Run Time Environments

ALSU Textbook Chapter 7.1–7.3

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Preliminaries

- During the execution of a program, the same name in the source can denote different data objects.
- The allocation and deallocation of data objects is managed by the run-time support package.

Terminologies:
- **environment**: the mapping of names to storage spaces. 
  \[
  \text{name} \rightarrow \text{storage space}
  \]
- **state**: the current value of a storage space. 
  \[
  \text{storage space} \rightarrow \text{value}
  \]
- **binding**: the association of a name to a storage location.

Each execution of a procedure is called an **activation**.
- Several activations of a recursive procedure may exist at the same time.
  - A recursive procedure needs not to call itself directly.
- **Life time**: the time between the first and last steps in a procedure.
Activation record (A.R.): data about an execution of a procedure.
Contents of A.R.

- Returned value for a function.
- Parameters:
  - **Formal parameters:** the declaration of parameters.
  - **Actual parameters:** the values of parameters for this activation.
- Links: where variables can be found.
  - **Control (or dynamic) link:** a pointer to the activation record of the caller.
  - **Access (or static) link:** a pointer to places of non-local data,
- Saved machine status.
- Local variables.
- Temporary variables.
  - Evaluation of expressions.
  - Evaluation of arguments.
  - Evaluation of array indexes.
  - \ldots
Issues in storage allocation

- There are two different approaches for run time storage allocation.
  - Static allocation.
    - Allocate all needed space when program starts.
    - Deallocate all space when program terminates.
  - Dynamic allocation.
    - Allocate space when it is needed.
    - Deallocate space when it is no longer needed.

- Need to worry about how variables are stored.
  - That is the management of activation records.

- Need to worry about how variables are accessed.
  - Global variables.
  - Locally declared variables, that is the ones allocated within the current activation record.
  - Non-local variables, that is the ones declared and allocated in other activation records and still can be accessed.
    - Non-local variables are different from global variables.
Static storage allocation

- code
- global data
- A.R. 1
- A.R. 2
- A.R. 3
- ...

activation records for all procedures
Static allocation: uses no stack and heap.

- Strategies:
  - For each procedure in the program, allocate a space for its activation record.
  - A.R.’s can be allocated in the static data area.
  - Names bound to locations at compiler time.
  - Every time a procedure is called, a name always refer to the same pre-assigned location.

- Used by simple or early programming languages.

Disadvantages:
- No recursion.
- Waste lots of space when procedures are inactive.
- No dynamic allocation.

Advantages:
- No stack manipulation or indirect access to names, i.e., faster in accessing variables.
- Values are retained from one procedure call to the next if block structure is not allowed.
  - For example: static variables in C.
On procedure calls,

- the calling procedure:
  - First evaluate arguments.
  - Copy arguments into parameter space in the A.R. of called procedure.
  - Conventions: call that which are passed to a procedure arguments from the calling side, and parameters from the called side.
  - May need to save some registers in its own A.R.
  - Jump and link: jump to the first instruction of called procedure and put address of next instruction (return address) into register RA (the return address register).

- the called procedure:
  - Copy return address from RA into its A.R.’s return address field.
  - control link := address of the previous A.R.
  - May need to save some registers.
  - May need to initialize local data.
Static storage allocation (3/3)

- On procedure returns,
  - the called procedure:
    - Restore values of saved registers.
    - Jump to address in the return address field.
  - the calling procedure:
    - May need to restore some registers.
    - If the called procedure is actually a function, that is the one that returns values, put the return value in the appropriate place.
Dynamic storage allocation

- **Code**: storage space for data that will not be changed during the execution: e.g., global data and constant, ...
- **Static Data**: storage space for activation records: local data, parameters, control info, ...
- **Heap**: for dynamic memory allocated by the program
- **Stack**: lower memory address
- **Dynamic Space**: higher memory address
Dynamic storage allocation for stack (1/3)

- **Stack allocation:**
  - Each time a procedure is called, a new A.R. is pushed onto the stack.
  - A.R. is popped when procedure returns.
  - A register (stack pointer or SP) points to top of stack.
  - A register (frame pointer or FP) points to start of current A.R.

