More on Runtime Environments

- *How to **efficiently** implement procedure call and return in the presence of **higher-order functions** ?*

  what are higher-order functions ?

  how to extend stack frames to support higher-order functions ?

  efficiency issues (execution time, space usage) ?

- *How to **efficiently** support memory allocation and de-allocation ?*

  what are the data representations ?

  what are the memory layout ?

  explicit vs implicit memory de-allocation ?
  (malloc-free vs. garbage collection)

Procedure Parameters (in Pascal)

- *Procedure parameters permit procedures to be invoked "out-of-scope";*

```
1   program main(input, output);
2
3     procedure b(function h(n : integer): integer);
4        var m : integer;
5        begin m := 6; writeln(h(2)) end;
6
7     procedure c;
8        var m : integer;
9        function f(n: integer): integer;
10          begin f := m + n end;
11       begin m := 0; b(f) end;
12   begin c end.
```

- ***Question**: how to get the correct environment when calling **h** inside **b** ?*

- ***Solution: must pass static link along** with **f** as if it had been called at the point it was passed (line 11).*

Restrictions in C & Pascal

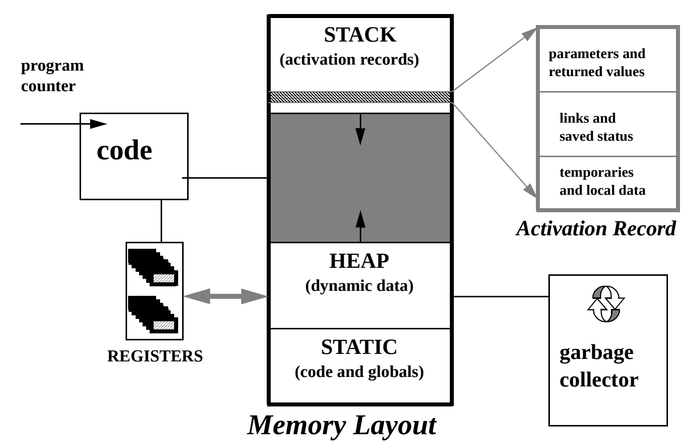
- ***C** does not allow nested procedures --- names in **C** are either local to some procedure or are global and visible in all procedures. Procedures in **C** can be passed as arguments or returned as results.*

- ***Pascal** (or **Modula-2**, **Modula-3**, **Algol**) allows procedure declarations to be nested, but procedure parameters are of restricted use, and procedures cannot be returned as result.*

- *Functional languages (e.g. ML, Haskell, Scheme, Lisp) support **higher-order** functions --- supporting both nested procedures and procedures passed as parameters or returned as results.*

  supporting it is a big challenge to the compiler writers !

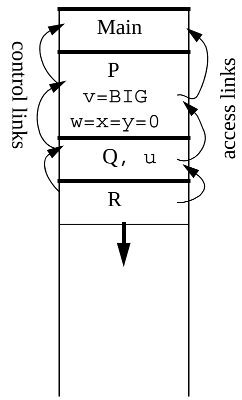
Traditional Stack Scheme



Procedure Activations

Nested Functions in ML

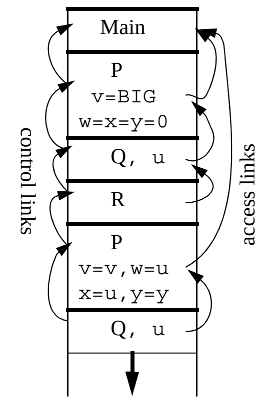
```
val BIG = big(N)

fun P(v,w,x,y) =
  let
   fun Q() =
    let val u = hd(v)

        fun R() =
          ... P(v,u,u,y) ...

     in ... R() ...
    end

   in ... Q() ...
  end

val result = P(BIG,0,0,0)
```



Procedure Activations (cont'd)

Nested Functions in ML

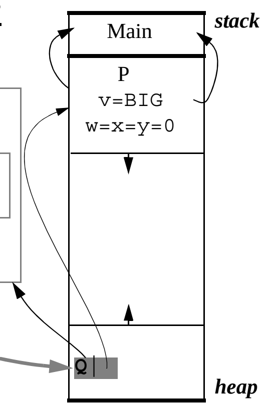
```
val BIG = big(N)

fun P(v,w,x,y) =
  let
   fun Q() =
    let val u = hd(v)

        fun R() =
          ... P(v,u,u,y) ...

     in ... R() ...
    end

   in ... Q() ...
  end

val result = P(BIG,0,0,0)
```



Higher-Order Functions

How to create a closure for Q ?

