

## Subprograms

©SoftMoore Consulting

Slide 1

1

## Subprograms

- The term *subprogram* will be used to mean either a *procedure* or a *function*.
- We have already addressed subprograms and issues of scope within the scanner, parser, and identifier table, so most of the effort required to implement subprograms involves modifications of the AST classes.

©SoftMoore Consulting

Slide 2

2

## Grammar Rules Relevant to Subprograms

- `subprogramDecls = ( subprogramDecl )* .`
- `subprogramDecl = procedureDecl | functionDecl .`
- `procedureDecl = "procedure" procId ( formalParameters )? "is" initialDeclPart statementPart procId ";" .`
- `functionDecl = "function" funcId ( formalParameters )? "return" typeName "is" initialDeclPart statementPart funcId ";" .`
- `formalParameters = "(" parameterDecl ( "," parameterDecl )* ")" .`
- `parameterDecl = ( "var" )? paramId ":" typeName .`
- `procedureCallStmt = procId ( actualParameters )? ";" .`

©SoftMoore Consulting

Slide 3

3

## Grammar Rules Relevant to Subprograms (continued)

- `actualParameters = "(" expressions ")" .`
- `returnStmt = "return" ( expression )? ";" .`
- `functionCall = funcId ( actualParameters )? .`

©SoftMoore Consulting

Slide 4

4

## Relevant Parser Methods (based on grammar rules)

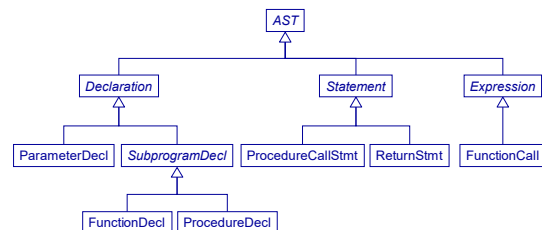
- `fun parseSubprogramDecls() : List<SubprogramDecl>`
- `fun parseSubprogramDecl() : SubprogramDecl?`
- `fun parseProcedureDecl() : ProcedureDecl?`
- `fun parseFunctionDecl() : FunctionDecl?`
- `fun parseFormalParameters() : List<ParameterDecl>`
- `fun parseParameterDecl() : ParameterDecl?`
- `fun parseProcedureCallStmt() : ProcedureCallStmt?`
- `fun parseActualParameters() : List<Expression>`
- `fun parseReturnStmt() : ReturnStmt?`
- `fun parseFunctionCall() : FunctionCall?`

©SoftMoore Consulting

Slide 5

5

## Relevant AST Classes



©SoftMoore Consulting

Slide 6

6

### Procedure Example – Parameters

```
var x : Integer;

procedure inc(var n : Integer) is
begin
  n := n + 1;
end inc;

begin
  x := 5;
  inc(x);
  writeLn(x);
end.
```

What value is printed? If "var" is removed from the parameter declaration, what value is printed?

©SoftMoore Consulting

Slide 7

7

### Procedure Example – Scope

```
var x : Integer;
var y : Integer;

procedure P1 is
  var x : Integer;
  var n : Integer;
begin
  x := 5; // which x?
  n := y; // which y?
end P1;

begin
  x := 8; // which x?
end.
```

Variables and constants can be declared at the program (global) level or at the subprogram level, introducing the concept of scope.

©SoftMoore Consulting

Slide 8

8

### The Scope Level of a Variable Declaration

- During code generation, when a variable or named value is referenced in the statement part of a program or subprogram, we need to be able to determine where the variable was declared.
- Class `IdTable` contains a property named `scopeLevel` that returns the block nesting level for the current scope.
  - PROGRAM for objects declared at the outermost (program) scope.
  - SUBPROGRAM for objects declared within a subprogram.
- When a variable is **declared**, the declaration is initialized with the current level.
 

```
val varDecl = VarDecl(identifiers, varType, idTable.scopeLevel)
```

©SoftMoore Consulting

Slide 9

9

### Example: Scope Levels

```
var x : Integer; // scope level of declaration is PROGRAM
var y : Integer; // scope level of declaration is PROGRAM

procedure P1 is // scope level of declaration is PROGRAM
  var x : Integer; // scope level of declaration is SUBPROGRAM
  var b : Integer; // scope level of declaration is SUBPROGRAM
begin
  ... x ... // x was declared at SUBPROGRAM scope
  ... b ... // b was declared at SUBPROGRAM scope
  ... y ... // y was declared at PROGRAM scope
end p;

begin
  ... x ... // x was declared at PROGRAM scope
  ... y ... // y was declared at PROGRAM scope
  ... P1 ... // P1 was declared at PROGRAM scope
end.
```

©SoftMoore Consulting

Slide 10

10

### Class IdTable

- Class `IdTable` supports the ability to open new scopes and to search for declarations, both within the current scope and in enclosing scopes.
- Class `IdTable` is implemented as a stack of maps from identifier strings (names of things) to their declarations. (Note that, since we don't allow subprograms to be nested, our stack has at most two levels.)
- When a new scope is opened, a new map is pushed onto the stack. When a scope is closed, the top map is popped off the stack.

