Lecture #24: Achieving Runtime Effects—Functions

- 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)
```

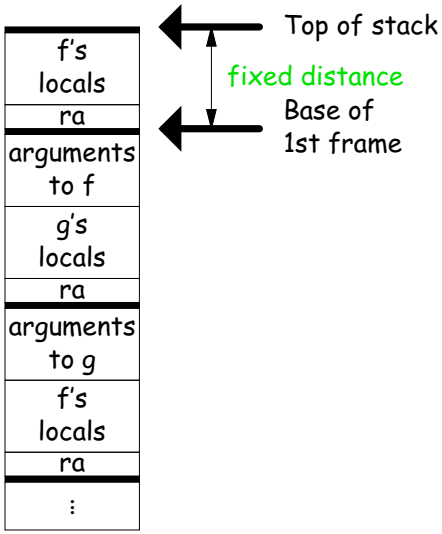
⟹ becomes ⟹

```
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.

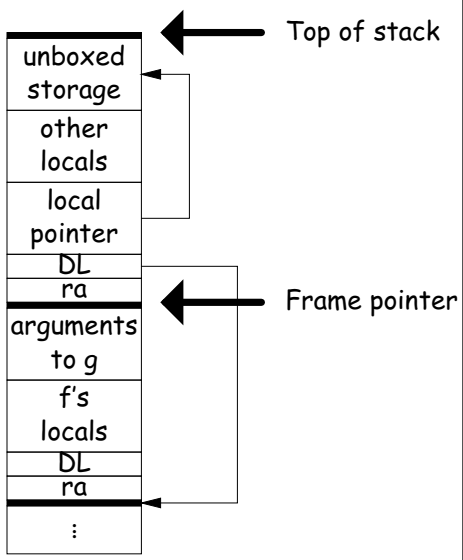
2: Add recursion

- 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.
- So dynamic links not really needed. Suppose f calls g calls f, as at right.
- If stack pointer in register, all variables and next frame are at known offsets from stack pointer.



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 need dynamic link (DL).
- Can still insure fixed offsets of data from frame base (*frame pointer*).
- Suppose f calls g, which has variable-sized unboaxed array (see right).

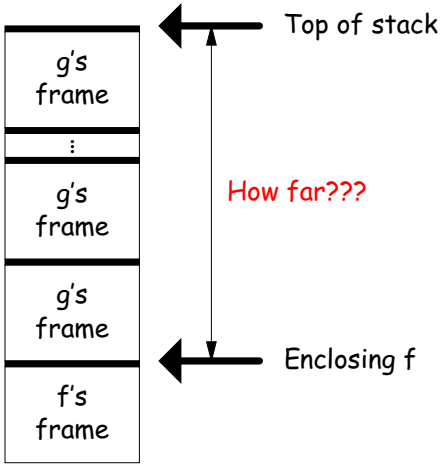


4: Allow Nesting of Functions, Up-Level Addressing

- 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 recent Python):

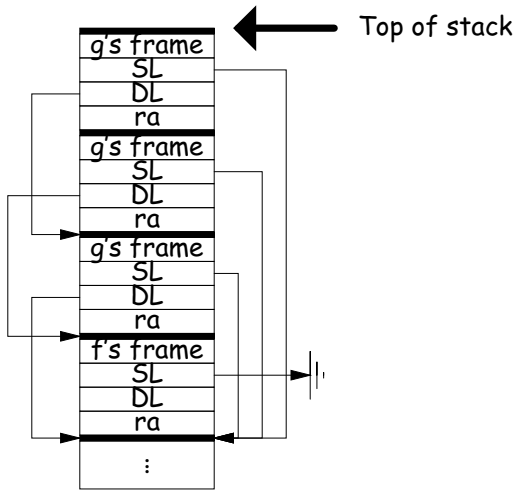
```
def f ():
  y = 42  # Local to f
  def g (n, q):
     if n == 0: return q+y
     else: return g (n-1, q*2)
```

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



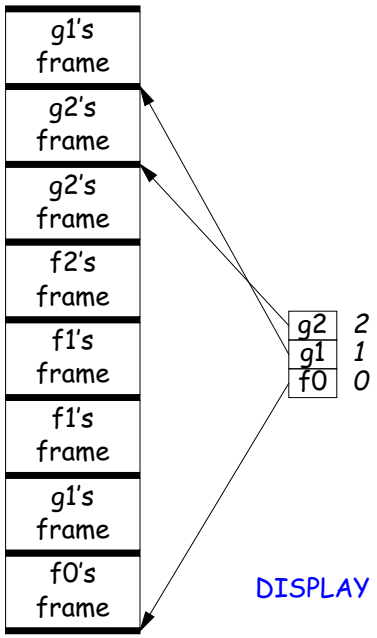
Static Links

- 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
    def f1 ():
       def f2 (): ... g2 () ...
       def g2 (): ... g1 () ...
    def g1 (): ... f1 () ...
```

- 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