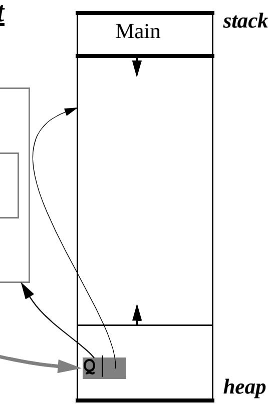
```
fun P(v,w,x,y) =
  let
   fun Q() =
    let val u = hd(v)

        fun R() =
          ...(u,w+x+y+3)...

     in ... R() ...
    end
  in Q
  end

val S = P(BIG,0,0,0)
val result = S()
```



Higher-Order Functions (cont'd)

Q lost track of its environment

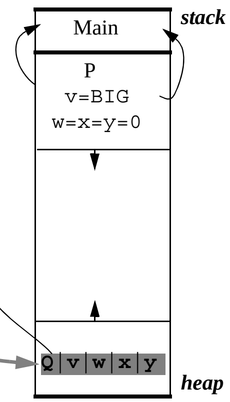
```
fun P(v,w,x,y) =
  let
   fun Q() =
    let val u = hd(v)

        fun R() =
          ...(u,w+x+y+3)...

     in ... R() ...
    end
  in Q
  end

val S = P(BIG,0,0,0)
val result = S()
```



Higher-Order Functions (cont'd)

Q must copy the frame !

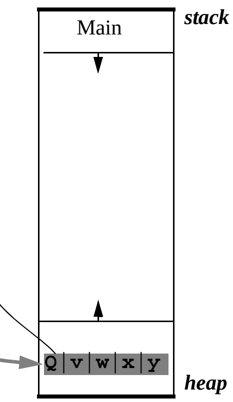
```
fun P(v,w,x,y) =
  let
    fun Q() =
     let val u = hd(v)
         fun R() =
           ...(u,w+x+y+3)...
      in ... R() ...
     end
   in Q
  end
val S = P(BIG,0,0,0)
val result = S()
```



Higher-Order Functions (cont'd)

Q's environment is in the heap!

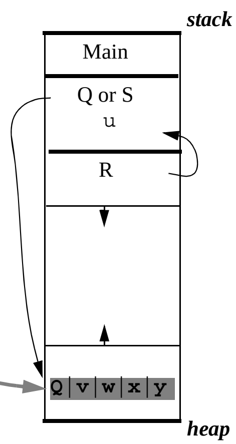
```
fun P(v,w,x,y) =
  let
    fun Q() =
     let val u = hd(v)
         fun R() =
           ...(u,w+x+y+3)...
      in ... R() ...
     end
   in Q
  end
val S = P(BIG,0,0,0)
val result = S()
```



Applying Higher-Order Functions

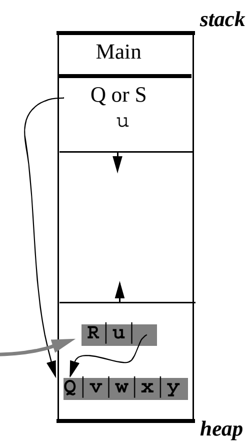
Accessing the Closure Q !

```
fun P(v,w,x,y) =
  let
    fun Q() =
     let val u = hd(v)
         fun R() =
           ...(u,w+x+y+3)...
      in ... R() ...
     end
   in Q
  end
val S = P(BIG,0,0,0)
val result = S()
```



