Lecture #25: Achieving Runtime Effects—Functions

Administrivia

- Proj3 Java files (mostly) out (need some testing stuff).
- Deadline for Project 3 will be pushed a bit due to delays (not too much, because of ACM Programming Contest).

General Considerations

- Language design and runtime design interact. Semantics of functions make good example.
- Levels of function features:
  1. Plain: no recursion, no nesting, fixed-sized data with size known by compiler.
  2. Add recursion.
  3. Add variable-sized unboxed data.
  4. Allow nesting of functions, up-level addressing.
  5. Allow function values w/ properly nested accesses only.
  6. Allow general closures.
  7. Allow continuations.
- Tension between these effects and structure of machines:
  - Machine languages typically only make it easy to access things at addresses like $R + C$, where R is an address in a register and C is a relatively small integer constant.
  - Therefore, fixed offsets good, data-dependent offsets bad.

1: No recursion, no nesting, fixed-sized data

- Total amount of data is bounded, and there is only one instantiation of a function at a time.
- So all variables, return addresses, and return values can go in fixed locations.
- No stack needed at all.
- Characterized FORTRAN programs in the early days.
- In fact, can dispense with call instructions altogether: expand function calls in-line. *E.g.*,

```
def f (x):
   x *= 42
   y = 9 + x;
   g (x, y)

f (3)
```

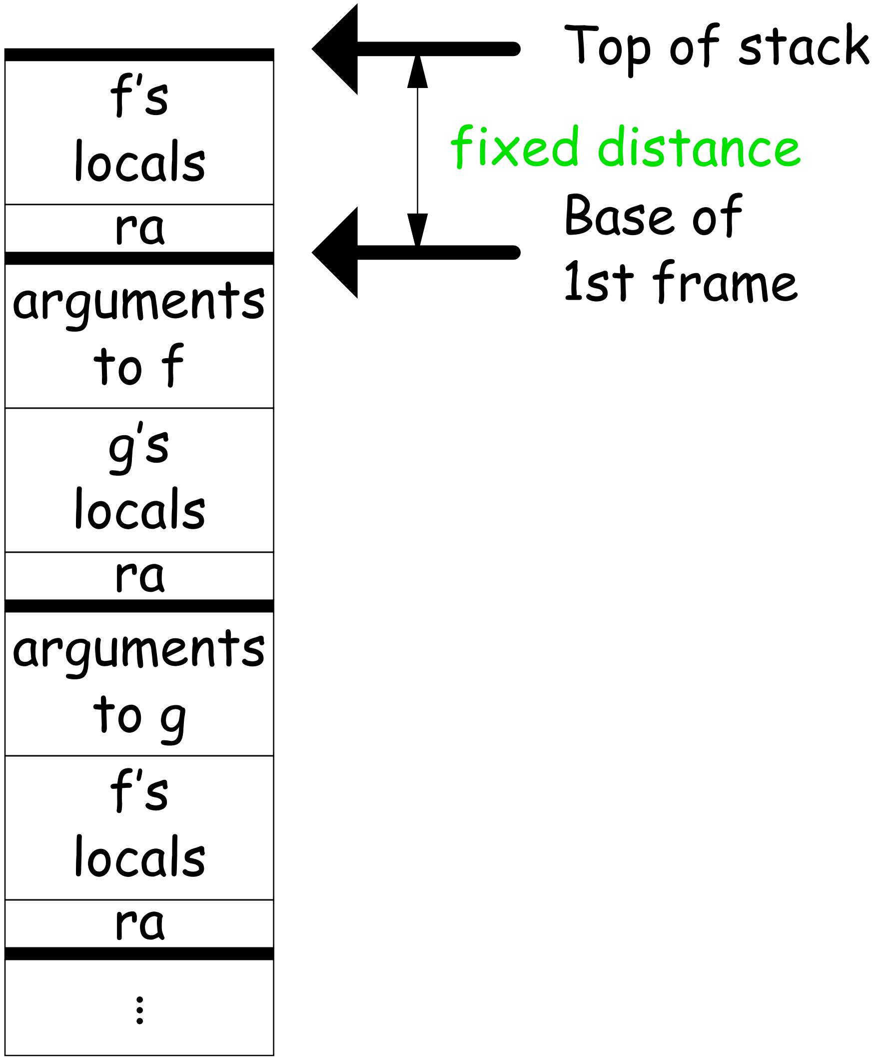
⟹ becomes ⟹

```
x_1 = 3
x_1 *= 42
y_1 = 9 + x_1
g (x_1, y_1)
```

- However, program may get bigger than you want. Typically, one inlines only small, frequently executed functions.

