Lecture #15: Introduction to Runtime Organization

Status

- Lexical analysis
  - Produces tokens
  - Detects & eliminates illegal tokens
- Parsing
  - Produces trees
  - Detects & eliminates ill-formed parse trees
- Static semantic analysis
  - Produces *decorated tree* with additional information attached
  - Detects & eliminates remaining static errors
- Next are the dynamic "back-end" phases: ⟸ *we are here*
  - Code generation (at various semantic levels)
  - Optimization

Run-time environments

Before discussing code generation, we need to understand what we are trying to generate.

- We'll use the term *virtual machine* to refer to the compiler's target.
- Can be just a bare hardware architecture (small embedded systems).
- Can be an interpreter, as for Java, or an interpreter that does additional compilation at execution, as in modern Java JITs
- For now, we'll stick to hardware + conventions for using it (the *API: application programmer's interface*) + some *runtime-support library.*

Code Generation Goals and Considerations

- *Correctness:* execution of generated code must be consistent with the programs' specified dynamic semantics.
- In general, however, these semantics do not completely specify behavior, often to allow compiler to accomplish other goals, such as...
- *Speed:* produce code that executes as quickly as possible, or reliably meets certain timing constraints (as in real-time systems).
- *Size:* minimize size of generated program or of runtime data structures.
- Speed and size optimization can be conflicting goals. Why?
- *Compilation speed:* especially during development or when using JITs.
- Most complications in code generation come from trying to be fast as well as correct, because this requires attention to special cases.

Subgoals and Constraints

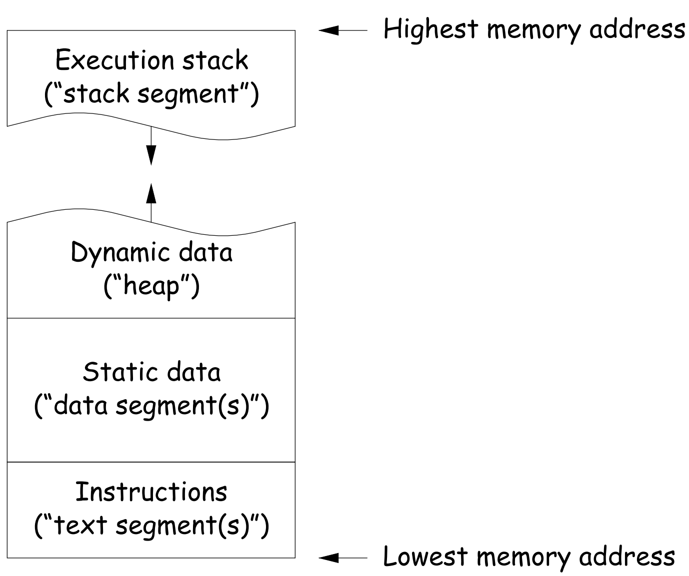
- Subgoals for improving speed and size:
  - Minimize instruction counts.
  - Keep data structure static, known at compilation (e.g., known constant offsets to fields). Contrast Java and Python.
  - Maximize use of registers ("top of the memory hierarchy").
- Subgoals for improving compilation speed:
  - Try to keep analyses as *local* as possible (single statement, block, procedure), because their compilation-time cost tends to be nonlinear.
  - Simplify assumptions about control flow: procedure calls "always" return, statements generally execute in sequence. (Where are these violated?)

Activations and Lifetimes (Extents)

- An invocation of procedure P is an *activation* of P.
- The *lifetime of an activation* of P is all the steps to execute P, including all the steps in procedures P calls.
- The *lifetime (extent) of a variable* is the portion of execution during which that variable exists (whether or not the code currently executing can reference it).
- Lifetime is a dynamic (run-time) concept, as opposed to scope, which is static.
- Lifetimes of procedure activations and local variables properly nest (in a single thread), suggesting a *stack* data structure for maintaining their runtime state.
- Other variables have extents that are not coordinated with procedure calls and returns.

Memory Layout

Characteristics of procedure activations and variables give rise to the following typical data layout for a (single-threaded) program:



Activation Records

- The information needed to manage one procedure activation is called an *activation record (AR)* or *(stack) frame.*
- If procedure F (the *caller*) calls G (the *callee,* typically G's activation record contains a mix of data about F and G:
  - *Return address* to instructions in F.
  - *Dynamic link* to the AR for F.
  - Space to save registers needed by F.
  - Space for G's local variables.
  - Information needed to find non-local variables needed by G.
  - Temporary space for intermediate results, arguments to and return values from functions that G calls.
  - Assorted machine status needed to restore F's context (signal masks, floating-point unit parameters).
- Depending on architecture and compiler, registers typically hold part of AR (at times), especially parameters, return values, locals, and pointers to the current stack top and frame.

