

COMP151: Object-Oriented Programming

Procedures and Functions: Scope and Parameter Passing, Activation Records

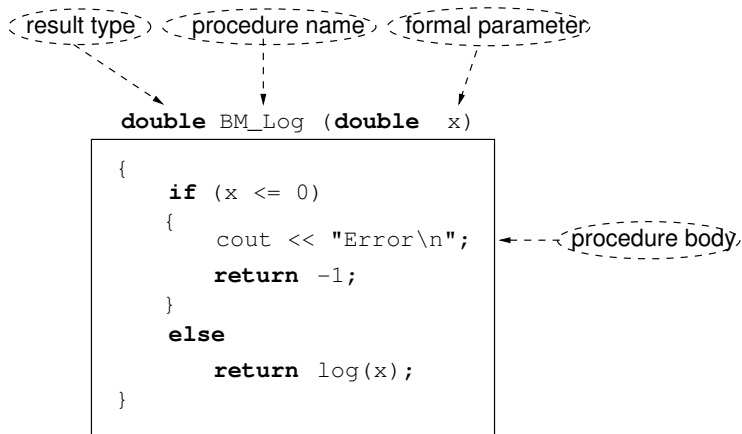
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Spring 2007

Elements of a Procedure



A call of the procedure will be something like:

```
BM_Log(2.5);    /* 2.5 is the actual parameter */
```

Procedure

- function (function procedure):
 - returns a result to the caller
 - extends the built-in operators (+, -, ×, /). e.g. sin(x)
- procedure (proper procedure):
 - does not return a result
 - extends the built-in actions/statements. e.g. free(x)
- But they are both called “functions” in C.
- And, unfortunately, functions are called “procedures” in Scheme.
- Procedures/functions are called using prefix notation.
i.e. <procedure-name> (<formal-parameter-list>)
(c.f. Built-in binary operations are in infix notation.)
- The parentheses “(” and “)” are redundant.
- The use of a procedure = a call of the procedure.
- The execution of a procedure body = an activation of the procedure.

Procedure: Benefits

- Modular Design: program \longrightarrow set of subprograms
 - better organization \Rightarrow easier to read/maintain
 - easier to develop (“divide-and-conquer”)
- Procedure Abstraction: during the design phase, it abstracts away from *how* it works, and let’s think in terms of *what* it does.
- Implementation Hiding: allows programmers to modify the underlying algorithm *without* affecting the high-level design.
- Libraries: allow procedures of well-designed interface to be shared (reusable codes)

```
int factorial(int x)
{
    if (x < 0)
        exit(-1);
    else if (x <= 1)
        return 1;
    else
        return x*factorial(x-1);
}
```

- A recursive procedure can have **multiple** activations in progress at the same time.

e.g $F(4) \Rightarrow 4 * F(3) \Rightarrow 4 * (3 * F(2)) \Rightarrow 4 * (3 * (2 * F(1)))$

Recursion: Example 1

```
boolean Even(int x)
{
    if (x == 0)
        return TRUE;
    else
        return Odd(x-1);
}
```

```
boolean Odd(int x)
{
    if (x == 0)
        return FALSE;
    else
        return Even(x-1);
}
```

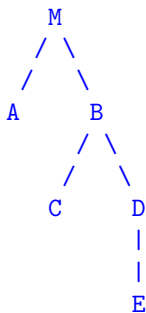
- In this example, two recursive procedures run in “parallel”, calling each other.

Activation Tree: Example 2

```
int main()
{
    A(); B();
}

void B()
{
    C(); D();
}

void D()
{
    E();
}
```

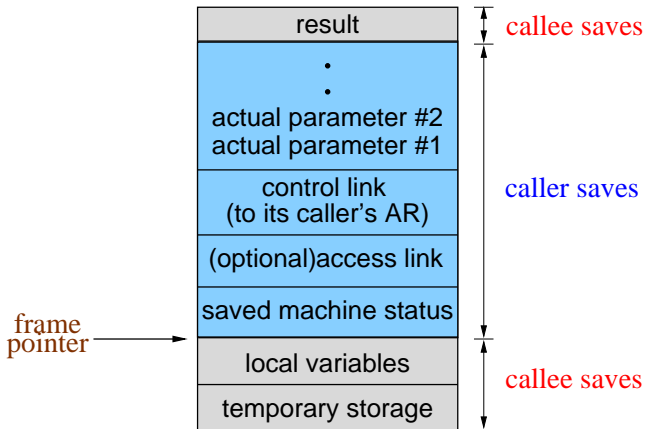


- if $P()$ calls $Q()$, then Q is a **child** of P .
- if $P()$ calls $Q()$ and then $R()$, then Q appears to the **left** of R .