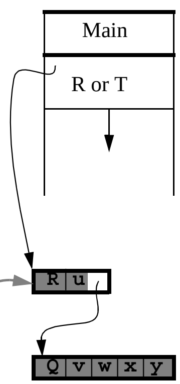
Nested Higher-Order Functions

```
fun P(v,w,x,y) =
  let
    fun Q() =
     let val u = hd(v)
         fun R() =
           ...(u,w+x+y+3)...
      in R
     end
   in Q
  end
val S = P(BIG,0,0,0)
val T = S()

val result = T()
```



Linked Closures

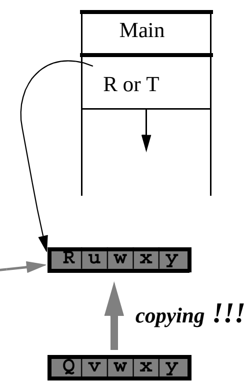
```
fun P(v,w,x,y) =
  let
    fun Q() =
     let val u = hd(v)
        fun R() =
          ...(u,w+x+y+3)...
      in R
     end
   in Q
  end
val S = P(BIG,0,0,0)
val T = S()
val result = T()
```



Fast creation, Slow access !

Flat Closures

```
fun P(v,w,x,y) =
  let
    fun Q() =
     let val u = hd(v)
        fun R() =
          ...(u,w+x+y+3)...
      in R
     end
   in Q
  end
val S = P(BIG,0,0,0)
val T = S()
val result = T()
```



Slow creation, Fast access !

Better Representations ?

- Closures cannot point to stack frame

  (different life time, so you must copy.)

- Linked closures --- fast creation, slow access

  Flat closures --- slow creation, fast access

- Stack frames with access links are similar to linked closures

  (accessing non-local variables is slow.)

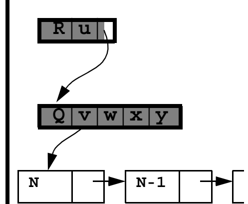
GOAL : We need good closure representations that have both fast access and fast creation !

Space Usage

Space Leaks for Linked Closures

```
fun P(v,w,x,y) =
  let fun Q() =
        let val u = hd(v)
            fun R() = (u,w+x+y+3)
         in R
        end
   in Q
  end

fun loop (n,res) =
  if n<1 then res
  else (let val S = P(big(N),0,0,0)
            val T = S()
         in loop(n-1,T::res)
        end)

val result = loop(N,[])
```

Linked Closures : $O(N^2)$

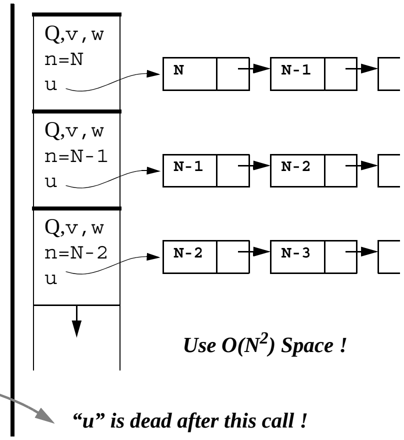


Flat Closures : $O(N)$

Space Usage (cont'd)

<u>Space Leaks for Stack Allocations</u>

```
fun P(x) = ......

fun Q(n) = let
  val u = big(n)
  val v = P(u)
  val w = hd(u)
in
  if n > 0
  then Q(n-1)+v(w)
  else ...
end

val result = Q(N)
```



Better Space Usage ?

- The **<u>safe for space complexity</u>** rule :

  Local variable must be assumed dead after its last use within its scope !

- Stacks and linked closures are NOT safe for space
- Flat closures are safe for space
- SML/NJ : **unsafe version** = (2 to 80) x **safe version**

Drawbacks of Stack Allocation

- inefficient space usage
- slow access to non-local variables
- expensive copying between stack and heap