![Diagram of stack allocation](image)

before procedure call  
after procedure call  
return from procedure call

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Dynamic storage allocation for stack (2/3)

- **On procedure calls,**
  - **the calling procedure:**
    - May need to save some registers in its own A.R..
    - May need to set an optional access link.
    - Push parameters onto stack.
    - *Jump and Link:* jump to the first instruction of called procedure and put address of next instruction into register RA.
  - **the called procedure:**
    - Save return address in RA.
    - Save old FP (in the control link space).
    - Set new FP (FP := SP).
    - Set new SP
      \[(SP := SP + (size of parameters) + (size of RA) + (size of FP)).\]
      (These sizes can be computed at compile time.)
    - May need to save some registers.
    - Push local data (produce actual data if initialized or just allocate spaces if not)
Dynamic storage allocation for stack (3/3)

- On procedure returns,
  - the called procedure:
    - Restore values of saved registers if needed.
    - Load return address into special register RA.
    - Restore SP (SP := FP).
    - Restore FP (FP := control link).
    - Return.
  - the calling procedure:
    - May need to restore some registers.
    - If a function that was called, put the return value into the appropriate place.
Use a tree structure to record the changing of the activation records.

Example:

```plaintext
code
main{
    r();
    q(1);
}

r{
    ...
}

q(int i)
{
    if(i>0) then q(i-1);
}
```

Diagram:

```
main
    ▼
   /  ▼
r()   q(1)
     ▼
    q(0)
```

```plaintext
Compiler notes #7, 20070615, Tsan-sheng Hsu
```
Dynamic storage allocation for heap

- Storages requested from programmers during execution:
  - Example:
    - PASCAL: `new` and `free`.
    - C: `malloc` and `free`.
  - Issues:
    - Garbage collection.
    - Dangling reference.
    - Segmentation and fragmentation.

- More or less O.S. issues.
Accessing global and local variables

- **Global variables:**
  - Access by using names.
  - Addresses known at compile time.

- **Local variables:**
  - Stored in the activation record of declaring procedure.
  - Access a local variable \( v \) in a procedure \( P \) by \( \text{offset}(v) \) from the frame pointer (FP).

  ▶ *Let local\_start(\( P \)) be the amount of spaces used by data in the activation record of procedure \( P \) that are allocated before the local data area.*

  ▶ *The value local\_start(\( P \)) can be computed at compile time.*

  ▶ *The value offset(\( v \)) is the amount of spaces allocated to local variables declared before \( v \).*

  ▶ *The address of \( v \) is FP + local\_start(\( P \)) + offset(\( v \)).*

  ▶ *The actual address is only known at run time, depending on the value of FP.*
int P()
{
    int I,J,K;
    ...
}

- **Address of J is FP** +\(\text{local\_start}(P) + \text{offset}(J)\).
  - \(\text{offset}(J)\) is \(1 \times \text{sizeof(int)}\) and is known at compile time.
  - \(\text{local\_start}(P)\) is known at compile time.
  - Actual address is only known at run time, i.e., depends on the value of FP.
Code generation routine

- Code generation:
  - gen([address #1], [assignment], [address #2], operator, address #3);
    - Use switch statement to actually print out the target code;
    - Can have different gen() for different target codes;

- Variable accessing: depend on type of [address #i], generate different codes.
  - Watch out the differences between \( l \)-address and \( r \)-address.
  - Parameter: FP+param_start+offset.
  - Local variable: FP+local_start+offset.
  - Local temp space: FP+temp_start+offset.
  - Global variable: GDATA+offset.
  - Registers, constants, ...  
  - Non-local variable: to be discussed.
Example for memory management

Diagram showing memory management with:
- Code
- Static area
- Return value
- Parameters
- Control link
- Access link
- Saved machine status
- Local variables
- Temp space

FP and SP arrows indicating the movement of data and control flow.
Variable-length local data

- Allocation of space for objects the sizes of which are not known at compile time.
  - Example: Arrays whose size depends on the value of one or more parameters of the called procedure.
  - Cannot calculate proper offsets if they are allocated on the A.R.