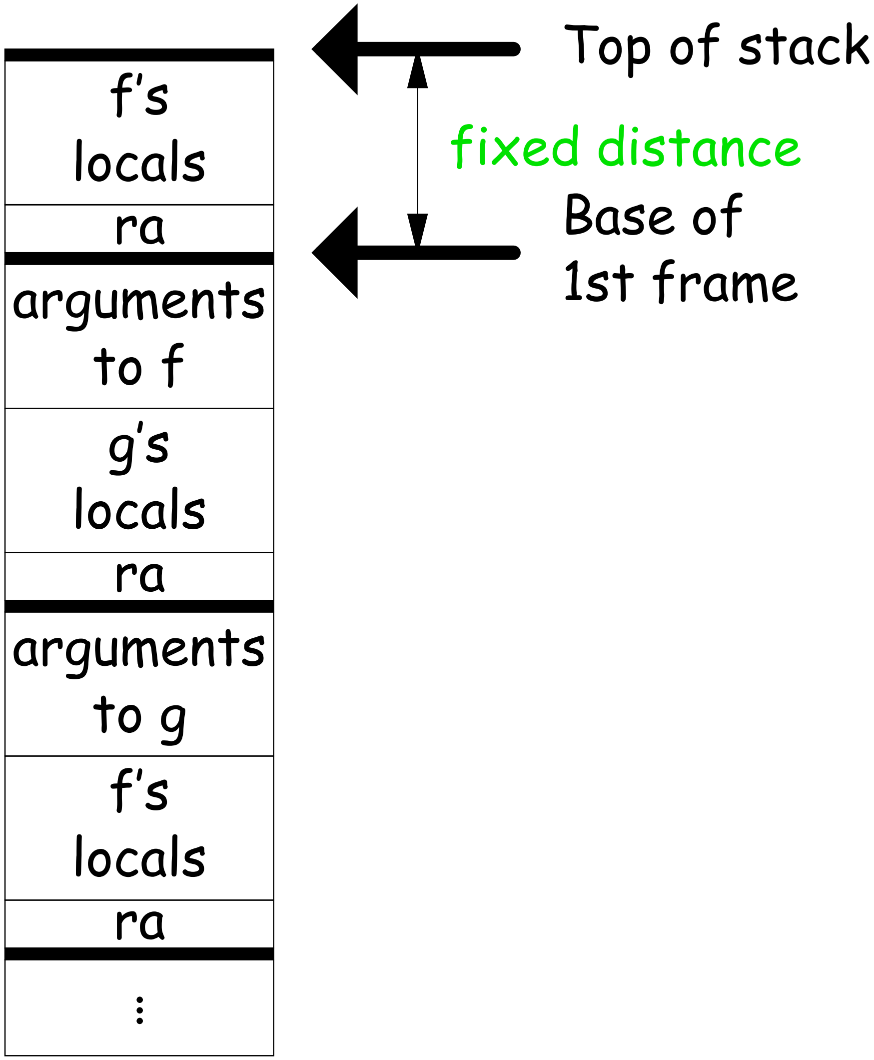
2: Add recursion

- Now, total amount of data is unbounded, and several instantiations of a function can be active simultaneously.
- Calls for some kind of expandable data structure: a stack.
- However, variable sizes still fixed, so size of each activation record (stack frame) is fixed.
- All local-variable addresses and the value of dynamic link are known offsets from stack pointer, which is typically in a register.



Calling Sequence when Frame Size is Fixed

- So dynamic links not really needed.
- Suppose f calls g calls f, as at right.
- When called, the initial code of g (its *prologue*) decrements the stack pointer by the size of g's activation record.
- g's exit code (its *epilogue*):
  - increments the stack pointer by this same size,
  - pops off the return address, and
  - branches to address just popped. to it.



f's locals

ra

arguments to f

g's locals

ra

arguments to g

f's locals

ra

⋮

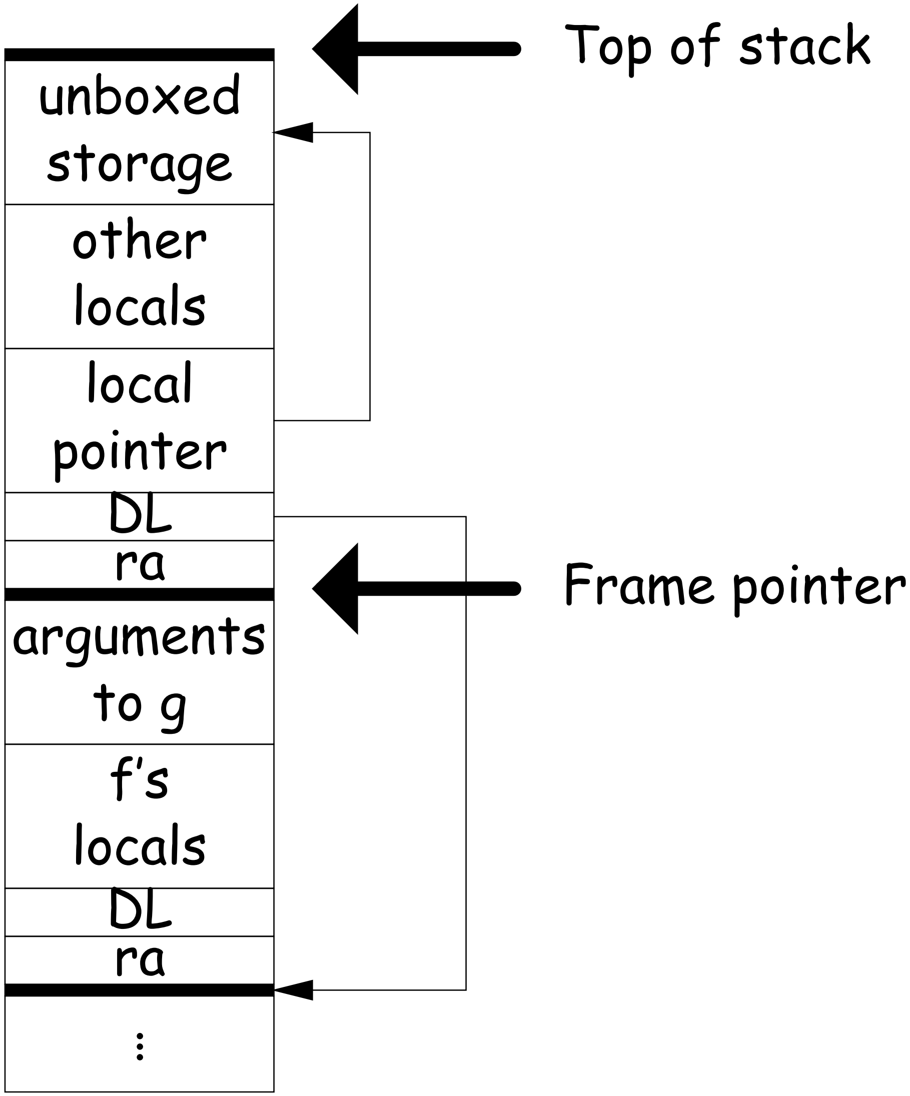
Top of stack

fixed distance

Base of 1st frame

3: Add Variable-Sized Unboxed Data

- "Unboxed" means "not on heap."
- Boxing allows all quantities on stack to have fixed size.
- So Java implementations have fixed-size stack frames.
- But does cost heap allocation, so some languages also provide for placing variable-sized data directly on stack ("heap allocation on the stack")
- `alloca` in C, e.g.
- Now we do need dynamic link (DL).
- But can still insure fixed offsets of data from frame base (*frame pointer*) using pointers.
- To right, f calls g, which has variable-sized unboaxed array (see right).