Calling Conventions

- Many variations are possible:
  - Can rearrange order of frame elements.
  - Can divide caller/callee responsibilities differently.
  - Don't need to use an array-like implementation of the stack: can use a linked list of ARs.
- An organization is better if it improves execution speed or simplifies code generation
- The compiler must determine, at compile-time, the layout of activation records and generate code that correctly accesses locations in the activation record.
- Furthermore, it is common to compile procedures separately and without access of each other's details, which motivates the the imposition of *calling conventions*.

Static Storage

- Here, "static storage" refers to variables whose extent is an entire execution and whose size is typically fixed before execution.
- Not generally stored in an activation record, but assigned a fixed address once.
- In *C/C++* variables with file scope (declared `static` in *C*) and with external linkage ("global") are in static storage.
- Java's "static" variables are an odd case: they don't really fit this picture (why?)

Heap Storage

- Variables whose extent is greater than that of the AR in which they are created can't be kept there:

```
Bar foo() { return new Bar(); }
```

- Call such storage *dynamically allocated*.
- Typically allocated out of an area called the *heap* (confusingly, not the same as the heap used for priority qeues!)

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_1 = 3
   x *= 42                              x_1 *= 42
   y = 9 + x;       ⟹ becomes ⟹         y_1 = 9 + x_1
   g (x, y)                             g (x_1, y_1)

f (3)
```

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

1: Calling conventions

- If we don't use function inlining, will need to save return address, parameters.
- There are many options. Here's one example, from the IBM 360, of calling function F from G and passing values 3 and 4:

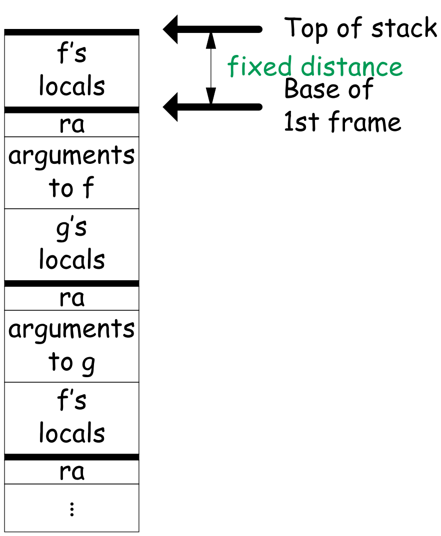
```
GArgs  DS    2F          Reserve 2 4-byte words of static storage */
       ...
       ENTRY G
G      ...
       LA    R1,GArgs    Load Address of arguments into register 1
       LA    R0,3        Store 3 and 4 in GArgs+0 and GArgs+4
       ST    R0,GArgs
       LA    R0,4
       ST    R0,GArgs+4
       BAL   R14,F       Call ("Branch and Link") to F, R14 gets return point
```

and F might contain

```
FRet   DS    F
       ENTRY F
F      ST    R14,FRet    Save return address
       L     R2,0(R1)    Load first argument.
       ...
       L     R14,FRet    Get return address
       BR    R14         Branch to it
```

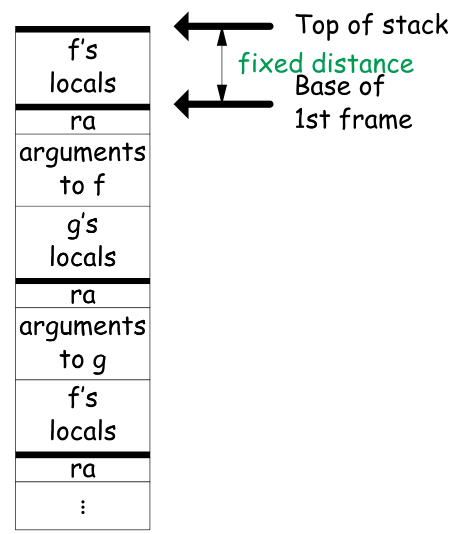

2: Add recursion

- 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.
- (The diagram shows the conventions we use in the ia32, where we'll define a stack frame as starting *after* the return address.)



2: 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.



2: Calling sequence from ia32

C code:

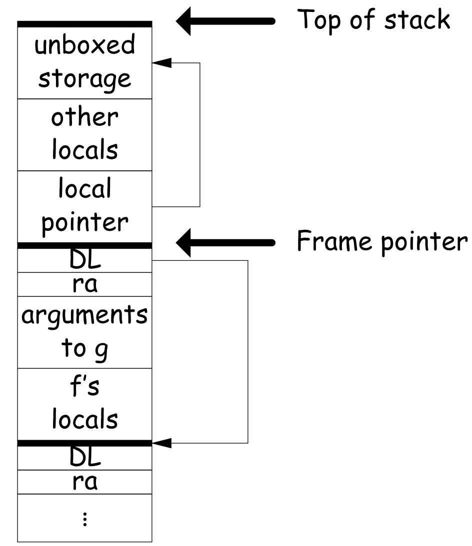
```
int
f (int x, int y)
{
  int s;
  s = 1;
  while (y > 0) {
    s *= x;
    y -= 1;
  }
  return s;
}