- Strategy:
  - Allocate these objects at the bottom of A.R.
    - *Automatically de-allocated when the procedure is returned.*
  - Keep a pointer to such an object inside the local data area.
  - Need to de-reference this pointer whenever it it used.
Accessing non-local variables

- Two scoping rules for accessing non-local data.
  - Lexical or static scoping.
    - PASCAL, C and FORTRAN.
    - The correct address of a non-local name can be determined at compile time by checking the syntax.
    - Can be with or without block structures.
    - Can be with or without nested procedures.
  - Dynamic scoping.
    - LISP.
    - A use of a non-local variable corresponds to the declaration in the “most recently called, still active” procedure.
    - The question of which non-local variable to use cannot be determined at compile time. It can only be determined at run-time.
Lexical scoping with block structures (1/2)

- **Block**: a statement containing its own local data declaration.
- **Scoping** is given by the following so called most closely nested rule.
  - The scope of a declaration in a block $B$ includes $B$ itself.
  - If $x$ is used in $B$, but not declared in $B$, then we refer to $x$ in a block $B'$, where
    - $B'$ has a declaration $x$, and
    - $B'$ is more closely nested around $B$ than any other block with a declaration of $x$.

- If a language does not allow nested procedures, then
  - a variable is either global, or is local to the procedure containing it;
  - at runtime, all the variables declared (including those in blocks) in a procedure are stored in its A.R., with possible overlapping;
  - during compiling, proper offset for each local data is calculated using information known from the block structure.
Lexical scoping with block structures (2/2)

- Maintain the current offset in a procedure.
- Maintain the amount of spaces used in each block.
  - Initialize to 0 when a block is opened.
  - Subtract the total amount of spaces used in the block from the current offset when this block is closed.

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Lexical scoping with nested procedures

- **Nested procedure**: a procedure that can be declared within another procedure.

- **Issues**:
  - What are the procedures that can be called at a given location?
  - What are the variables that can be accessed at a given location during compiler time?
  - How to access these variables during run time?
Calling procedures

- A procedure $Q_i$ can call any procedure that is its children, older siblings, direct ancestors or the older siblings of its direct ancestor.
  - The procedure $Q_{i+1}$ that is declared in $Q_i$.
  - The procedure $Q_{i-1}$ who declares $Q_i$.
  - The procedure $Q_{i-j}$ who declares $Q_{i-j+1}$, $j > 1$.
  - The procedure $P_j$ whom is declared together with, and before, $Q_j$, $j \leq i$.

- Use the symbol table to find the procedures that can be called.
A procedure can only access the variables that are either local to itself or global in a procedure that is its direct ancestor.

- When you call a procedure, a variable name follows the lexical scoping rule.
- Use the access link to link to the procedure that is lexically enclosing the called procedure.
- Need to set up the access link properly to access the right storage space.
Accessing variables (2/2)

**Nesting depth:**
- Depth of main program = 1.
- Add 1 to depth each time entering a nested procedure.
- Substrate 1 from depth each time existing from a nested procedure.
- Each variable is associated with a nesting depth.
- Assume in a depth-\(h\) procedure, we access a variable at depth \(k\), then
  - \(h \geq k\).
  - Follow the access static link \(h - k\) times, and then use the offset information to find the address.

```latex
program main
   procedure P
       procedure R
       end
       R
    end
    procedure Q
        P
    end
    Q
 end.
```

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Algorithm for setting the links

- The control link is set to point to the A.R. of the calling procedure.

