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, ...)

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Typical Runtime Layout

**Activation Record**

- code
- registers
- garbage collector

**Memory Layout**

- program counter
- stack (activation records)
- heap (dynamic data)
- static (code and globals)
- links and saved status
- temporaries and local data
- parameters and returned values

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Example: Nested Functions

```plaintext
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
      if 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
```

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Activation Trees

- input: 10, 32, 567, -1, 789, 3, 18, 0, -51
- p -> partition
- q -> quicksort
- e -> exchange
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 \( f \) are 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 \( g(a_1, \ldots, a_n) \), 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 \( a_1, \ldots, a_n \) 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)
   - Jump to \( g \)'s code

2. **Entry sequence** (the first thing done after entering 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)

3. **Return sequence** (the callee \( g \) exits and returns back to \( f \))
   - Put the return result into a designated register
     (optional: restore callee-save 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

```plaintext
1 let type intArray = array of int
2 var a := intArray[9] of 0
3 function readarray() = ...
4 function writearray() = ...
5 function exchange(x: int, y: int) =
6     let var z := a[x] in
7         a[x] := a[y];
8         a[y] := z
9     end
10 function quicksort(m: int, n: int) =
11     let function partition(y: int, z: int) : int =
12         let var i := y var j := z + 1
13         in while (i < j) do
14             if i < j then exchange(i,j);
15             if i < j then exchange(i,j)
16         end
17         in if n > m then (let var i := partition(m,n) in
18             quicksort(m, i-1);
19             quicksort(i+1, n)
20             end)
21         in readarray(); quicksort(0,8); writearray()
22     end
```

Input:
```
10, 32, 567, -1, 789, 3, 18, 0, -51
```
Static Link

- Static link (also called access link) is used to implement lexical scoping.
- 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.

```
main()
  a
  m=0, n=8
q(0,8)
  1=4
  m=0, n=3
q(0,3)
  y=3
  i=3
p(0,3)
  l=4, j=3
  x=0, y=3
z(0,3)
```

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$(p)$ calls partition$(p)$.
- If $n_q \geq n_p$, $p$ and $q$ must have common calling "prefix" of functions at depths $1, \ldots, n_p-1$; 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 calls exchange -- 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.

```
main()
  a
  m=0, n=8
q(0,8)
  1=4
  m=0, n=3
q(0,3)
  y=3
  i=3
p(0,3)
  l=4, j=3
  x=0, y=3
z(0,3)
```

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)
```
### 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

**Conventional**:

- Reserve \( k \) special registers!

  Every function promises to always preserve these registers!

**Example**: \( k=3 \) \( (x_{0}, x_{1}, x_{2}) \)

-function \( f(u,v,w) = \)

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

- function \( g(x,y,z) = \)

  ```
  in x+y+z end
  ```

- `f return`
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 heuristics !

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

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 intermediate 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 !)