Run Time Environment

Activation Records
Procedure Linkage
Name Translation and Variable Access

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Procedure Abstraction

- What is a Procedure?
  - Basic Unit of Abstraction and Program Reasoning

- Why do We use Them?
  - To allow us to build (very) large programs
  - Conceptually allows us to abstracts from all the details

- How to Generate Code?
  - Storage Allocation
  - Scoping, i.e., what is visible and where?
  - Control Transfer
The Procedure as a Control Abstraction

Procedures have well-defined control-flow

The Algol-60 procedure call
• Invoked at a call site, with some set of actual parameters
• Control returns to call site, immediately after invocation

```c
int p(a,b,c)
int a, b, c;
{
   int d;
   d = q(c,b);
   ...
}
```

```c
s = p(10,t,u);
...
```
The Procedure as a Control Abstraction

Procedures have well-defined control-flow

The Algol-60 procedure call

• Invoked at a call site, with some set of actual parameters
• Control returns to call site, immediately after invocation

```c
int p(a,b,c)
    int a, b, c;
    {
        int d;
        d = q(c,b);
        ...
    }
int q(x,y)
    int x,y;
    {
        return x + y;
    }
...
```
The Procedure as a Control Abstraction

Procedures have well-defined control-flow

The Algol-60 procedure call
- Invoked at a call site, with some set of *actual parameters*
- Control returns to call site, immediately after invocation

```plaintext
int p(a,b,c)
    int a, b, c;
    {
        int d;
        d = q(c,b);
        ...
    }

int q(x,y)
    int x,y;
    {
        return x + y;
    }

... s = p(10,t,u);
... ...
```
The Procedure as a Control Abstraction

Procedures have well-defined control-flow

The Algol-60 procedure call
- Invoked at a call site, with some set of actual parameters
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The Procedure as a Control Abstraction

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- Invoked at a call site, with some set of *actual parameters*
- Control returns to call site, immediately after invocation

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int p(a,b,c)
    int a, b, c;
    {
        int d;
        d = q(c,b);
        ...
    }

