COMP3031: Programming Languages

Procedures and Functions: Scope and Parameter Passing, Activation Records

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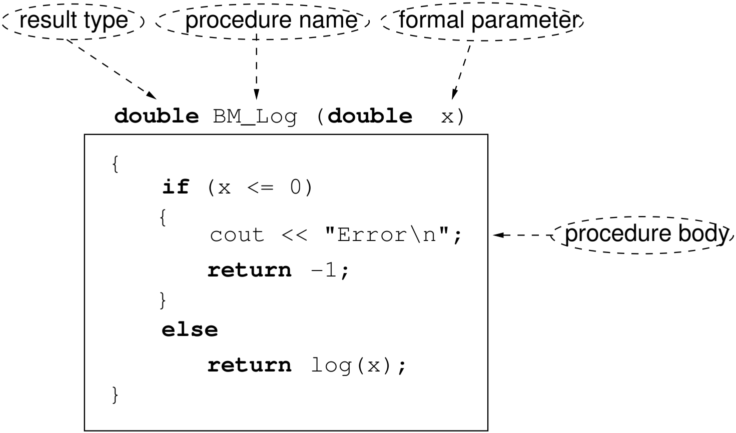
Fall 2012

Elements of a Procedure



```
double BM_Log (double  x)
{
    if (x <= 0)
    {
        cout << "Error\n";
        return -1;
    }
    else
        return log(x);
}
```

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 $(+, -, \times, /)$. 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 ⟶ set of subprograms
    - better organization ⇒ 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)

Recursion

```
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();
}
```

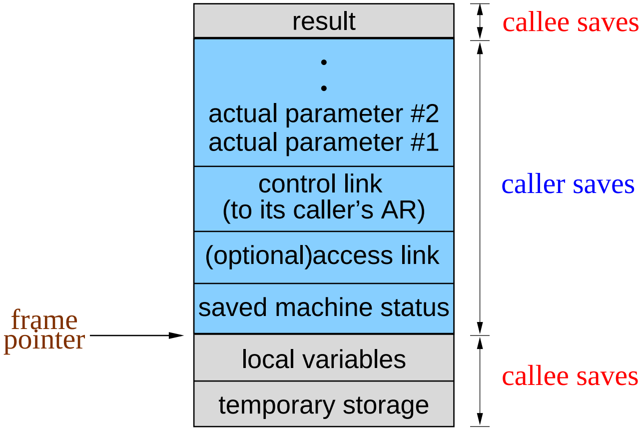
```
   M
  / \
 /   \
A     B
     / \
    /   \
   C     D
         |
         |
         E
```

- 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 <u>activation record</u> (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.

Activation Records ..

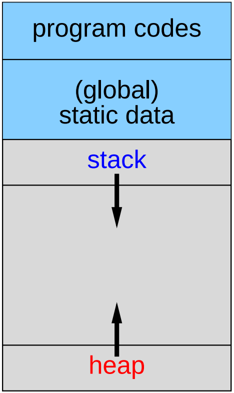
- access link (static link) — points to the most recent AR of the innermost enclosing procedure in which $P()$ is defined.
  - used to implement the lexical scope rule.
  - Pascal has access links.
  - C does not need access links as C does not allow nested procedures. Thus, all variables are either 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.

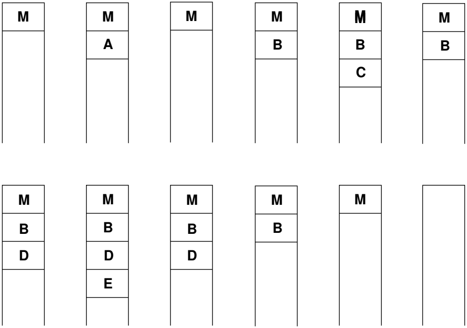
Activations can be managed in the

- 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);
  }
}
```

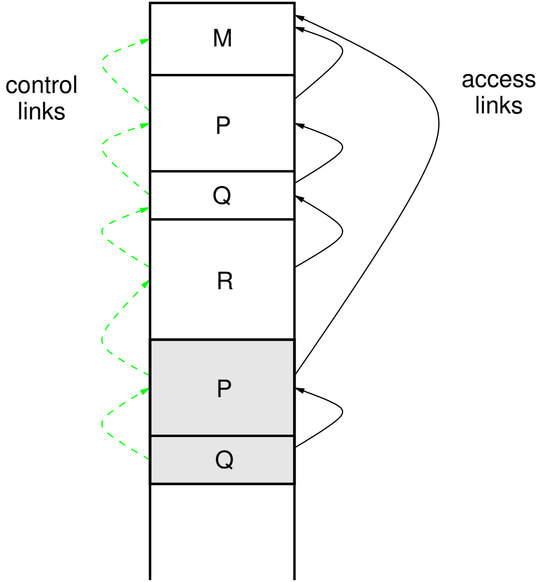
Tail-Recursion Elimination: Example 3 ..

```
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
- location(x) $\longleftarrow$ value(x) $+ 1$
- l-value(x) $\longleftarrow$ 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;
}
```

Lexical Scope Rule

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 = { , , , }

- *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 = { , , , }

- 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;
```

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

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 = { , , , }

CBVR

- 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 = , j =
- if CBVR: i = , j =

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 = { , , , }
- 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.

CBN: Example 8 ..

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

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

$\Rightarrow$ conflict between the actuals ($A[i]$) and locals (i)
$\Rightarrow$ renaming locals in the procedure body of P(x)
$\Rightarrow$ 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;
```

$\Rightarrow$ conflict between n of main program and n of P(x)
$\Rightarrow$ renaming locals in the caller of P(x)
$\Rightarrow$ 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