Other Uses of the Dynamic Link

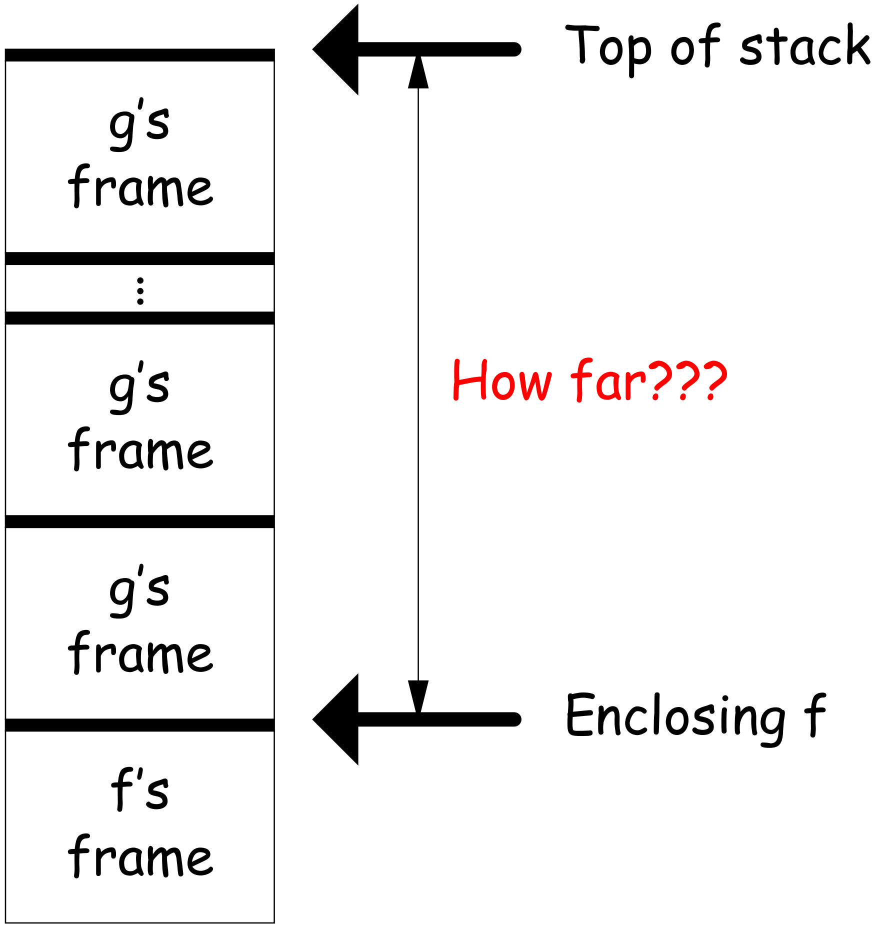
- Often use dynamic link even when size of AR is fixed.
- Allows use of same strategy for all ARs, simplifies code generation.
- Makes it easier to write general functions that *unwind* the stack (i.e., pop ARs off, thus returning).

4: Allow Nesting of Functions, Up-Level Addressing

- When functions can be nested, there are three classes of variable:
  a. Local to function.
  b. Local to enclosing function.
  c. Global
- Accessing (a) or (c) is easy. It's (b) that's interesting.
- Consider (in Pyth or Python):

```
def f ():
  y = 42   # Local to f
  def g (n, q):
     if n == 0: return q+y
     else: return g (n-1, q*2)
```

- Here, y can be any distance away from top of stack.



Top of stack

g's frame

⋮

g's frame

g's frame

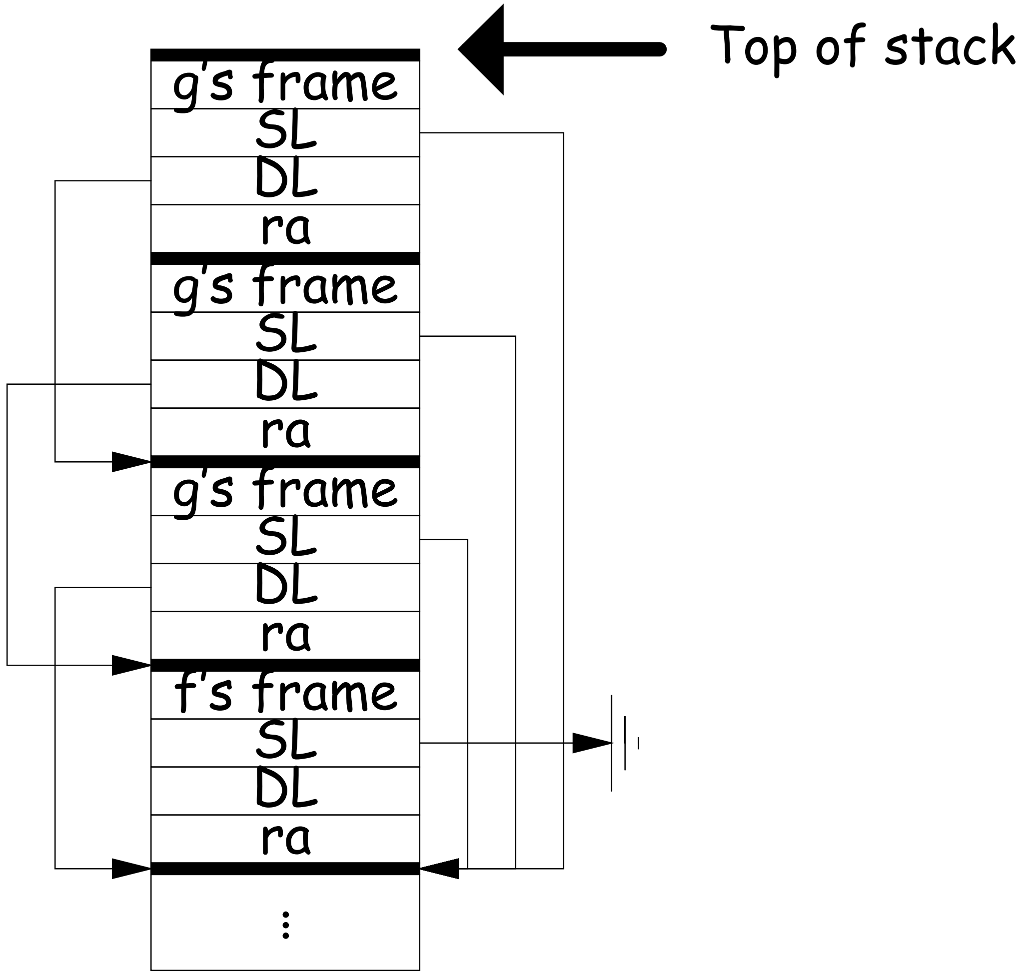
How far???

Enclosing f

f's frame

Static Links

- To overcome this problem, *go* back to environment diagrams!
- Each diagram had a pointer to *lexically enclosing environment*
- In Pyth example from last slide, each 'g' frame contains a pointer to the 'f' frame where that 'g' was defined: the *static link* (SL)
- To access local variable, use frame-base pointer (or maybe stack pointer).
- To access global, use absolute address.
- To access local of nesting function, follow static link once per difference in levels of nesting.