int q(x,y)
    int x, y;
    {
        return x + y;
    }
```

- Most Languages Allow Recursion
Compilation Issues

• How to Generate Code
  – Storage for Local Variables
  – Transfer of Arguments and Return Results

• How to Execute a Procedure
  – How to Access Local and Non-Local Variables
  – How to Communicate between Caller and Callee
  – How to Transfer Control between Caller and Callee

• The Role of the Symbol Table
  – Keep track of where names are defined and declared
  – Scope and Lifetime
Run-Time Storage Organization

Classical Organization

- Code, Static, & Global Data have known size
  → Use symbolic labels in the code

- Heap & Stack grow and shrink over time
  → Stack used for Activation Records (AR)
  → Heap for data (including AR) whose lifetime extends beyond activation.

- This is a virtual address space
Activation Record Basics

- **parameters**: Space for parameters to the current routine
- **register save area**: Saved register contents
- **return value**: If function, space for return value
- **return address**: Address to resume `caller`
- **access link**: Help with non-local access
- **caller’s ARP**: To restore caller’s AR on a return
- **local variables**: Space for local values & variables (including spills)

One **AR** for each invocation of a procedure
Activation Records on the Stack

• What Happens on a Call?
  • Passing of Arguments
  • Transfer of Control

• What Happens on a Return?
  • Recovery of Results (if any)
  • Transfer of Control

• Need to Save/Restore Execution Context?
  • ARP, PC, Access Link,
  • Register Values
Procedure Linkages

Standard procedure linkage

Procedure has
- standard prolog
- standard epilog

Each call involves a
- pre-call sequence
- post-return sequence

These are completely predictable from the call site and depend on the number & type of the actual parameters.
Procedure Linkages

**Pre-Call** Sequence

- Sets up Callee’s basic AR
- Helps preserve its own environment

**The Details**

- **Allocate Space for the Callee’s AR**
  - except space for local variables
- Evaluates each parameter & stores value or address
- Saves return address, caller’s ARP into callee’s AR
- If access links are used
  - Find appropriate lexical ancestor & copy into callee’s AR
- Save any caller-save registers
  - Save into space in caller’s AR
- Jump to address of callee’s prolog code
Procedure Linkages

Post-Return Sequence
• Finish restoring caller’s environment
• Place any value back where it belongs

The Details
• Copy return value from callee’s AR, if necessary
• Free the callee’s AR
• Restore any caller-save registers
• Restore any call-by-reference parameters to registers, if needed
  – Also copy back call-by-value/result parameters
• Continue execution after the call
Procedure Linkages

**Prolog Code**

- Finish setting up the callee’s environment
- Preserve parts of the caller’s environment that will be disturbed

**The Details**

- Preserve any callee-save registers
- If *display* is being used
  - Save display entry for current lexical level
  - Store current ARP into display for current lexical level
- Allocate space for local data
  - Easiest scenario is to extend the AR
- Find any static data areas referenced in the callee
- Handle any local variable initializations

With heap allocated AR, may need to use a separate heap object for local variables
Procedure Linkages

**Epilog** Code

- Wind up the business of the callee
- Start restoring the caller’s environment

**The Details**

- Store return value? No, this happens on the return statement
- Restore callee-save registers
- Free space for local data, if necessary *(on the heap)*
- Load return address from AR
- Restore caller’s ARP
- Jump to the return address

*If ARs are stack allocated, this may not be necessary. (Caller can reset stacktop to its pre-call value).*
Simplified Example

1. program sort(input, output);
2. var a: array [0..10] of integer;
3.   x, i: integer;
4. procedure readarray;
5.   var i : integer;
6. begin ... a... end { readarray } ;
7. procedure exchange(i, j: integer);
8. begin
9.   x := a[i]; a[i] := a[j]; a[j] := x;
10. end { exchange } ;
11. procedure quicksort(m, n : integer);
12. var k, v: integer;
13. function partition(y, z : integer) : integer;
14. var i, j : integer;
15. begin ... a ...
16.   ... v ...
17.   ... exchange(i,j); ...
18. end { partition };
19. begin ... end { quicksort }
20. begin ... end { sort }

sort
ret address
arp link
a,x

quicksort(1,9)
ret address
arp link
k,v

quicksort(1,3)
ret address
arp link
k,v

partition(1,3)
ret address
arp link
i,j
Activation Record Details

Where do activation records live?

- If lifetime of AR matches lifetime of invocation, **AND**
- If code normally executes a "return" ⇒ Keep ARs on a stack

- If a procedure can outlive its caller, **OR**
- If it can return an object that can reference its execution state ⇒ ARs **must** be kept in the heap

- If a procedure makes no calls ⇒ AR can be allocated statically

Efficiency prefers static, stack, then heap
Activation Record Details

How does the Compiler find the Variables?

• They are at known offsets from the AR pointer
• Code nesting level and AR offset within a procedure
  – Level specifies an ARP, offset is the constant

Variable-length data

• If AR can be extended, put it after local variables
• Leave a pointer at a known offset from ARP
• Otherwise, put variable-length data on the heap

Initializing local variables

• Must generate explicit code to store the values
• Among the procedure’s first actions
Storage for Blocks within a Single Procedure

- Fixed length data can always be at a constant offset from the beginning of a procedure
  - In our example, the a declared at level 0 will always be the first data element, stored at byte 0 in the fixed-length data area
  - The x declared at level 1 will always be the sixth data item, stored at byte 20 in the fixed data area
  - The x declared at level 2 will always be the eighth data item, stored at byte 28 in the fixed data area
  - But what about the a declared in the second block at level 2?
Variable-length Data

Arrays
→ If size is fixed at compile time, store in fixed-length data area
→ If size is variable, store descriptor in fixed length area, with pointer to variable length area
→ Variable-length data area is assigned at the end of the fixed length area for block in which it is allocated

| a | b | v | b | x | x | y(8) | v(a) |

Includes variable length data for all blocks in the procedure ...
Translating Local Names

How does the compiler represent a specific instance of $x$?

• Name is translated into a *static coordinate*
  
  – $<\text{level}, \text{offset}>$ pair
  
  – “level” is lexical nesting level of the procedure
  
  – “offset” is *unique* within that scope

• Subsequent code will use the static coordinate to generate addresses and references

• “level” is a function of the table in which $x$ is found
  
  – Stored in the entry for each $x$

• “offset” must be assigned and stored in the symbol table
  
  – Assigned at compile time
  
  – Known at compile time
  
  – Used to generate code that executes at run-time
Scoping Rules

• Scoping
  – Define which instance each name refers to

• Lexical Scoping
  – Look at the source text of the code
  – Determine the closest (nesting structure) name
  – Ex. FORTRAN, C, Pascal.

• Dynamic Scoping
  – Check at Run-Time the closest variable with the same name
  – Ex. Scheme, Lisp, Miranda, etc.
Lexical Scoping Example

1. program sort(input, output);
2. var a: array [0..10] of integer;
3. x, i: integer;
4. procedure readarray;
5. var i : integer;
6. begin ... a... end { readarray } ;
7. procedure exchange(i, j: integer);
8. begin
9.  x := a[i]; a[i] := a[j]; a[j] := x;
10. end { exchange } ;
11. procedure quicksort(m, n : integer);
12. var k, v: integer;
13. function partition(y, z : integer) : integer;
14. var i, j : integer;
15. begin ... a...
16. .... v...
17. .... exchange(i,j); ...
18. end { partition }
19. begin ... end { quicksort }
20. begin ... end { sort }
Nested Procedures & Symbol Tables

1. program sort(input, output);
2. var a: array [0..10] of integer;
3. x, i: integer;
4. procedure readarray;
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6. begin ... a ... end { readarray } ;
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9.   x := a[i]; a[i] := a[j]; a[j] := x;
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15. begin ... a ...
16.   ... v ...
17. end { partition }
18. begin ... end { quicksort }
19. begin ... end { sort }
20. begin ... end { sort }
Static Allocation

- Local variables are bound to fixed location in storage
  - Values can be retained across procedure call (static)
  - Save PC in AR but no need for stack

- Limitations:
  - Fixed size variables only
  - Does not support recursion
  - No dynamic memory allocation

- Advantages:
  - Simplified code generation