Part I

Activation Records

Activation Records: Memory Layout



Activation Records

When a procedure is activated, **temporary** memory called activation record (AR) is allocated to run the procedure.

AR of procedure $P()$ usually contains memory for:

- **returned result** (if $P()$ is a proper function)
- **actual parameters**
- **control link (dynamic link)** — points to the AR of P 's caller.
e.g. if $F()$ calls $P()$, then the control link in P 's AR points to F 's AR.

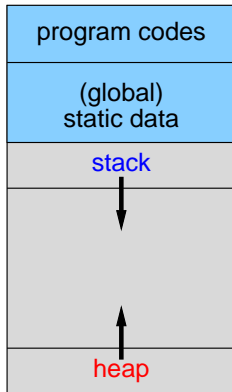
- **access link (static link)** — points to the **most recent** AR of the **innermost** enclosing procedure in which $P()$ is defined.
 - used to implement the **lexical scope rule**.
 - Pascal has access links.
 - C does **not** need access links as C does **not** allow nested procedures. Thus, all variables are either local or global.
 - C++, however, **does** have nested scopes.
 - Scheme also uses lexical scope, so needs access links.
 - Lisp uses the **dynamic scope rule**, so doesn't need access links.
- **saved machine status**: e.g.
 - **registers values** just before $P()$'s activation
 - **return program counter** so as to resume caller's execution when $P()$ is done
- **local variables**
- **temporary storage**

Where to Put Activation Records?

The figure shows the memory layout of a C program during its execution.

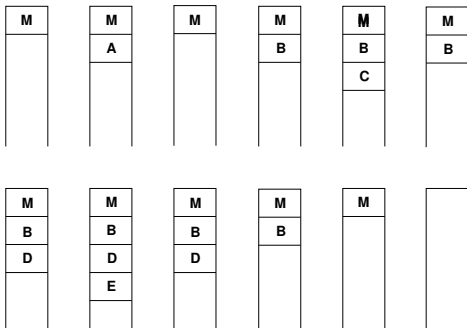
Activations can be managed in the

- **stack**: traditional method for imperative language
- **heap**: if the **activation** of a procedure or function may be returned as a result, stored in a variable and used in an outer scope then its activation record must be stored in a heap so that its variables still exist when it is used.
(e.g. functional programming languages)



Stack Discipline

A language that uses a stack to manage activation records is said to obey a stack discipline — last-in/first-out.



- Thus, AR is also called a stack frame.
- Advantage: efficient
- Disadvantage: doesn't allow function activations to be stored or passed around dynamically

Activation of a C Function (no access links)

When a procedure $Q()$ is called in the body of procedure $P()$, P and Q share responsibility in filling Q 's AR:

- P evaluates the **actual parameters** and put their values in Q 's AR.
- P stores information in Q 's AR so that when Q is done, P may continue execution from where it is left.
- P set Q 's **control link** to point to its AR.
- Q allocates space for its **locals**, and some **temporary storage**.
- The body of the procedure is executed.
- Control returns to the caller P , and Q 's AR, which is no longer needed, is popped out of the stack. The **frame pointer** is also reset from the control link.

Tail-Recursion Elimination

Tail-recursive procedure: when the **last** executable statement in its body is the **recursive** call.

- Recursion **simplifies programming**, but naive implementation pays a price of worse efficiency since procedure call involves a lot of overhead.
- This problem can be eliminated by **replacing** any tail-recursive call with a **loop**.
- Scheme actually **requires** elimination of tail-recursion in its language specification.

Tail-Recursion Elimination: Example 3

```
int bsearch(int* a, int x, int lo, int hi)
{
    if (lo > hi) return NOT_FOUND;
    int k = (lo + hi) / 2;
    if (x == a[k]) {
        return k;
    } else if (x < a[k]) {
        return bsearch(a, x, lo, k-1);
    } else if (x > a[k]) {
        return bsearch(a, x, k+1, hi);
    }
}
```

Tail-Recursion Elimination: Example 3 ..

```
int bsearch(int* a, int x, int lo, int hi)
{
    while (1) {
        if (lo > hi) return NOT_FOUND;
        int k = (lo + hi) / 2;
        if (x == a[k]) {
            return k;
        } else if (x < a[k]) {
            // a = a;
            // x = x;
            // lo = lo;
            hi = k-1;
        } else if (x > a[k]) {
            // a = a;
            // x = x;
            lo = k+1;
            // hi = hi;
        }
    }
}
```