The Global Display

- Historically, first solution to nested function problem used an array indexed by call level, rather than static links.

```
def f0 ():
  q = 42; g1 ()
  def f1 ():
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```
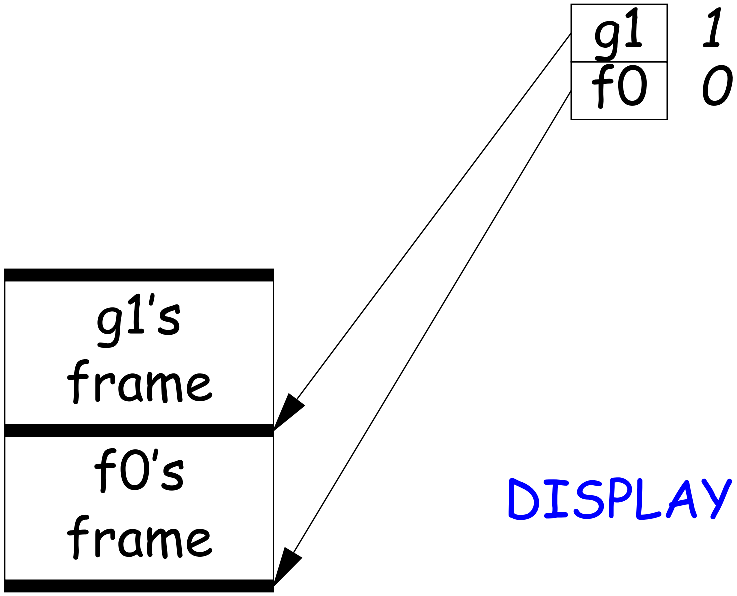

- Each time we enter a function at lexical level k (i.e., nested inside k functions), save pointer to its frame base in DISPLAY[k]; restore on exit.
- Access variable at lexical level k through DISPLAY[k].
- Relies heavily on scope rules and proper function-call nesting



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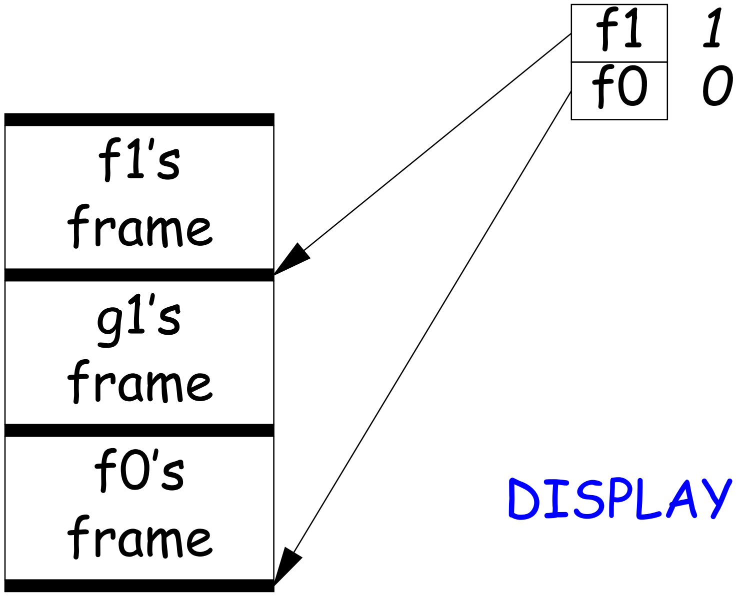

