Compiler Construction
Lent Term 2013
Lecture 6 (of 16)

- Functions as "first class" values
- Heap allocated closures
- A few simple optimizations:
  - Inline expansion
  - Constant folding
  - Eliminating tail recursion

Timothy G. Griffin
tgg22@cam.ac.uk
Computer Laboratory
University of Cambridge

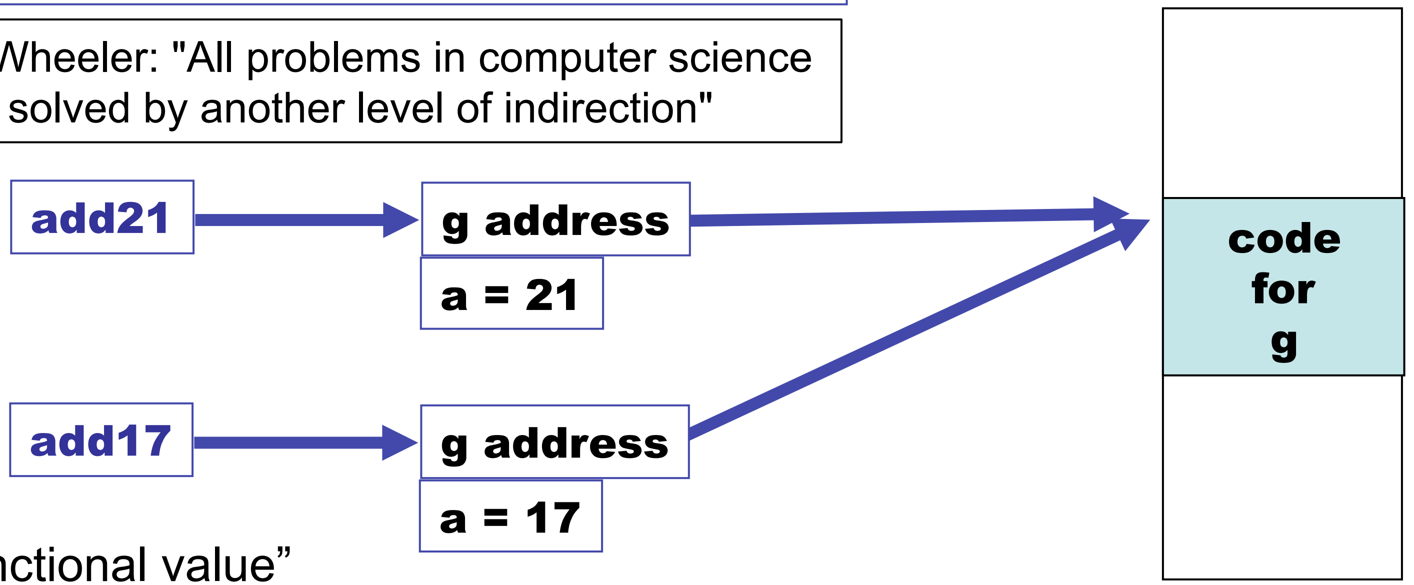
Idea --- a functional value is a pointer to a “closure”

```
fun f(a : int) : int -> int
{
   fun g(x :int) : int {return a + x;}
   return g;
}

let add21 : int -> int  = f(21);
let add17 : int -> int  = f(17);

add17(3) + add21(-1)
```

Problem: in the simple call stack the argument “a” (needed in body of g) does not survive the destruction of f’s activation record.

A <u>closure</u> is a record containing the address of a function AND the values of its free variables

David Wheeler: "All problems in computer science can be solved by another level of indirection"