```
subroutine A()
  integer i
  real a(100), b(10,10)
  do 100 i=1, 10
    a(i*10) = b(i,10)
  100: continue
end

subroutine B()
  integer i, c(10)
  do 200 i=1, 10
    c(i) = 0
  200: continue
end
```
Lexical Scopes Without Nested Procedures

- Easy location of variables
  - Either local, i.e., in the AR
  - Global, i.e. at specified global offset

- Why Do with Need a Stack?

1. program sort(input, output);
2. var a: array [0..10] of integer;
3. x: integer;
4. procedure readarray;
5. var i : integer;
6. begin ... a... end { readarray } ;
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8. begin
9.   x := a[i]; a[i] := a[j]; a[j] := x;
10. end { exchange } ;
11. function partition(y, z : integer) : integer;
12. var i, j : integer;
13. begin ... a ...
14. ... exchange(i,j); ...
15. end { partition }
16. procedure quicksort(m, n : integer);
17. var k, v: integer;
18. begin ... end { quicksort }
19. begin ... end { sort }
Lexical Scope With Nested Procedures

- Problem!
  - Now quicksort might have to access $a, x$ at sort ...
  - Also, partition needs to access $k, v$ at quicksort
  - But which one?
- Need to keep Track of Depth
  - (static) Nesting Depth
    - sort at depth 1
    - readarray, quicksort at depth 2
    - partition at depth 3
  - Implementation
    - Link Chasing in AR
    - Reflect Nesting Structure During Calls
    - Display indexed by depth