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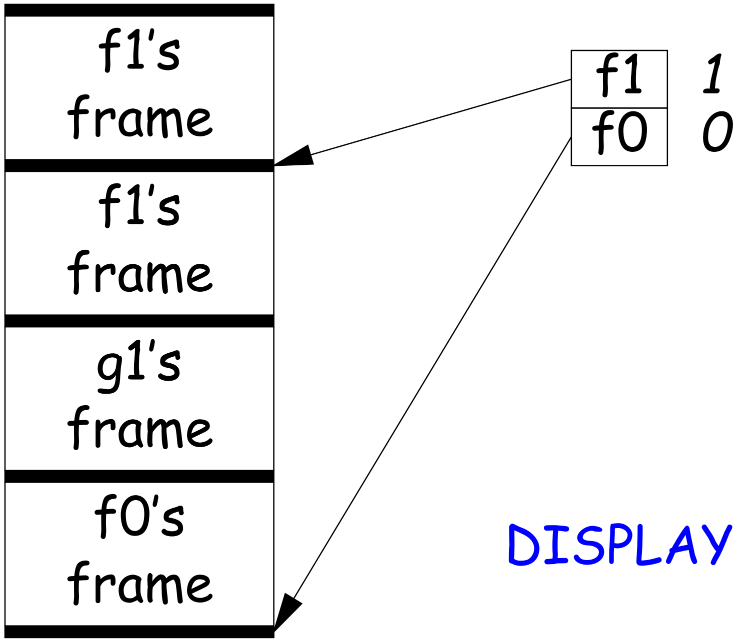

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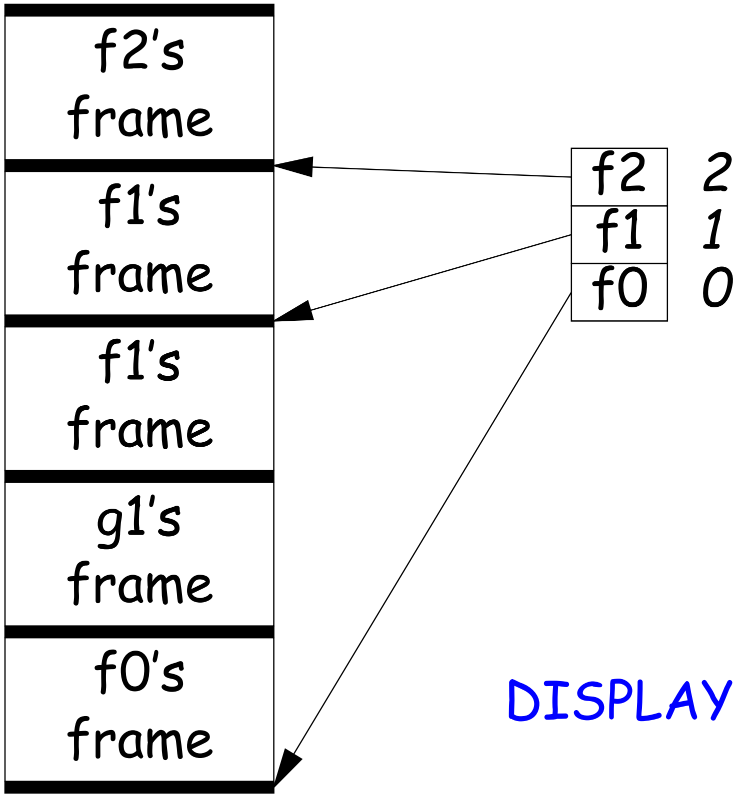

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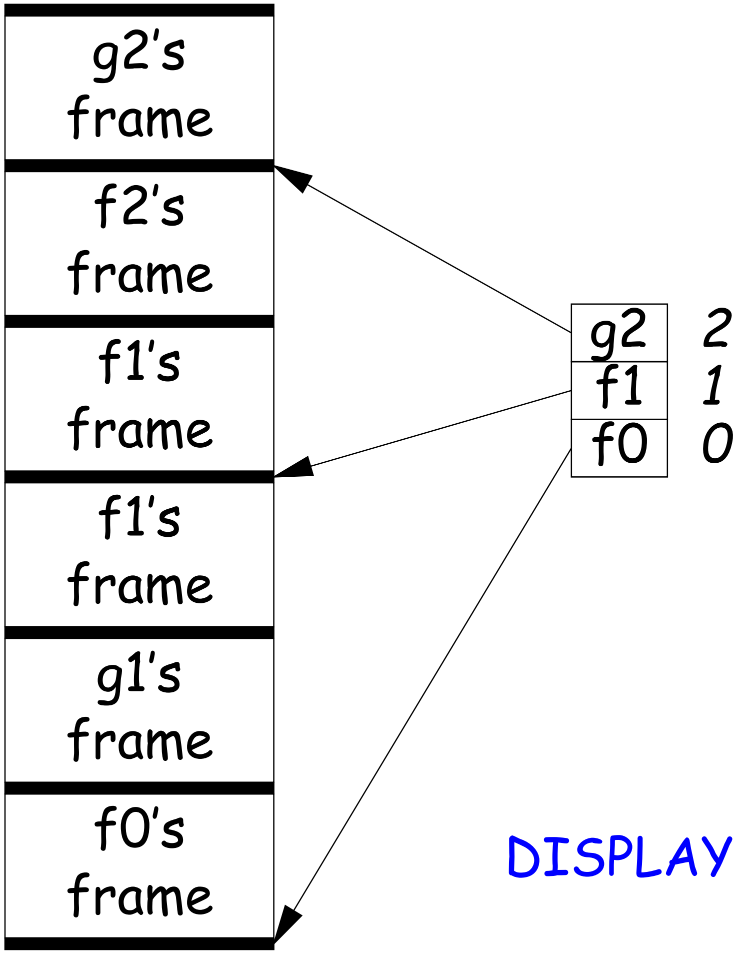

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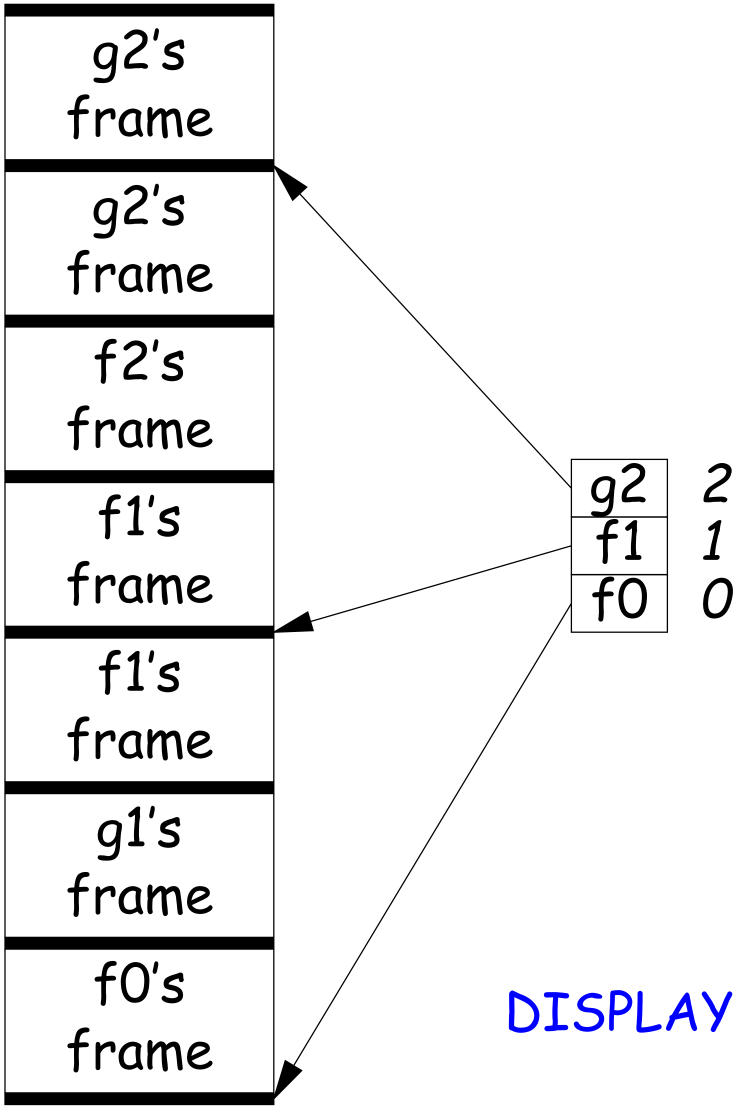

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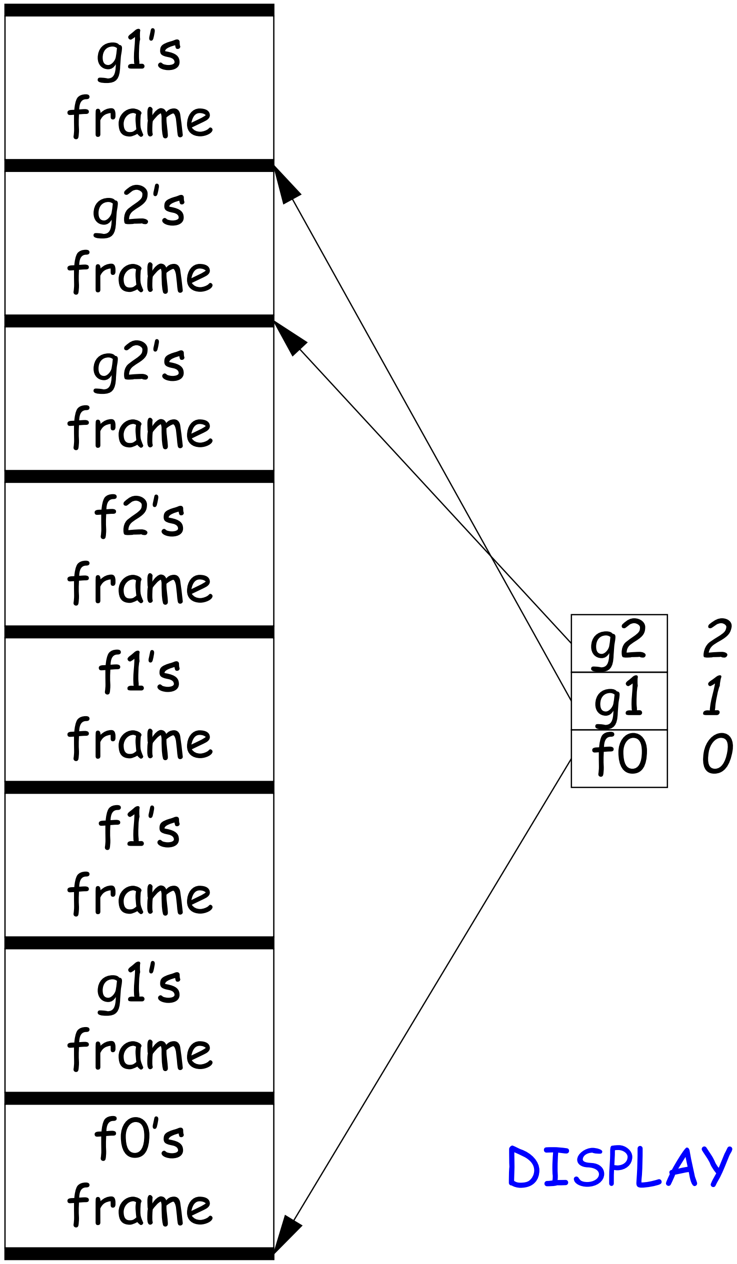


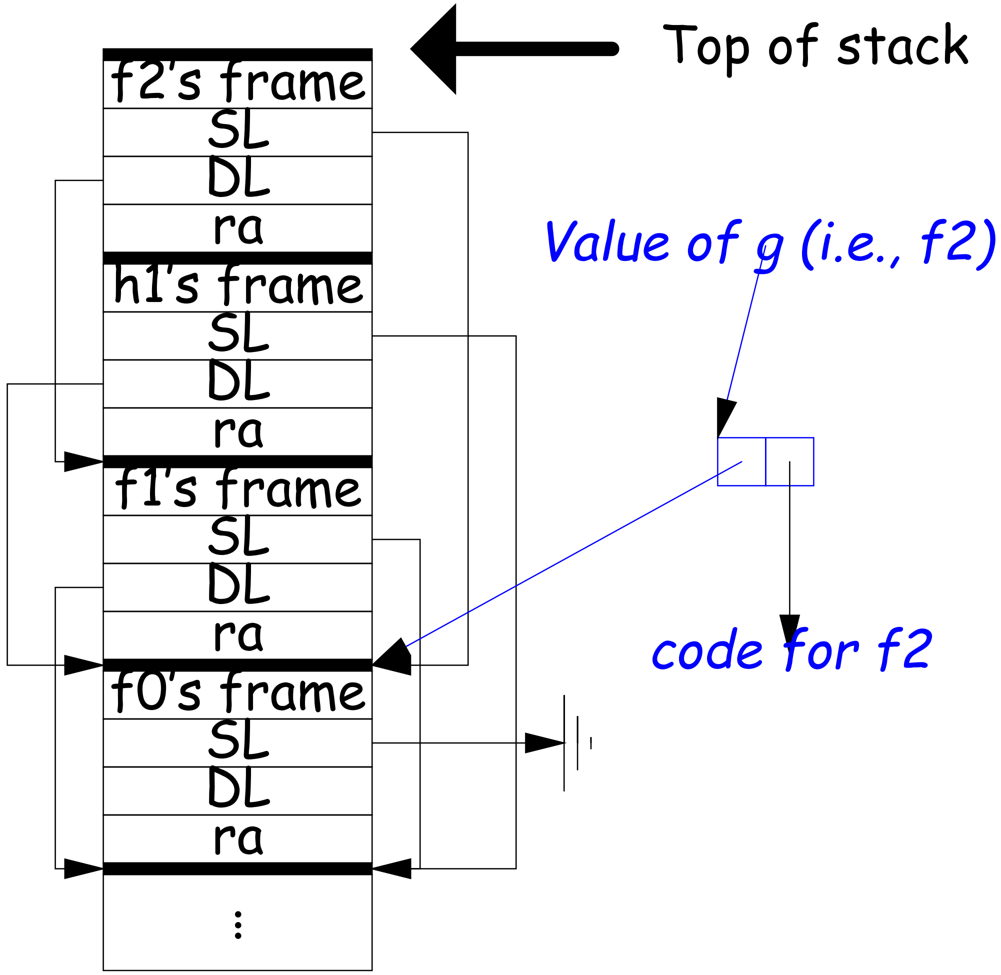
5: Allow Function Values, Properly Nested Access

- In C, C++, no function nesting.
- So all non-local variables are global, and have fixed addresses.
- Thus, to represent a variable whose value is a function, need only to store the address of the function's code.
- But when nested functions possible, function value must contain more.
- When function is finally called, must be told what its static link is.
- Assume first that access is properly nested: variables accessed only during lifetime of their frame.
- So can represent function with address of code + the address of the frame that contains that function's definition.
- It's environment diagrams again!!

Function Value Representation