Activation of a Scheme Function (access links): Example 4

```
(define M (lambda (j k)

  (define P (lambda (x y z)

    (define Q (lambda ()

      (define R (lambda ()
        (P j k z)))          ; end R

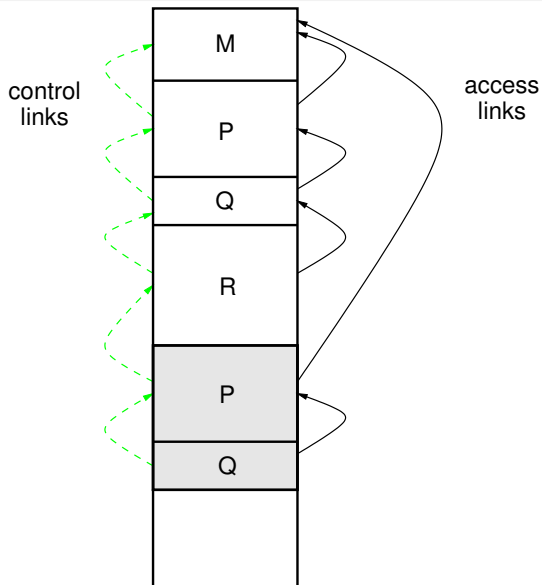
      (* (R) y)))          ; end Q

    (+ (Q) x)))          ; end P

  (P j k 2)))          ; end M
```

Activation of a Scheme Function (access links): Example 4

..



Part II

Parameter Passing

Parameter-Passing: Running Example

```
int a[] = {1, 2, 3, 4};
void Swap(int ... x, int ... y)
{
    int temp = x;
    x = y;
    y = temp;
    a[1] = 0;      // nonlocal a[]
}

int main()
{
    int j = 1; Swap(j, a[j]);
}
```

- Result depends on the relation between the actuals and formals.

l-Value and r-Value of Variables

What does it mean by:

```
x = x + 1;
```

- variable x is assigned the sum of 1 and the value of x
- $\text{location}(x) \leftarrow \text{value}(x) + 1$
- $\text{l-value}(x) \leftarrow \text{r-value}(x) + 1$
- the meaning of the variable “ x ” is overloaded

Macro Expansion, Inline Function

- A macro preprocessor in C/C++ supports language extensions:

```
#define BUFFER_SIZE 1024
#define BIGGER(a,b) ((a)>(b) ? (a) : (b))
```

- C++'s inline functions are better macros allowing type-checking:

```
inline int Bigger(int a, int b)
    { return (a > b) ? a : b; }
```

However, it is just a recommendation to the compiler to expand the procedure before compilation; the compiler might not do so!

- Macro expansion is more efficient: no overhead in procedure calls.
- Macro expansion cannot handle recursion
⇒ should be used only on simple codes

Scope Rules for Variable Names

Scope rules of a language determine which declaration of a name “x” applies to an occurrence of “x” in a program.

- static/lexical scope rules: the binding of name occurrences to declarations is done statically, at **compile time**.
- dynamic scope rules: the binding of name occurrences to declarations is done dynamically, at **run time**.
- Most languages use lexical scope rule.
- Dynamic scope are used for **macros** and **inline functions**.

Scope of Names: Example 5

```
int main()
{
    int j;           // apply to S1,S5,S6
    int k;           // apply to S1,S2,S3,S4,S6
    S1;

    for (...)
    {
        int j;       // apply to S2,S4
        S2;

        while (...)
        {
            int j;   // apply to S3
            S3;
        }
        S4;
    }

    while (...)
    {
        int k;       // apply to S5
        S5;
    }
    S6;
}
```

Renaming Principle of Local Variables:

Consistent renaming of local names in the source text does not change the meaning of a program.

- Under lexical scope rule, we can always rename local variables until each name has only one declaration in the entire program.
- Most-closely-nested rule: an occurrence of a name is in the scope of the innermost enclosing declaration of the name.

Dynamic Scope Rule: Example 6

```
program dynamic_scope(input, output);  
  var x : real;  
  procedure show;  
    begin write(x) end;  
  procedure tricky;  
    var x : real;  
    begin x = 1.2; show end;  
  
  begin x := 5.6; show; tricky; end.
```

- What is the output if lexical scope rule is used?
- What is the output if dynamic scope rule is used?
- **Dynamic scope rule** may be implemented by **macros**.