- How to properly set the access link at compile time?
  - Procedure $P$ at depth $n_P$ calls procedure $X$ at depth $n_X$:
    - If $n_P < n_X$, then $X$ is enclosed in $P$ and $n_P = n_X - 1$.
      - Same with setting the control link.
    - If $n_P \geq n_X$, then it is either a recursive call or calling a previously declared procedure.
      - Observation: go up the access link once, then the depth is decreased by 1.
      - Hence, the access link of $X$ is the access link of $P$ going up $n_P - n_X + 1$ times.
  - Content of the access link in the A.R. for procedure $P$:
    - Points to the A.R. of the procedure $Q$ who encloses $P$ lexically.
    - An A.R. of $Q$ must be active at this time.
    - Several A.R.’s of $Q$ (recursive calls) may exist at the same time, it points to the latest activated one.
Program sort
var a: array[0..10] of int;
  x: int;
procedure r
var i: int;
begin ... r
end

procedure e(i,j)
begin ... e
  a[i] <-> a[j]
end

procedure q
  var k,v: int;
  procedure p
  var i,j;
  begin ... p
    call e
  end
  begin ... q
    call q or p
  end
begin ... sort
  call q
end
Accessing non-local data using DISPLAY

**Idea:**
- Maintain a global array called DISPLAY.
  - Using registers if available.
  - Otherwise, stored in the static data area.
- When procedure $P$ at nesting depth $k$ is called,
  - $\text{DISPLAY}[1], \ldots, \text{DISPLAY}[k-1]$ hold pointers to the A.R.’s of the most recent activation of the $k - 1$ procedures that lexically enclose $P$.
  - $\text{DISPLAY}[k]$ holds pointer to $P$’s A.R.
  - To access a variable with declaration at depth $x$, use $\text{DISPLAY}[x]$ to get to the A.R. that holds $x$, then use the usual offset to get $x$ itself.
  - Size of DISPLAY equals maximum nesting depth of procedures.
- Bad for languages allow recursions.

**To maintain the DISPLAY:**
- When a procedure at nesting depth $k$ is called
  - Save the current value of $\text{DISPLAY}[k]$ in the save-display area of the new A.R.
  - Set $\text{DISPLAY}[k]$ to point to the new A.R., i.e., to its save-display area.
- When the procedure returns, restore $\text{DISPLAY}[k]$ using the value saved in the save-display area.
DISPLAY: example

DISPLAY

sort(1)
a,x

q(2)
k,v
access link

q(2)
k,v
access link

p(3)
i,j
access link

e(2)
access link

static links

saved display

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Access links v.s. DISPLAY

- **Time and space trade-off.**
  - Access links require more time (at run time) to access non-local data, especially when non-local data are many nesting levels away.
  - DISPLAY probably require more space (at run time).
  - Code generated using DISPLAY is simpler.
Dynamic scoping

- Dynamic scoping: a use of a non-local variable refers to the one declared in the “most recently called, still active” procedure.
- The question of which non-local variable to use cannot be determined at compile time.
- It can only be determined at run time.
- May need symbol tables at run time.
- Two major methods for implement non-local accessing under dynamic scoping.
  - Deep access.
  - Shallow access.
Dynamic scoping – Example

program main
  procedure UsesX
  begin
    write(x);
  end
  procedure DeclaresX
    var x: int;
  begin
    x := 100;
    call UsesX;
  end
  procedure test
    var x : int;
  begin
    x := 30;
    call DeclaresX;
    call UsesX;
  end
begin
  call test;
end

- Which $x$ is it in the procedure UsesX?
- If we were to use static scoping, this is not a legal statement; No enclosing scope declares $x$. 
Deep access

Def: given a use of a non-local variable, use control links to search back in the stack for the most recent A.R. that contains space for that variable.

Requirements:

- Be able to locate the set of variables stored in each A.R. at run time.
- Need to use the symbol table at run time.
Shallow access

Idea:
- Maintain a current list of variables.
- Space is allocated (in registers or in the static data area) for every possible variable name that is in the program (i.e., one space for variable $x$ even if there are several declarations of $x$ in different procedures).
- For every reference to $x$, the generated code refers to the same location.

When a procedure is called,
- it saves, in its own A.R., the current values of all of the variables that it declares (i.e., if it declares $x$ and $y$, then it saves the values of $x$ and $y$ that are currently in the space for $x$ and $y$);
- it restores those values when the procedure returns.
Comparisons of deep and shallow accesses

- Shallow access allows fast access to non-locals variables, but there is an overhead on procedure entry and exit that is proportional to the number of local variables.
- Deep access needs to use a symbol table at run time.