```
def f0 (x):
   def f1 (y):
     def f2 (z):
       return x + y + z
     print h1 (f2)
   def h1 (g): g (3)
   f1 (42)
```

- Call `f0` from the main program; look at the stack when `f2` finally is called (see right).
- When `f2`'s value (as a function) is computed, current frame is that of `f1`. That is stored in the value passed to `h1`.
- Easy with static links; global display technique does not fare as well [why?]

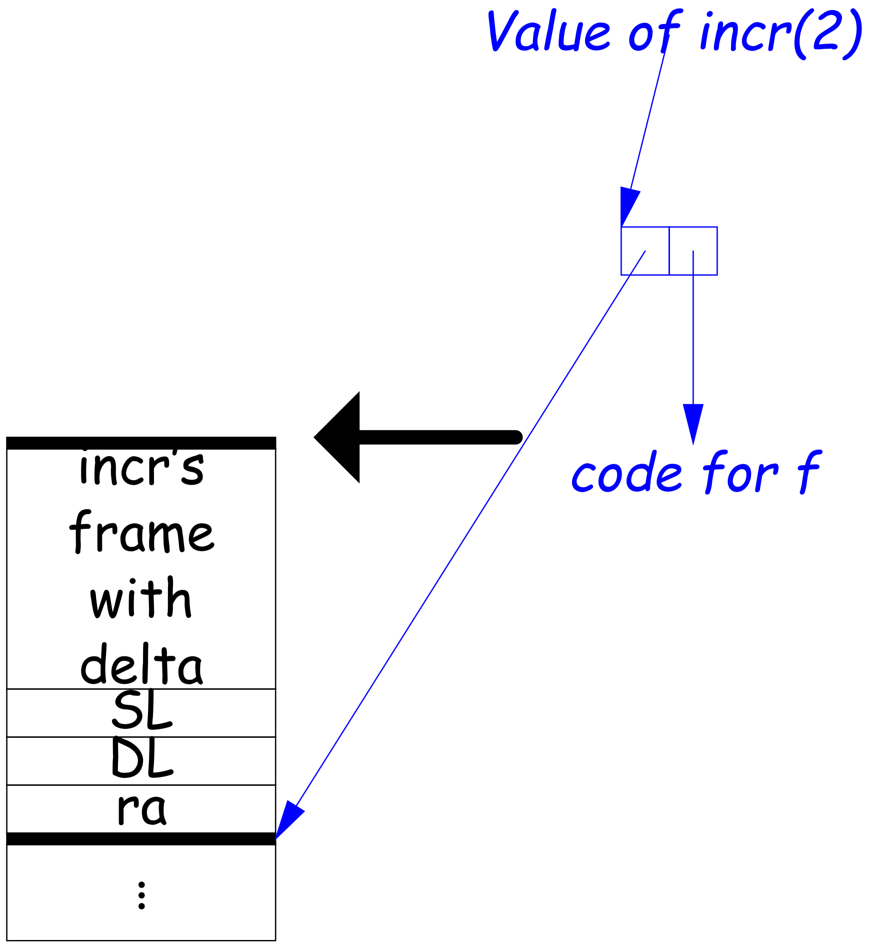


6: General Closures

- What happens when the frame that a function value points to goes away?
- If we used the previous representation (#5), we'd get a *dangling pointer* in this case:

```
def incr (n):
   delta = n
   def f (x):
     return delta + x
   return f

p2 = incr(2)
print p2(3)
```



During execution of incr(2)

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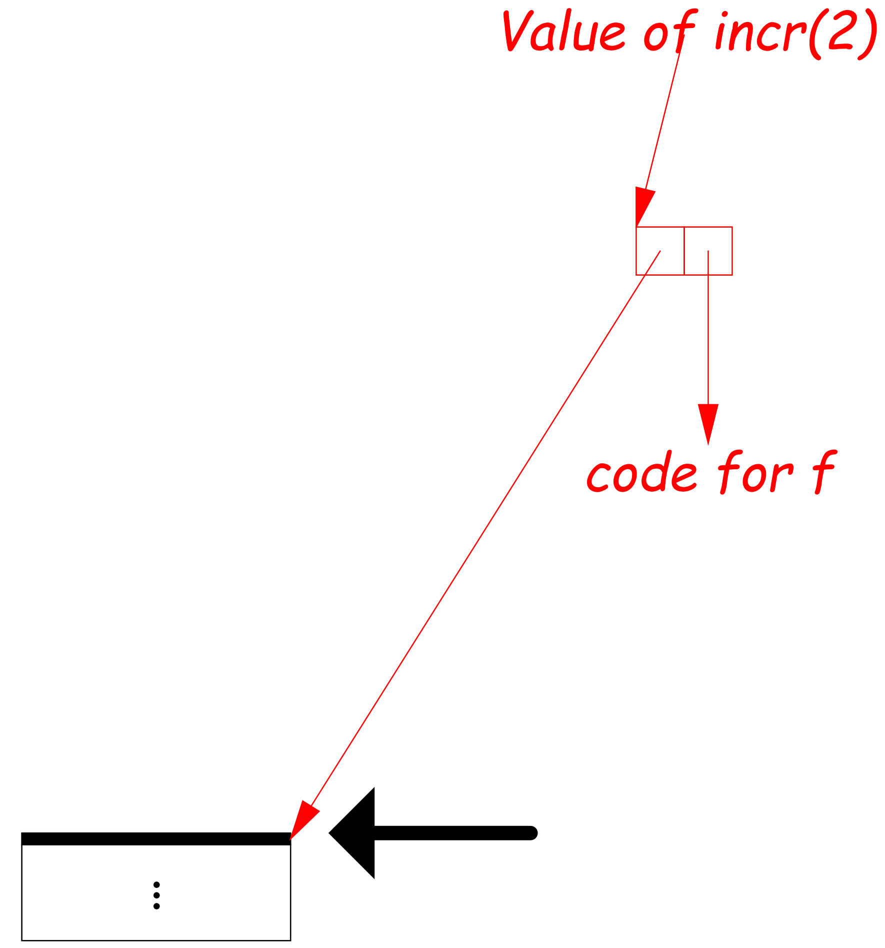
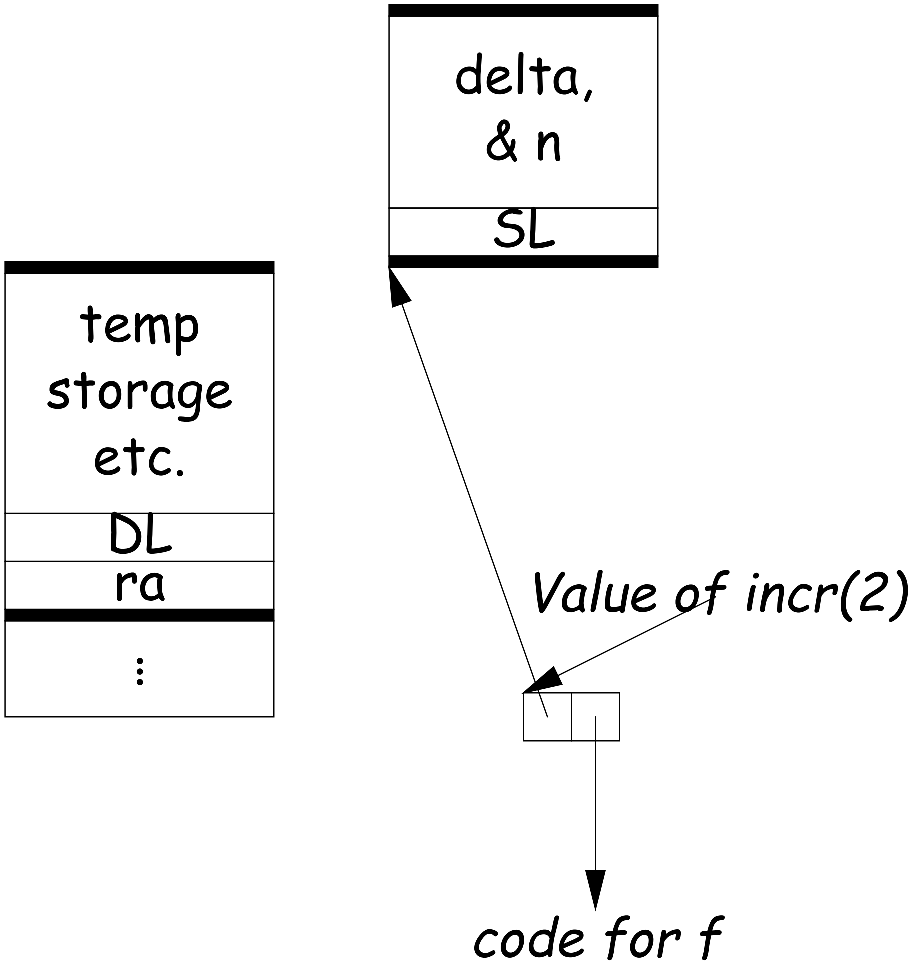


After return from incr(2)
delta is gone

Representing Closures

- Could just forbid this case (as some languages do):
  - Algol 68 would not allow pointer to f (last slide) to be returned from incr.
  - Or, one could allow it, and do something random when f (i.e. via delta) is called.
- Scheme and Python allow it and do the right thing.
- But must in general put local variables (and a static link) in a record on the heap, instead of on the stack.



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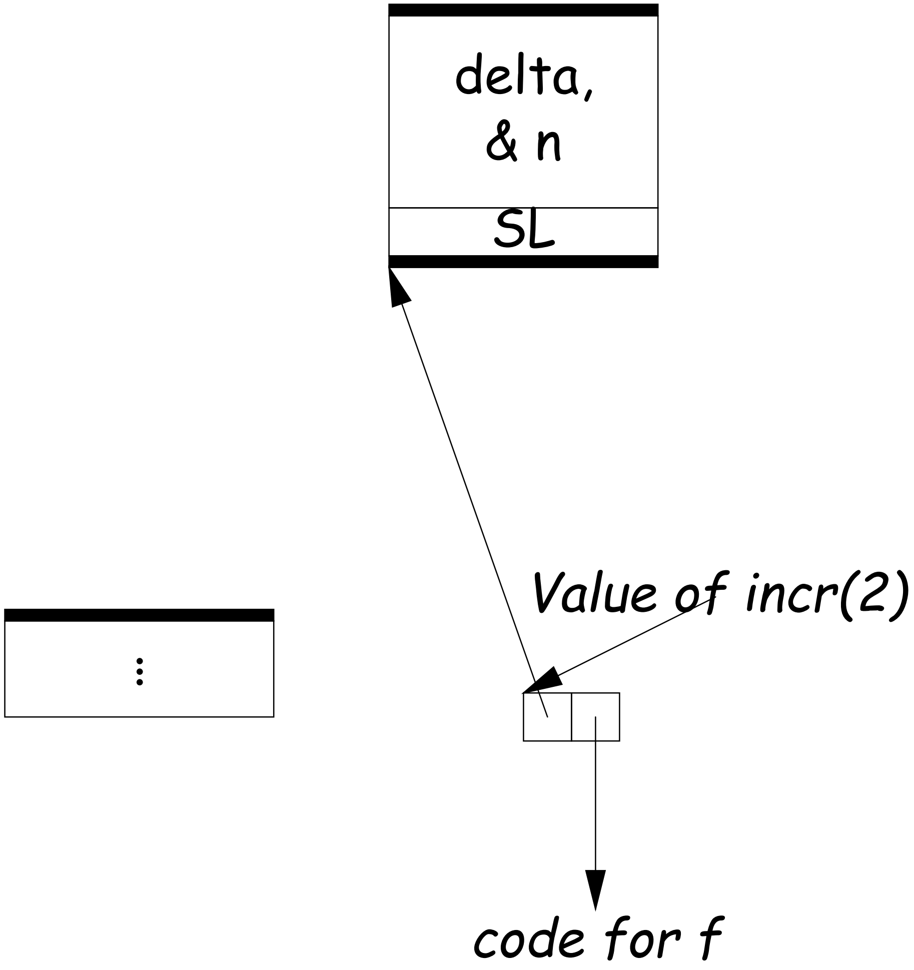
- Scheme and Python allow it and do the right thing.
- But must in general put local variables (and a static link) in a record on the heap, instead of on the stack.
- Now frame can disappear harmlessly.



7: Continuations

- Suppose function return were not the end?

```
def f (cont): return cont
x = 1
def g (n):
  global x, c
  if n == 0:
     print "a", x, n,
     c = call_with_continuation (f)
     print "b", x, n,
  else: g(n-1); print "c", x, n,
g(2); x += 1; print; c()
```

```
# Prints:
#  a 1 0 b 1 0 c 1 1 c 1 2
#  b 2 0 c 2 1 c 2 2
#  b 3 0 c 3 1 c 3 2
...
```

- The *continuation*, c, passed to f is "the function that does whatever is supposed to happen after I return from f."
- Can be used to implement exceptions, threads, co-routines.
- Implementation? Nothing much for it but to put all activation frames on the heap.
- Distributed cost.
- However, we can do better on special cases like exceptions.

Summary

	Problem	Solution
1.	Plain: no recursion, no nesting, fixed-sized data with size known by compiler, first-class function values.	Use inline expansion or use static variables to hold return addresses, locals, etc.
2.	#1 + recursion	Need stack.
3.	#2 + Add variable-sized unboxed data	Need to keep both stack pointer and frame pointer.
4.	#3 – first-class function values + Nested functions, up-level addressing	Add static link or global display.
5.	#4 + Function values w/ properly nested accesses: functions passed as parameters only.	Static link, function values contain their link. (Global display doesn't work so well)
6.	#5 + General closures: first-class functions returned from functions or stored in variables	Store local variables and static link on heap.
7.	#6 + Continuations	Put everything on the heap.