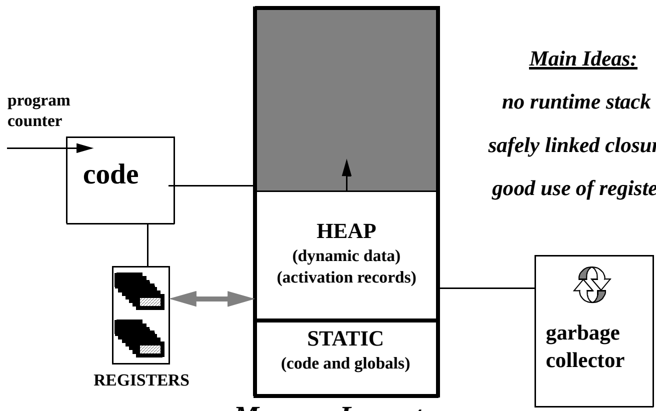
  (activation records cannot be shared by closures)
- scanning roots is expensive in generational GC
- very slow first-class continuations (`call/cc`)
- correct implementation is complicated and messy

Efficient Heap-based Compilation

An efficient heap-based scheme has the following advantages:

- very good space usage (safe for space complexity !)
- very fast closure creation and closure access
- closures can be shared with activation records
- fast `call/cc` and fast generational GC
- simple implementation

Pure Heap-based Scheme



Memory Layout

Main Ideas:

no runtime stack !

safely linked closures

good use of registers

CS421 COMPILERS AND INTERPRETERS

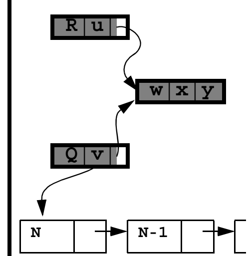
Safely Linked Closures

Safe for Space : use O(N) space

```
fun P(v,w,x,y) =
  let fun Q() =
        let val u = hd(v)
            fun R() = (u,w+x+y+3)
         in R
        end
   in Q
  end

fun loop (n,res) =
  if n<1 then res
  else (let val S = P(big(N),0,0,0)
            val T = S()
         in loop(n-1,T::res)
        end)

val result = loop(N,[])
```

THE TRICK:

Variables w,x,y have same life time !



CS421 COMPILERS AND INTERPRETERS

Safely Linked Closures (cont'd)

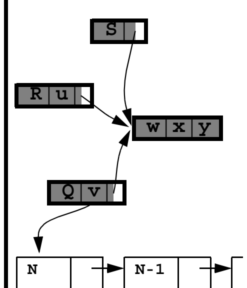
Shorter Access Path !

```
fun P(v,w,x,y) =
  let fun Q() =
        let val u = hd(v)
            fun R() =
              let fun S() = w+x+y+3
               in (S,u)
              end
         in R
        end
   in Q
  end

val T = P(big(N),0,0,0)
```

The number of links traversed is at most 1 .

THE TRICK:

Variables w,x,y have same life time !



CS421 COMPILERS AND INTERPRETERS

Good 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 $\mathbf{k}$ *arguments (* $\mathbf{k} = \mathbf{4}$ *or* $\mathbf{6}$*) of a function are passed in registers* $\mathbf{R_p}$*, ...,* $\mathbf{R_{p+k-1}}$*, 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 memory before calling* `g`*,*

Good 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.*
- *Allocate* ***closures*** *in registers or use* ***callee-save registers***
- *When all fails --- save to the stack frame or to the heap.*

Closures in Registers ? No !

Module FOO: (in file "foo.sml")

```
fun pred(x) = ...v(w,x) ...
val result = BAR.filter(pred,...)
```

"pred" is an escaping function !

Its closure must be built on the heap !

Module BAR : (in file "bar.sml")

```
fun filter(p,l) =
  let fun h(s,z) =
        if (s=[]) then rev z
        else
         (let val a = car s
              val r = cdr s
           in if p a then h(r,a::z)
              else h(r,z)
          end)
   in h(l,[])
  end
```

Escaping functions:

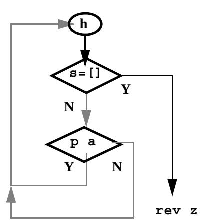
functions whose call sites are not all known at compile time !

Closures in Registers ? Yes !

```
fun filter(p,l) = let

  fun h(s,z) =
    if (s=[]) then rev z
    else
     (let val a = car s
          val r = cdr s
       in if p a then h(r,a::z)
          else h(r,z)
      end)

in h(l,[])
end
```

Known functions:

functions whose call sites are all known at compile time !

