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

```
Memory Layout

<table>
<thead>
<tr>
<th>Execution stack</th>
<th>Dynamic data</th>
<th>Static data</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&quot;stack segment&quot;)</td>
<td>(&quot;heap&quot;)</td>
<td>(&quot;data segment(s)&quot;)</td>
<td>(&quot;text segment(s)&quot;)</td>
</tr>
</tbody>
</table>

Highest memory address

Lowest memory address
```
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 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:

```java
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 queues!)
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.,

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

⇒ becomes

```python
x_1 = 3
x_1 *= 42
y_1 = 9 + x_1
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:

```c
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):

```assembly
/ 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.
```

```assembly
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.
```
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 unboxed 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 \textit{unwind} the stack (i.e., pop ARs off, thus returning).
3: Calling sequence for the ia32

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.

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);
}
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):

    ```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

Assembly excerpt for f0:

C code:

```c
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: / 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: \texttt{f1}

\texttt{f1} / Static link to \texttt{f0}'s frame is in \%ecx

\begin{verbatim}
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 \texttt{f0}'s frame
movl 8(%ebp), %eax / Move n1 ... 
movl %eax, -16(%ebp) / ...to new local
movl %ebx, -12(%ebp) / Save static link to \texttt{f0} in local
movl 4(%ebx), %edx / Fetch s from \texttt{f0}'s frame
movl %edx, (%esp) / And pass to \texttt{f2}
lea -16(%ebp), %ecx / Pass static link to my frame to \texttt{f2}
call f2
movl %eax, %esi    / Save \texttt{f2}(s)
movl (%ebx), %eax  / Fetch n0 from \texttt{f0}'s frame...
movl %eax, (%esp)  / ... and pass to \texttt{f1}
movl %ebx, %ecx    / Also pass on my static link
call \texttt{f1}
addl %eax, %esi    / Compute \texttt{f2}(s) + \texttt{f1}(n0)
movl %ebx, %ecx    / Pass same static link to \texttt{g1}
call \texttt{g1}
lea (%esi,%eax), %eax / Compute \texttt{f2}(s)+\texttt{f1}(n0)+\texttt{g1}()
addl $32, %esp    / EPI
popl %ebx          / EPI: restore \%ebx
popl %esi          / EPI: restored \%esi
popl %ebp          / EPI
ret
\end{verbatim}

\texttt{C code:}

\begin{verbatim}
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 \texttt{f1} points to:
int n1’ Copy of n1
int SL Static link
to \texttt{f0}'s frame */
\end{verbatim}
Calling sequence for the ia32: \( g_1 \)

**C code:**

```c
int f0 (int n0)
{
    int s = -n0;
    int g1 () { return s; } g1: / Static link (to f0’s frame) in %ecx
    int f1 (int n1) {
        int f2 () {
            return n0 + n1
            + s + g1 ();
        }
        return f2 (s) + f1 (n0)
        + g1 ();
    }
    f1 (10);
}
```

**Assembly excerpt for \( g_1 \):**

```assembly
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

Assembly excerpt for f2:

C code:

```c
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:

```assembly
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.

```python
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.
The Global Display

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```python
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 \( \text{DISPLAY}[k] \); restore on exit.

• Access variable at lexical level \( k \) through \( \text{DISPLAY}[k] \).

• Relies heavily on scope rules and proper function-call nesting.
The Global Display

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

```python
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.

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The Global Display

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```python
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.

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The Global Display

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```python
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.

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The Global Display

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

```python
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 \( \text{DISPLAY}[k] \); restore on exit.

- Access variable at lexical level \( k \) through \( \text{DISPLAY}[k] \).

- Relies heavily on scope rules and proper function-call nesting.
The Global Display

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

  ```python
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:

```c
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
f0: ...
  movl _DISPLAY+0,%eax / PRO: Save old _DISPLAY[0]...
  movl %eax,-12(%ebp) / PRO: ...somewhere
  movl %ebp,_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]
  ...
  ...
  ...
  ...

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!!
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:

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

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

![Diagram of function execution]

Value of incr(2)

code for f

During execution of incr(2)
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:

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

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

Value of incr(2)

code for f

After return from incr(2)
delta is gone

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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.

\[
\begin{array}{c}
\text{temp storage etc.} \\
\text{DL} \\
\text{ra} \\
: \\
\end{array}
\]

\[
\begin{array}{c}
\text{delta, } \\
\& n \\
\text{SL} \\
\end{array}
\]

\text{Value of incr(2)}

\text{code for f}
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- 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?

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