framesize)
  (when implementing Tiger, frame-size of each function is a compile-time constant)

- *Must maintain a separate FP and SP if (1) the frame size of a function may vary (2) the frames are not always contiguous (e.g., linked list)*

A Snapshot of Running Quicksort



- ***Remaining questions**: how to find the value of local variables and non-local variables ?*
- ***Local variables** are allocated in the current stack frame --- we can access them through the **Frame Pointer** (notice, the actual value of FP is unknown until runtime, but the each local-variable's offset to FP is known at compile time)*
- ***Non-local variables** must be accessed through the **static link**, or by using some other tricks ......*

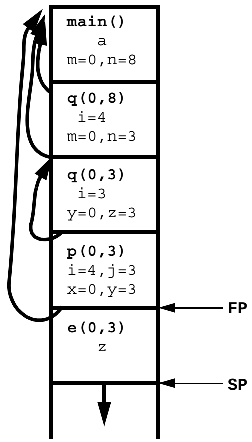
Non-Local Variables

```
1 let type intArray = array of int
      var a := intArray [9] of 0
  2   function readarray () = ...
  2   function writearray () = ...
  2   function exchange(x : int, y : int) =
         let var z := a[x] in a[x] := a[y]; a[y] := z end

  2   function quicksort(m : int, n : int) =
         let function partition(y : int, z : int) : int =
          3    let var i := y          var j := z + 1
                in (while (i < j) do
                      (i := i+1; while a[i] < a[y] do i := i+1;
                       j := j-1; while a[j] > a[y] do j := j-1;
                       if i < j then exchange(i,j));
                    exchange(y,j); j)
               end

          in if n > m then (let var i := partition(m,n)
                             in quicksort(m, i-1);
                                quicksort(i+1, n)
                            end)
         end
   in readarray(); quicksort(0,8); writearray()
  end
```

nesting depth

input: 10, 32, 567, -1, 789, 3, 18, 0, -51

Static Link

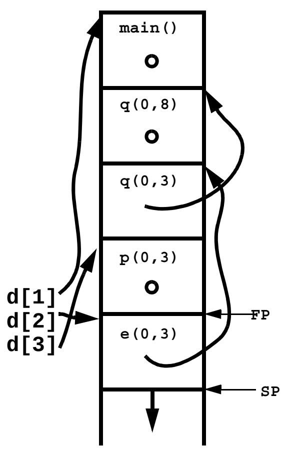


- ***Static link*** *(also called **access link**) is used to implement <u>lexical scoping</u>.*
- *If function **p** is nested **immediately** within **q** in the source code, then the static link in activation of **p** is a point to the **most recent** activation of **q**.*
- *Non-local variable **v** is found by following static links to an activation (i.e, frame) that contains **v***
- *If **v** is declared at depth n_v and accessed in **p** declared at depth n_p, then we need follow n_p-n_v static links*

Static Link (cont'd)

- *Suppose function **q** at depth n_q calls function **p** at depth n_p . The question is how to access non-local variables once we are inside **p** ? or what is the static link inside **p**'s activation.*
- *If $n_q < n_p$, then $n_q = n_p - 1$, **p** is nested within **q**; the static link in **p**'s activation = **q**'s activation; e.g.,* `quicksort` *(2) calls* `partition` *(3).*
- *If $n_q >= n_p$, **p** and **q** must have common calling "prefix" of functions at depths **1, ..., n_p-1;** the static link in **p**'s activation is the activation found by following n_q - n_p + 1 access links in caller **q**; e.g.,* `partition`*(3) calls* `exchange`*(2) --- follow* `3-2+1=2` *links inside* `partition`*'s activation.*
- *Two alternatives to the **static link** method for accessing non-local variables:*
  *1. **Display*** *2. **Lambda-Lifting***

Display



- *One alternative to static link is to maintain pointers to the current activation at depth **k** using a **display** array **d[1...].***
- *Upon **entry** to **p** at depth **k** : save **d[k]** in **p**'s activation; **d[k]** = **p**'s activation*
- *Upon **exit** from **p** at depth **k**: **d[k]** = saved "**d[k]**" inside **p**'s activation*
- ***display** ---- **pros**: faster access, constant call/return cost; **cons**: uses up registers, awkward when functions being passed as arguments.*

Lambda-Lifting

```
let type intArray = array of int
    var a := intArray [9] of 0
    function readarray (a : intArray) = ...
    function writearray (a : intArray) = ...
    function exchange(a : intArray, x : int, y : int) =
       let var z := a[x] in a[x] := a[y]; a[y] := z end
    function quicksort(a: intArray, m : int, n : int) =
       let function partition(a: intArray, y : int, z : int) : int =
              let var i := y          var j := z + 1
               in (while (i < j) do
                     (i := i+1; while a[i] < a[y] do i := i+1;
                      j := j-1; while a[j] > a[y] do j := j-1;
                      if i < j then exchange(i,j));
                   exchange(y,j); j)
              end
        in if n > m then (let var i := partition(a,m,n)
                           in quicksort(a, m, i-1);
                              quicksort(a, i+1, n)
                          end)
       end
 in readarray(a); quicksort(a,0,8); writearray(a)
end
```

Rewriting the program by treating non-local variables as formal parameter

Parameter Passing

how to map actual parameters to formal parameters?