int
g(int q)
{
  return f(q, 5);
}
```

Assembly excerpt (GNU operand order):

```
  / PRO = Prologue, EPI = Epilogue
f:         / Return address (RA) at SP, x at SP+4, y at SP+8
   subl  $4, %esp       / PRO: Decrement SP to make space for s
   movl  $1, (%esp)     / s = 1
.L2:
   cmpl  $0, 12(%esp)   / compare 0 with y (now at SP+12)
   jle   .L3
   movl  (%esp), %eax   / tmp = s
   imull 8(%esp), %eax  / tmp *= x
   movl  %eax, (%esp)   / s = tmp
   leal  12(%esp), %eax / tmp = &y
   decl  (%eax)         / *tmp -= 1
   jmp   .L2
.L3:
   movl (%esp), %eax    / return s in EAX
   addl $4, %esp        / EPI: Restore stack pointer so RA on top,
   ret                  / EPI: then pop RA and return.

g: ...
   movl $5, 4(%esp)     / Put q and 5 on stack (q on top).
   movl 12(%esp), %eax  / tmp = q
   movl %eax, (%esp)    / top of stack = q
   call f               / branch to f and push address of next.
next:
```


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).

3: Calling sequence for the ia32

C code:

```
int
f (int x, int y)
{
  int s;
  s = 1;
  while (y > 0) {
    s *= x;
    y -= 1;
  }
  return s;
}

int
g(int q)
{
  return f(q, 5);
}
```

Assembly excerpt (GNU operand order):

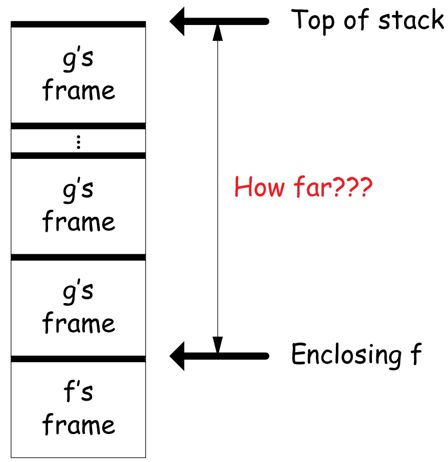
```
f:         / Return address (RA) at SP, x at SP+4, y at SP+8
   pushl %ebp            / PRO: Save old dynamic link.
   movl  %esp, %ebp      / PRO: Set ebp to current frame base.
   subl  $4, %esp        / PRO: Decrement SP to make space for s
   movl  $1, -4(%ebp)    / s = 1
.L2:
   cmpl  $0, 12(%ebp)    / compare 0 with y (now at BP+12)
   jle   .L3
   movl  -4(%ebp), %eax  / tmp = s
   imull 8(%ebp), %eax   / tmp *= x
   movl  %eax, -4(%ebp)  / s = tmp
   leal  12(%ebp), %eax  / tmp = &y
   decl  (%eax)          / *tmp -= 1
   jmp   .L2
.L3:
   movl -4(%ebp), %eax   / return s
   leave                 / EPI: Restore %esp to %ebp+4 and %ebp to 0(%ebp
   ret                   / EPI: then pop RA and return.
g: ...
   movl $5, 4(%esp)      / Put q and 5 on stack (q on top).
   movl 8(%ebp), %eax    / tmp = q
   movl %eax, (%esp)     / top of stack = q
   call f                / branch to f and push address of next.
next:
```

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 Python):

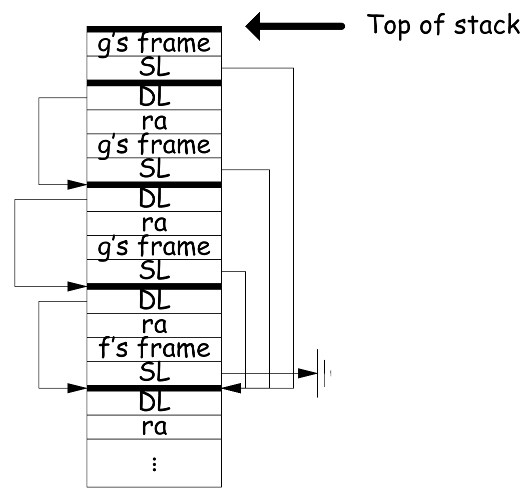
```
def f ():
  y = 42  # Local to f
  def g (n, q):
     if n == 0: return q+y
     else: return g (n-1, q*2)
```

- 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 Python 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.



Calling sequence for the ia32: f0

C code:

```
int
f0 (int n0)
{
  int s = -n0;
  int g1 () { return s; }
  int f1 (int n1) {
    int f2 () {
      return n0 + n1
             + s + g1 ();
    }
    return f2 (s) + f1 (n0)
           + g1 ();
  }
  f1 (10);
}
```

Assembly excerpt for f0:

```
f0:  / Does not need to be passed a static link
        pushl   %ebp                / PRO
        movl    %esp, %ebp          / PRO
        subl    $40, %esp           / PRO
        movl    8(%ebp), %eax       / Fetch n0
        movl    %eax, -16(%ebp)     / Move n0 to new local variable
        movl    -16(%ebp), %eax     / Negate n0...
        negl    %eax
        movl    %eax, -12(%ebp)     / ... and store in s
        leal    -16(%ebp), %eax     / Compute static link to f0's frame
        movl    $10, (%esp)         / Pass argument 10...
        movl    %eax, %ecx          / ... and static link ...
        call    f1                  / ... to f1
        leave                       / EPI
        ret                         / EPI
/ Static link into f0's frame points to:
/       int     n0'                 / Copy of n0
/       int     s
```


Calling sequence for the ia32: f1

C code:

```
int
f0 (int n0)
{
  int s = -n0;
  int g1 () { return s; }
  int f1 (int n1) {
    int f2 () {
      return n0 + n1
             + s + g1 ();
    }
    return f2 (s) + f1 (n0)
           + g1 ();
  }
  f1 (10);
}

/* Static link to f1 points to:
  int n1'    Copy of n1
  int SL     Static link
             to f0's frame */
```

```
f1: / Static link to f0's frame is in %ecx
        pushl   %ebp                / PRO
        movl    %esp, %ebp          / PRO
        pushl   %esi                / PRO: Save %esi
        pushl   %ebx                / PRO: Save %ebx
        subl    $32, %esp           / PRO
        movl    %ecx, %ebx          / Save link to f0's frame
        movl    8(%ebp), %eax       / Move n1 ...
        movl    %eax, -16(%ebp)     / ...to new local
        movl    %ebx, -12(%ebp)     / Save static link to f0 in local
        movl    4(%ebx), %edx       / Fetch s from f0's frame
        movl    %edx, (%esp)        / And pass to f2
        leal    -16(%ebp), %ecx     / Pass static link to my frame to f2
        call    f2
        movl    %eax, %esi          / Save f2(s)
        movl    (%ebx), %eax        / Fetch n0 from f0's frame...
        movl    %eax, (%esp)        / ... and pass to f1
        movl    %ebx, %ecx          / Also pass on my static link
        call    f1
        addl    %eax, %esi          / Compute f2(s) + f1(n0)
        movl    %ebx, %ecx          / Pass same static link to g1
        call    g1
        leal    (%esi,%eax), %eax   / Compute f2(s)+f1(n0)+g1()
        addl    $32, %esp           / EPI
        popl    %ebx                / EPI: restore %ebx
        popl    %esi                / EPI: restored %esi
        popl    %ebp                / EPI
        ret                         / EPI
```

Calling sequence for the ia32: g1

C code:

```
int
f0 (int n0)
{
  int s = -n0;
  int g1 () { return s; }
  int f1 (int n1) {
    int f2 () {
      return n0 + n1
             + s + g1 ();
    }
    return f2 (s) + f1 (n0)
           + g1 ();
  }
  f1 (10);
}
```

Assembly excerpt for g1:

```
g1:  / Static link (to f0's frame) in %ecx
        pushl   %ebp              / PRO
        movl    %esp, %ebp        / PRO
        movl    %ecx, %eax        / Fetch s from ...
        movl    4(%eax), %eax     / ... f0's frame
        popl    %ebp              / EPI
        ret                       / EPI
```


Calling sequence for the ia32: f2

C code:

```
int
f0 (int n0)
{
  int s = -n0;
  int g1 () { return s; }
  int f1 (int n1) {
    int f2 () {
      return n0 + n1
             + s + g1 ();
    }
    return f2 (s) + f1 (n0)
           + g1 ();
  }
  f1 (10);
}
```

Assembly excerpt for f2:

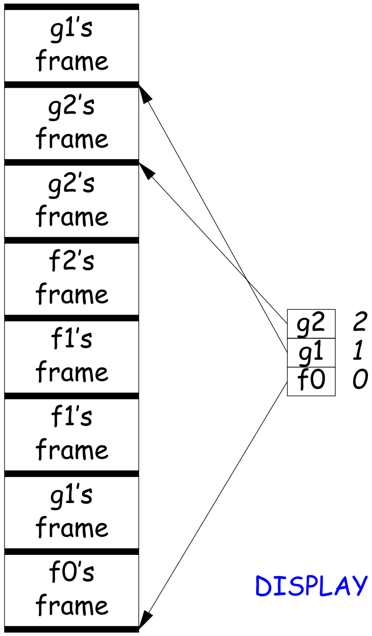
```
f2: / Static link (into f1's frame) in %ecx
        pushl   %ebp              / PRO
        movl    %esp, %ebp        / PRO
        pushl   %ebx              / PRO: Save %ebx
        movl    %ecx, %eax        / Fetch static link to f0
        movl    4(%eax), %edx     / ... from f1's frame
        movl    (%edx), %ecx      / ... to get n0 from f0's frame
        movl    (%eax), %edx      / Fetch n1 from f1's frame
        addl    %edx, %ecx        / Add n0 + n1
        movl    4(%eax), %edx     / Fetch static link to f0 again
        movl    4(%edx), %edx     / Fetch s from f0's frame
        leal    (%ecx,%edx), %ebx / And add to n0 + n1
        movl    4(%eax), %eax     / Fetch static link to f0...
        movl    %eax, %ecx        / ... and pass to g1
        call    g1
        leal    (%ebx,%eax), %eax / Add g1() to n0 + n1 + s
        popl    %ebx              / EPI: Restore %ebx
        popl    %ebp              / EPI
        ret                       / EPI
```


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



Using the global display (sketch)

C code:

```
int
f0 (int n0)
{
  int s = -n0;
  int g1 () { return s; }
  int f1 (int n1) {
    int f2 () {
      return n0 + n1
             + s + g1 ();
    }
    return f2 (s) + f1 (n0)
           + g1 ();
  }
  f1 (10);
}
```

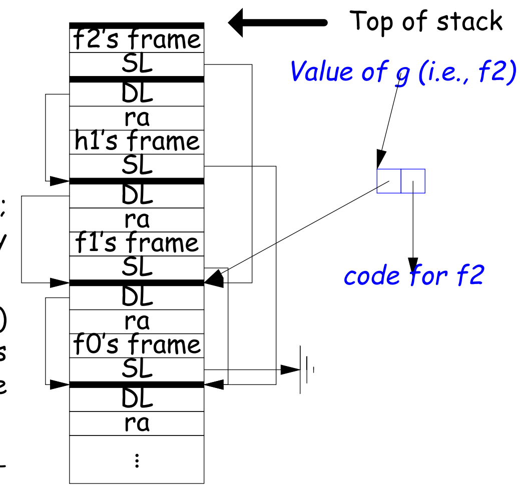
```
f0: ...
    movl  _DISPLAY+0,%eax   / PRO: Save old _DISPLAY[0]...
    movl  %eax,-12(%ebp)    / PRO: ...somewhere
    movl  %epb,_DISPLAY+0   / PRO: Put my %ebp in _DISPLAY[0]
    ...
    movl  -12(%ebp),%ecx    / EPI: Restore old _DISPLAY[0]
    movl  %ecx,_DISPLAY+0   / EPI

f1: ...
    movl  _DISPLAY+4,%eax   / PRO: Save old _DISPLAY[1]...
    movl  %eax,-12(%ebp)    / PRO: ... somewhere
    movl  %ebp,_DISPLAY+4   / PRO: Put my %ebp in _DISPLAY[1]
    ... likewise for epilogue.