```
1. program sort(input, output);
2. var $a$: array [0..10] of integer;
3.  $x$: integer;
4. procedure readarray;
5.   var $i$: integer;
6.   begin ... a... end { readarray } ;
7. procedure exchange($i, j$: integer);
8.   begin 
10.   end { exchange } ;
11. procedure quicksort($m, n$: integer);
12.   var $k, v$: integer;
13.   function partition($y, z$: integer) : integer;
14.     var $i, j$: integer;
15.     begin ... a ...
16.       ... v ...
17.       ... exchange($i,j$); ...
18.     end { partition }
19.     begin ... end { quicksort }
20.     begin ... end { sort }
```
Activation Records on the Stack

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| partition(1,3) | access link | i,j            | exchange(1,3) | access link |
Lexical Scoping Example

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17.  ... exchange(i,j); ...
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19. begin ... end { quicksort }
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Access Links and How to Use Them

- Suppose procedure \( p \) at lexical nesting depth \( n_p \) refers to non-local variable \( a \) at depth \( n_q \leq n_p \), then \( a \) can be found:
  1. Follow \( n_p - n_q \) access links from AR of \( p \)
  2. Access the variable at offset \( a \) in ‘that’ AR

- Example:
  - partition code at depth = 3 refers to \( v \) and \( a \) at depth 2 and 1 for which the code should traverse 1 and 2 access links respectively.

- Since \( (n_p - n_q) \) can be computed at compile-time this tracing “method” is always feasible.

- What happens if \( n_q > n_p \)?
Access Links and How to Use Them

• Suppose procedure p at lexical nesting depth \( n_p \) refers to non-local variable \( a \) at depth \( n_q \leq n_p \), then \( a \) can be found:
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• Since \( (n_p - n_q) \) can be computed at compile-time this tracing “method” is always feasible.

• What happens if \( n_q > n_p \)?
  - Variable \( a \) is not visible! The compiler will never allow this access.
How to Set Up Access Links?

• Procedure $p$ at depth $n_p$ calls $q$ at depth $n_q$

• Code generated as part of the calling sequence:
  – Case $n_q > n_p$: procedure $q$ is nested more deeply than $p$; it must be declared within $p$, i.e. $n_q = n_p + 1$; **Why**?
    • **Action**: copy ARP pointer of the caller’s to the callee’s access link as this creates an additional indirection (another level)
  – Case $n_q \leq n_p$: all the ARs of the procedures up to $p$ are the same, simply need to access the link of the most recent invocation of $p$;
    • **Action**: Follow $n_q - n_p + 1$ access links you reach the correct AR of procedure $r$ that encloses $p$ to set the access link in the AR of $q$. 
How to Set Up Access Links?

- Code generated as part of the calling sequence:
  - Case $n_q > n_p$: procedure $q$ is nested more deeply than $p$; it must be declared within $p$, \textit{i.e.} $n_q = n_p + 1$; \textbf{Why?}
    - \textbf{Action}: copy ARP pointer of the caller’s to the callee’s access link

- Example:
  - quicksort ($n_p=2$) calls \texttt{partition($n_p=3$)}
How to Set Up Access Links?

- Code generated as part of the calling sequence:
  - Case \( n_p > n_p \): all the ARs of the procedures up to \( p \) are the same, simply need to access the link of the most recent invocation of \( p \);
  - **Action**: Follow \( n_q - n_p + 1 \) access links you reach the correct AR of procedure \( r \) that encloses \( p \) to set the access link in the AR of \( q \).

- Example:
  - \( \text{quicksort} \ (n_p=2) \)
  - \( \text{calls quicksort} \ (n_p=2) \)