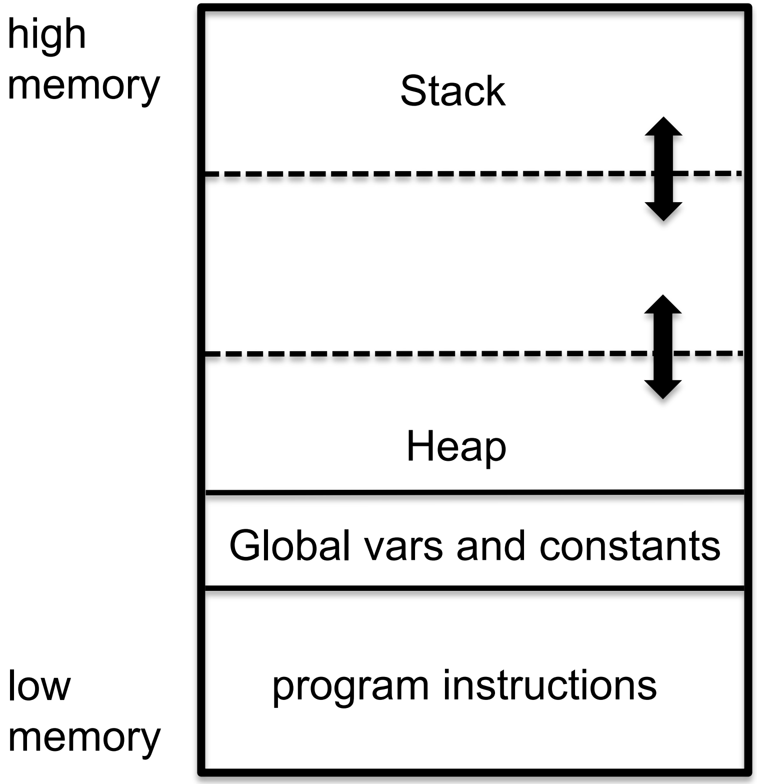
A “functional value” is a pointers to a closure.

Where should these closures be stored??

Code array

The Heap

Rough schematic of traditional
layout in (virtual) memory.



The heap is used for dynamically allocating memory. Typically either for very large objects or for those objects that are returned by functions/procedures and must outlive the associated activation record.

In languages like Java and ML, the heap must be managed automatically ("garbage collection")

Return to example: How do functional values find their free-var values?

```
fun f(a : int) : int -> int
{
   fun g(x :int) : int {return a + x;}
   return g;
}

let add21 : int -> int  = f(21);
let add17 : int -> int  = f(17);

add17(3) + add21(-1)
```

A possible intermediate representation

```
fun g(x, c) {return !(c+1) + x;}

fun f(a) {return ALLOCATE_CLOSURE (g, [a]);}

let add21 = f(21);
let add17 = f(17);

INVOKE_CLOSURE(add17, 3) + INVOKE_CLOSURE(add21, -1))
```

ALLOCATE_CLOSURE returns a pointer to the heap.

INVOKE_CLOSURE ?

Return to example: How do functional values find their free-var values?

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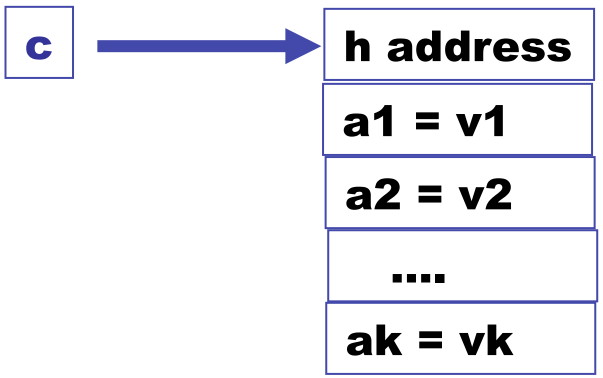


`INVOKE_CLOSURE(c, u1, …, un)`

- Push arguments ui on stack
- Push c on stack
- Call h:
  - Build activation record for h
  - Body of h must access non-local vars using indirection through c.

Another example

```
fun f(a : int) : int -> int
{
   fun g(x :int) : int {return a + x;}
   fun h(x :int) : int {return a * x;}
   if a < 20 then return g else return h;
}

let f21 : int -> int  = f(21);
let f17 : int -> int  = f(17);

f17(3) + f21(-1)
```

Closure conversion (similar to "lambda lifting")

```
fun f(a)
{
   fun g(x) {return a + x;}
   fun h(x) {return a * x;}
   if a < 20 then return g else return h;
}
```

```
fun g(x, c) {return !(c+1) + x;}
fun h(x, c) {return !(c+1) * x;}
fun f(a) {
 if a < 20
 then return ALLOCATE_CLOSURE (g, [a])
 else return ALLOCATE_CLOSURE (h, [a]);
}
```

A simple optimization with functions : Inline expansion

```
fun f(x) = x + 1
fun g(x) = x - 1
…
…
fun h(x) = f(x) + g(x)
```

↓ inline f and g

```
fun f(x) = x + 1
fun g(x) = x - 1
…
…
fun h(x) = (x+1) + (x-1)
```

(+) Avoid building activation records at runtime

(-) May lead to "code bloat" (apply only to functions with "small" bodies?)

Question: if we inline all occurrences of a function, can we delete its definition from the code?

What if it is needed at link time?