f2 and g1: no extra code, since they have no nested functions.
```

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)
```

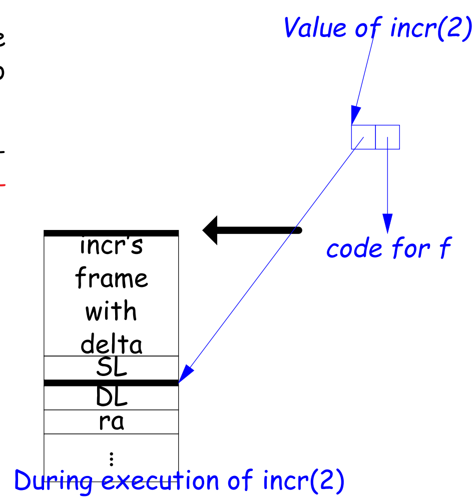


- Call `f0` from the main program; look at the stack when `f2` finally is called (see right).
- When `f2`'s value (as a function) is computed, current frame is that of `f1`. That is stored in the value passed to `h1`.
- Easy with static links; global display technique does not fare as well [why?]

6: General Closures

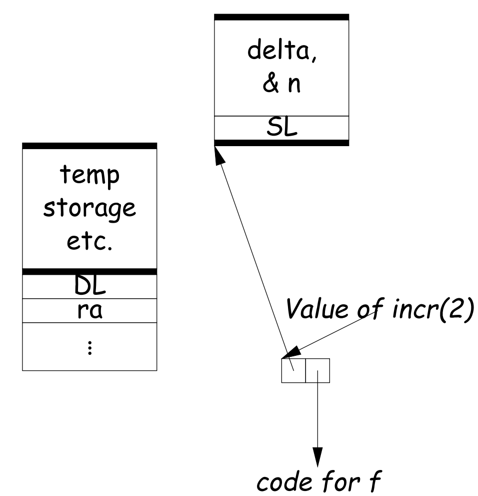
- What happens when the frame that a function value points to goes away?
- If we used the previous representation (#5), we'd get a *dangling pointer* in this case:

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

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



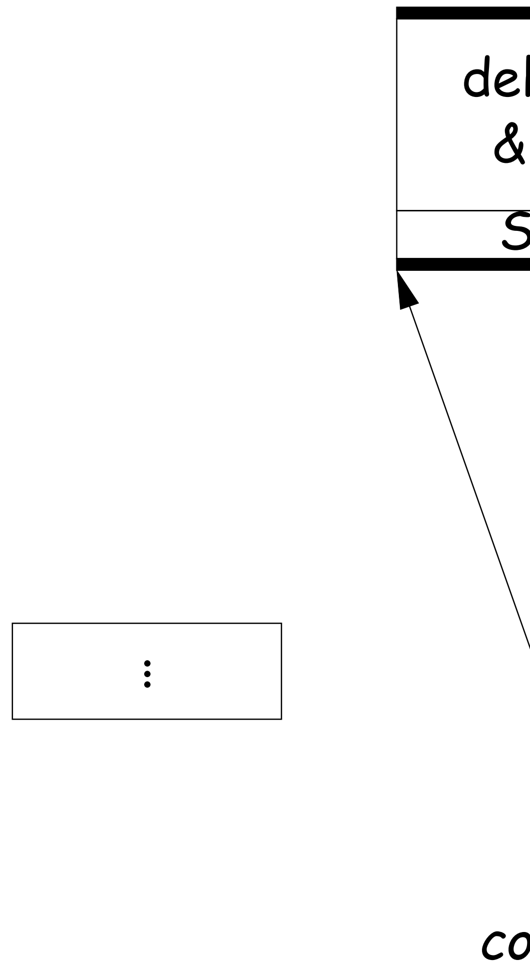
Representing Closures

- 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.



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.
- 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.