```
sort
  a,x
  quicksort(1,9)
    access link
     k,v

sort
  a,x
  quicksort(1,9)
    access link
     k,v
  quicksort(1,3)
    access link
     k,v
```
Lexical Scope with Nested Procedures

sort
   a,x
   quicksort(1,9)
   access link
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   a,x
   quicksort(1,9)
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   k,v
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   access link
   k,v
   partition(1,3)
   access link
   i,j

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   a,x
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   k,v
   quicksort(1,3)
   access link
   k,v
   partition(1,3)
   access link
   i,j
   exchange(1,3)
   access link

sort calls quicksort
   \( n_q = n_p + 1 \)

quicksort calls quicksort
   \( n_q = n_p \)

quicksort calls partition
   \( n_q = n_p + 1 \)

partition calls exchange
   \( n_p = n_q + 1 \)
Display

• Following Access Links can take a long Time

• Solution?
  – Keep an auxiliary array of pointers to AR on the stack
  – Storage for a non-local at depth $i$ is in the activation record pointed to by $d[i]$ called $display$.
  – Faster because you need to follow a single pointer

• How to Maintain the $display$?
  – When AR of procedure at depth $i$ is set up:
    • Save the value of $d[i]$ in the new AR
    • Set $d[i]$ to point to the new AR.
  – Just before an activation ends, $d[i]$ is reset to the saved value
    • Values in saved at a specific offset on the AR like ARP and return
Display: Example

- \( P \) at depth \( n_p \) calls \( Q \) at depth \( n_q \)
- Case \( n_q > n_p \): then \( n_q = n_p + 1 \)
  - First \( n_p \) elements of the display do not change; just set \( d[n_q] \) to new AR.
- Case \( n_q \leq n_p \):
  - Enclosing procedures at levels 1, ..., \( n_q-1 \) are the same; save old \( d[n_q] \) in new AR and make \( d[n_q] \) point to new AR.
Display: Example

- P at depth $n_p$ calls Q at depth $n_q$
- Case $n_q > n_p$: then $n_q = n_p + 1$
  - First $n_p$ elements of the display do not change; just set $d[n_q]$ to new AR.
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Display: Example

- P at depth $n_p$ calls Q at depth $n_q$

- Case $n_q > n_p$: then $n_q = n_p + 1$
  - First $n_p$ elements of the display do not change; just set $d[n_q]$ to new AR.

- Case $n_q \leq n_p$:
  - Enclosing procedures at levels 1, ..., $n_q-1$ are the same; save old $d[n_q]$ in new AR and make $d[n_q]$ point to new AR.

```
sort

a,x

quicksort(1,9)

k,v
```

```
d[1]
d[2]
d[3]
```
Display: Example

- P at depth $n_p$ calls Q at depth $n_q$
- Case $n_q > n_p$: then $n_q = n_p + 1$
  - First $n_p$ elements of the display do not change; just set $d[n_q]$ to new AR.
- Case $n_q \leq n_p$:
  - Enclosing procedures at levels 1, ..., $n_q-1$ are the same; save old $d[n_q]$ in new AR and make $d[n_q]$ point to new AR.
Complications

• Passing Functions as Arguments?
  – Just an address of the code, not that hard to implement
  – Need to verify at run-time the number of arguments.
  – Access Link needs to be passed to understand how to follow it…

• What if AR outlives Execution of Procedure?
  – When is this possible?
  – What to do?

• Dynamically Linked Libraries
  – What are the issues with “regular” libraries?

• Position-Independent Code
  – Why is this important?
Code Sharing

• Traditionally Link all Libraries with your code

• Drawbacks:
  – Space as each executable includes the code of all libraries it uses (big as every function needs to be included at link time)
  – Bugs in libraries require recompilation and linking

• Solution: Dynamically Linked Libraries
  – Loaded and linked on-demand during execution

• Advantages:
  – Single Copy in the system rather than replicated.
  – Executable has only what is really needs.
  – Bugs can be fixed later not requiring re-linking
Shared Libraries

• Make it Look Like a Statically Linked

• Linking?
  – Name Resolution: finding bindings for symbols

• Determine before hand if linking will succeed
  – Check for undefined or multiply defined symbols
  – Create a table of symbols for each shared library
  – Pre-execution linking checks the tables
  – Run-time dynamic linker is guaranteed to fail if and only if the pre-execution static linker would.
Summary

• What Have We Learned?
  – AR is a Run-time Structure to hold State regarding the Execution of a Procedure
  – AR can be allocated in Static, Stack or even Heap
  – Links allow Call-Return and Access to Non-local Variables
  – Symbol-Table plays Important Role

• Linkage Conventions
  – Saving Context before Call and restoring after Call
  – Need to understand how to generate code for body