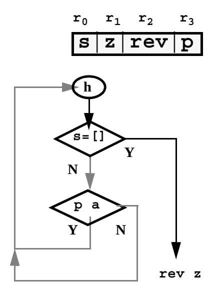


"h" is a known function !

Its closure can be put in registers ! ***(e.g., {rev,p})***

"Lambda Lifting"

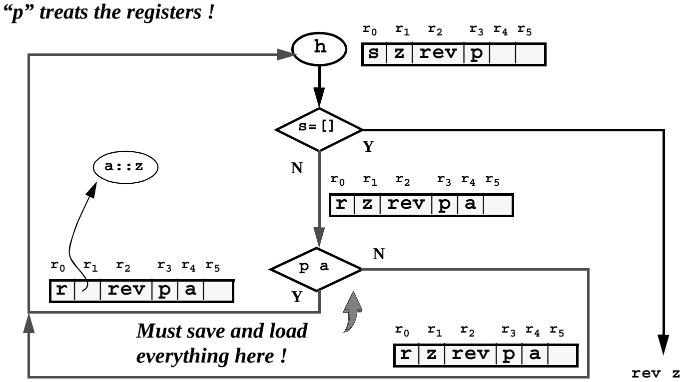
```
fun filter(p,l) = let

  fun h(s,z,rev,p) =
    if (s=[]) then rev z
    else
     (let val a = car s
          val r = cdr s
       in if p a then h(r,a::z,rev,p)
          else h(r,z,rev,p)
      end)

in h(l,[],rev,p)
end
```



known functions can be rewritten into functions that are fully closed !
(i.e. with no free variables !)

"Spilled Activation Records"

We do not know how "p" treats the registers !



CS421 COMPILERS AND INTERPRETERS

Callee-save Registers

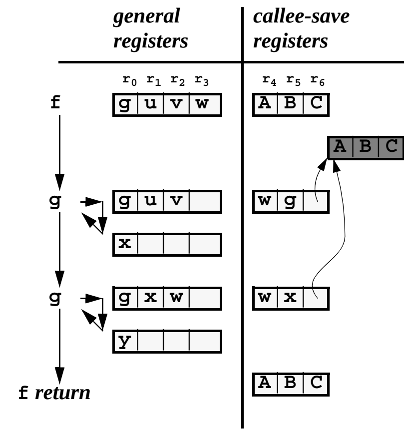
Convention :

Reserve k special registers !

Every function promises to always preserve these registers !

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

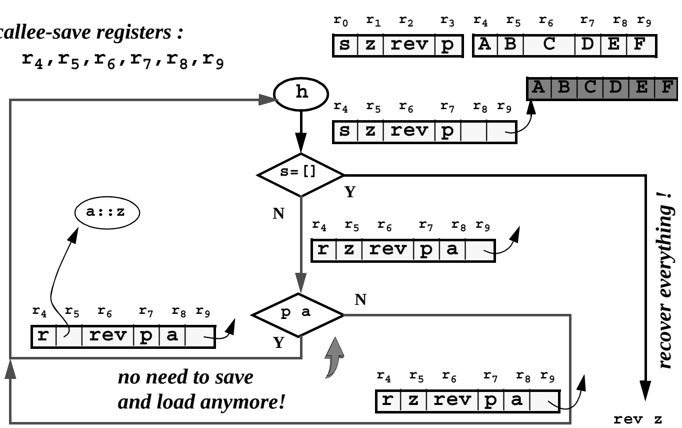
```
fun f(g,u,v,w) =
  let val x = g(u,v)
      val y = g(x,w)
   in x+y+w
  end
```



CS421 COMPILERS AND INTERPRETERS

Callee-save Registers (cont'd)

6 callee-save registers :
$r_4, r_5, r_6, r_7, r_8, r_9$



CS421 COMPILERS AND INTERPRETERS

Summary : A Uniform Solution

Take advantage of variable life time and compile-time control flow information !

"Spilled activation records" are also thought as closures !

- no runtime stack ---------- everything is sharable
- all use ***safely-linked closures*** ---------- to maximize sharing
- pass arguments and return results in registers
- allocating most closures in registers
- good use of callee-save registers