- ***call-by-value**: values of the actual arguments are passed and established as values of formal parameters. Modification to formals have no effect on actuals.* ***Tiger**, **ML**, **C** always use call-by-value.*

```
function swap(x : int, y : int) =
  let var t : int := x in x := y; y := t end
```

- ***call-by-reference**: locations of the actuals are passed; references to the formals include implicit indirection to access values of the actuals. Modifications to formals do change actuals. (supported in PASCAL, but not in **Tiger**)*

```
function swap(var x : int, var y : int) =
  let var t : int := x in x := y; y := t end
```


Use of Registers

- ***To avoid memory traffic**, modern compilers often pass arguments, return results, and allocate local variables in **machine registers**.*
- ***Typical parameter-passing convention on modern machines:***

  *the first **k** arguments (**k** = **4** or **6**) of a function are passed in registers R_p, ..., R_{p+k-1}, the rest are passed on the stack.*

- *Problem : extra memory traffic caused by passing args. in registers*

```
function g(x : int, y : int, z :int) : int = x*y*z

function f(x : int, y : int, z : int) =
  let val a := g(z+3, y+3, x+4) in a*x+y+z end
```

Suppose function `f` *and* `g` *pass their arguments in R_1, R_2, R_3; then* `f` *must save R_1, R_2, and R_3 to the stack frame before calling* `g`,

Use of Registers (cont'd)

how to avoid extra memory traffic?

- ***Leaf procedures** (or functions) are procedures that do not call other procedures; e.g, the function* `exchange` *. The parameters of **leaf procedures** can be allocated in registers without causing any extra memory traffic.*
- *Use **global register allocation**, different functions use different set of registers to pass their arguments.*
- *Use register windows (as on SPARC) --- each function invocation can allocate a fresh set of registers.*
- *Use **callee-save registers***
- *When all fails --- save to the corresponding slots in the stack frame.*

Callee-save Registers

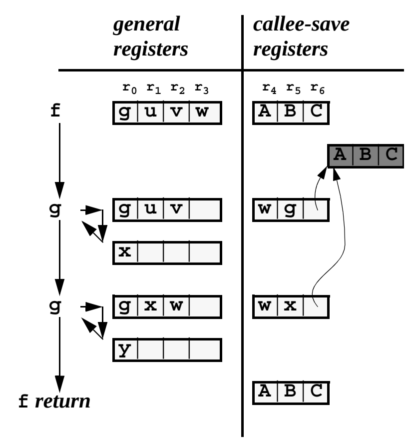
Convention :

Reserve k special registers !

Every function promises to always preserve these registers !

Example : k=3 (r_4, r_5, r_6)

```
fun f(u,v,w) =
  let val x = g(u,v)
      val y = g(x,w)
   in x+y+w
  end
```



Frame Resident Variables

Certain values must be allocated in stack frames because

- *the value is too big to fit in a single register*
- *the variable is passed by reference --- must have a memory address*
- *the variable is an array -- need address arithmetic to extract components*
- *the register that the variable stays needs to be used for other purpose!*
- *just too many local variables and arguments --- there are not enough registers !!! -------------- **SPILLING***

Open research problem: When to allocate local variables or passing arguments in registers ?

Needs good heauristics !

Stack Frames in Tiger

- *Using **abstraction** to avoid the machine-level details*
- *What do we need to know about each stack frame at compile time ?*

1. offsets of incoming arguments and the static links
2. offsets of all local variables
3. the frame size

```
signature FRAME =
sig type frame
    val newFrame : int -> frame * int list
    val allocLocal : frame -> int
     (* other stuff, eventually ... *)
end

structure PowerPCFrame : FRAME =
struct
  type frame = {formals: int, offlst: int list,
                locals: int ref, maxargs: int ref}
  ......
end

structure SparcFrame : FRAME = ....
```


Stack Frames in Tiger (cont'd)

- *In the **static environment** (i.e., the symbol table), associate each variable with the **access** information; associate each function with the layout information of its activation record (i.e, frame), a static link, and the caller's frame.*

```
type offset = int

datatype level
  = LEVEL of {frame: Frame.frame,
              slink_offset: offset,
              parent: level} * unit ref
  | TOP

type access = level * offset
```

- *When converting the **absyn** into intemediate code --- generate accessing code for each local or non-local variable, plus calling sequences for each function call.*

Limitation of Stack Frames

- *It does not support **higher-order functions** ---- it cannot support **"nested functions"** and **"procedure passed as arguments and results"** at the same time.*

C --- functions passed as args and results, but no nested functions;
PASCAL --- nested functions, but cannot be passed as args or res.

- ***Alternative** to the standard **stack allocation** scheme ----*

1. use a linked list of chunks to represent the stack

2. allocate the activation record on the heap --- no stack frame pop !

advantages: support higher-order functions and parallel programming well

(will be discussed several weeks later !)