Call-by-Reference (CBR): Running Example

```
// Using C++ syntax
// Declare as: void Swap(int& x, int& y)
// Call as: Swap(j, a[j]);
```

```
x and j refer to the same object;    // int& x = j;
y and a[j] refer to the same object; // int& y = a[j];
temp <- x; x <- y; y <- temp;
a[1] <- 0;
```

- $j =$
- $a = \{ \quad , \quad , \quad , \quad \}$

- x is called an **alias** of j , and y an **alias** of $a[j]$

Call-by-Value (CBV): Example 7

```
int square(int x) { return x*x; }
int main()
{
    int y = 8; y = square(y+y);
}
```

Under **CBV**,

```
u <- y+y           // done before calling square()
x <- r-value(u)    // int x = u;
result <- x*x
return result
```

CBV: Running Example

```
// Using C syntax
// Declare as: void Swap(int x, int y)
// Call as: Swap(j, a[j]);

x <- j;           // int x = j;
y <- a[j];       // int y = a[j];
temp <- x; x <- y; y <- temp;
a[1] <- 0;
```

- $j =$
- $a = \{ \quad , \quad , \quad , \quad \}$

- Actually **NO** swapping has happened.

CBV: To Simulate CBR

```
int a[] = {1, 2, 3, 4};
void Swap(int* x, int* y)
{
    int temp = *x;
    *x = *y;
    *y = temp;
    a[1] = 0;      // nonlocal a[]
}

int main()
{
    int j = 1; Swap(&j, &a[j]);
}
```

CBV: To Simulate CBR ..

```
// Using C syntax
// Declare as: void Swap(int* x, int* y)
// Call as: Swap(&j, &a[j]);

x <- l-value(j);      // int* x = &j;
y <- l-value(a[j]);   // int* y = &a[j];
temp <- r-value(object that x points to);
l-value(object that x points to)
    <- r-value(object that y points to);
l-value(object that y points to) <- temp;
a[1] <- 0;
```

- $j =$
- $a = \{ \quad , \quad , \quad , \quad \}$

Call-by-Value-Result: Running Example

```
// C, C++ don't use this; but assuming C++ syntax
// Call as: Swap(j, a[j]);
```

```
x ← r-value(j);      // Copy in the values
y ← r-value(a[j]);
```

```
temp ← x; x ← y; y ← temp; // Execute procedure
a[1] ← 0;
```

```
l-value(j) ← x;      // Copy out the results
l-value(a[j]) ← y;
```

- $j =$
- $a = \{ \quad , \quad , \quad , \quad \}$

- **CBVR** = **CBR** if the called procedure does not use any nonlocal variables.
- **CBVR** may differ from **CBR** if the called procedure has more than one way of accessing a location in the caller.

```
var i : integer;  
var j : integer;  
procedure foo(x, y); begin i := y end  
begin  
    i := 2; j := 3; foo(i,j);  
end
```

- if **CBR**: $i = \dots$, $j = \dots$
- if **CBVR**: $i = \dots$, $j = \dots$

Call-by-Name (CBN): Running Example

```
// C, C++ don't use this; but assuming C++ syntax
// Call as: Swap(j, a[j]);
```

```
// textually substitute j for x, a[j] for y
int temp = j;
j = a[j];
a[j] = temp;
a[1] = 0;
```

- $j =$
- $a = \{ \quad , \quad , \quad , \quad \}$
- **CBN** is **NOT** the same as macro expansion

CBN: Example 8

```
program TRY;  
  int n; n = 10;  
  procedure P(x);  
    begin int i; i = i + n; x = x + n; end;  
  
  begin  
    int i, n; int A[10];  
    i = 3; n = 5;  
    P(A[i]);  
  end;
```

- CBN does more than just textual substitution.

- if we simply substitute $A[i]$ for x in $P(x)$

$i = i + n; A[i] = A[i] + n;$

⇒ conflict between the actuals ($A[i]$) and locals (i)

⇒ renaming locals in the procedure body of $P(x)$

⇒ $\text{int } j; j = j + n; A[i] = A[i] + n;$

- if we simply do macro expansion in the main program

$i = 3; n = 5;$

$j = j + n; A[i] = A[i] + n;$

⇒ conflict between n of main program and n of $P(x)$

⇒ renaming locals in the caller of $P(x)$

⇒ $\text{int } i, m; i = 3; m = 5; j = j + n; A[i] = A[i] + n;$

Summary on Parameter Passing

Method	What is Passed	Language	Remarks
CBV	value	C, C++	simple, passed parameters will not change
CBR	address	FORTRAN, C++	be careful: passed parameters may change
CBVR	value + address	FORTRAN, Ada	can be better than CBR, but more expensive
CBN	text	Algol	complicated; not used anymore