Be careful with variable scope

Inline g in h

```
let val x = 1
    fun g(y) = x + y
    fun h(x) = g(x) + 1
in
   h(17)
end
```

NO →

```
let val x = 1
    fun g(y) = x + y
    fun h(x) = x + y + 1
in
   h(17)
end
```

YES →

```
let val x = 1
    fun g(y) = x + y
    fun h(z) = x + z + 1
in
   h(17)
end
```

Constant propagation and constant folding

```
let x = 2
let y = x - 1
let z = y * 17
```

```
let x = 2
let y = 2 - 1
let z = y * 17
```

```
let x = 2
let y = 1
let z = y * 17
```

```
let x = 2
let y = 1
let z = 1 * 17
```

```
let x = 2
let y = 1
let z = 17
```

Propagate constants and evaluate simple expressions at compile-time

Note : opportunities are often exposed after inline expansion!

David Gries : "Never put off till run-time what you can do at compile-time."

But be careful

How about this?

Replace

x * 0

with

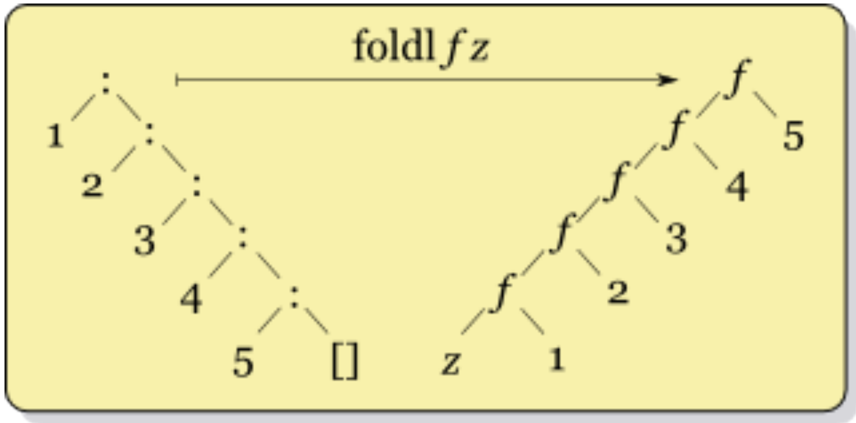
0

OOPS, not if x has type float!

NAN*0 = NAN,

Tail recursion

A recursive function exhibits tail recursion if on all recursive branches the last thing it does is call itself.



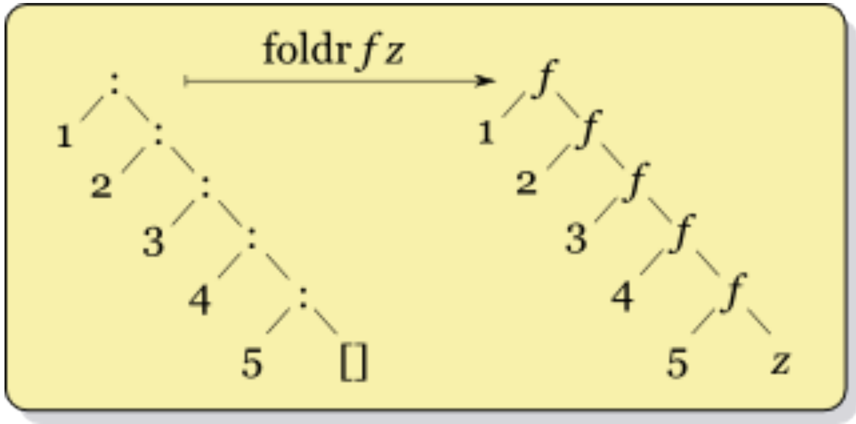

```
fun foldl f e []        = e
  | foldl f e (x::xr) = foldl f (f(x, e)) xr
```

We should be able to compile this to a LOOP in order to avoid constructing many activation records at runtime.
Exercise : How?

The ultimate tail-recursive function

```
fun while c b r =
    if c()
    then r
    else while c b (b ())
```

Of course not all recursive functions are tail recursive...




```
fun foldr f e []       = e
  | foldr f e (x::xr) = f(x, foldr f e xr)
```

The “last thing” this function does is call **f**, not **foldr**

Sometimes recursive functions can be rewritten to tail recursive versions

```
fun sum_list [] = 0
  | sum_list (x::rest) = x + (sum_list rest)
```

↓

```
fun sum_list il =
  let fun auxiliary carry [] = carry
        | auxiliary carry (x :: rest) =
            auxiliary (x + carry) rest
  in auxiliary 0 il end
```

Exercise : Think about trying to automate this kind of transformation in a compiler.