©SoftMoore Consulting

Slide 11

11

### Class IdTable (continued)

- Within a subprogram, searching for a declaration involves searching within the current level (top map in the stack containing all identifiers declared at SUBPROGRAM scope) and then within the enclosing scope (the map under the top containing all identifiers declared at PROGRAM scope).

©SoftMoore Consulting

Slide 12

12

### A Property and Selected Methods in the Modified Version of IdTable

```

/**
 * The current scope level.
 */
val scopeLevel : ScopeLevel ← ScopeLevel is an enum
                               class with only two values,
                               PROGRAM and SUBPROGRAM.
/**
 * Opens a new scope for identifiers.
 */
fun openScope()
/**
 * Closes the outermost scope.
 */
fun closeScope()

```

©SoftMoore Consulting

Slide 13

13

### A Property and Selected Methods in the Modified Version of IdTable (continued)

```

/**
 * Add a declaration at the current scope level.
 * @throws ParserException if the identifier token associated
 * with the declaration is already
 * defined in the current scope.
 */
fun add(decl : Declaration)

/**
 * Returns the Declaration associated with the identifier
 * token's text. Returns null if the identifier is not found.
 * Searches enclosing scopes if necessary.
 */
operator fun get(idToken : Token) : Declaration?

```

©SoftMoore Consulting

Slide 14

14

### Constraint Rules for Subprograms

- Return Statement
  - Type Rule: If the statement returns a value for a function, then the type of expression being returned must be the same as the function return type.
  - Miscellaneous Rule: If the return statement returns a value, then the return statement must be nested within a function declaration.
  - Miscellaneous Rule: If the return statement is nested within a function, then it must return a value.
  - Miscellaneous Rule: The return statement must be nested within a subprogram.\*

\*Handled by the parser using SubprogramContext.

©SoftMoore Consulting

Slide 15

15

### Constraint Rules for Subprograms (continued)

- Function Declaration
  - Miscellaneous Rule: There should be no var parameters
  - Miscellaneous Rule: There should be at least one return statement.
  - Miscellaneous Rule: All return statements must return a value.
- Subprogram Call (for both procedures and functions)
  - Type Rule: The number of actual parameters should be the same as the number of formal parameters, and each corresponding pair of parameter types should match.
- Procedure Call
  - Miscellaneous Rule: If the formal parameter is a var parameter, then the actual parameter must be a named value (not an arbitrary expression).

©SoftMoore Consulting

Slide 16

16

### Runtime Organization for Subprograms

Understanding the runtime organization for subprograms involves the following four major concepts

- Activation records
- Variable addressing
- Passing parameters and returning function values
- CVM instructions for subprograms

©SoftMoore Consulting

Slide 17

17

### CVM Instructions for Subprograms

- PROC (procedure/function)
- LDLADDR (load local address)
- LDGADDR (load global address)
- CALL (call subprogram)
- RET (return from a subprogram)

Note that CVM does not have separate instructions for procedures and functions.

©SoftMoore Consulting

Slide 18

18

### Active Subprograms

- When a program is running, a subprogram is said to be *active* if it has been called but has not yet returned.
- When a subprogram is called, we need to allocate space on the stack for its parameters and local variables. In addition, if the subprogram is a function, we need to allocate space on the stack for the return value.
- When the subprogram returns, the allocated stack space is released.

An active subprogram is one for which this space (activation record) is currently on the stack.

©SoftMoore Consulting

Slide 19

19

### Activation Record (a.k.a. Frame)

- An activation record is a run-time structure for each currently active subprogram. A new activation record is created every time a subprogram is called.
- Consists of up to five parts
  - return value part (for functions only)
  - parameter part (may be empty if there are no parameters)
  - context part (always 2 words)
    - saved values for PC and BP
  - local variable part (may be empty if there are no local variables)
  - temporary part
    - holds operands and results as statements are executed
    - is always empty at the beginning and end of every statement of the subprogram

©SoftMoore Consulting

Slide 20

20

### Return Value Part of an Activation Record

- A function call must first allocate space on the stack for the return value. The number of bytes allocated is the number of bytes for the return type of the function.
- The `emit()` method in class `FunctionCall` contains the following code.

```
// allocate space on the stack for the return value
emit("ALLOC ${funcDecl.type.size}")
```

©SoftMoore Consulting

Slide 21

21

### Parameter Part of an Activation Record

- For each *value* parameter, a subprogram call must emit code to leave the value of the actual parameter on the top of the stack.
- For each *variable* (var) parameter, a procedure call must emit code to leave the address of the actual parameter on the top of the stack. The actual parameter must be a named value, not an expression.

©SoftMoore Consulting

Slide 22

22

### Context Part of an Activation Record

- Dynamic Link – base address (BP) of the activation record for the calling subprogram
- Return address – address of the next instruction following the call to the subprogram

The values for BP and PC relative to the calling subprogram are saved (pushed) onto the stack by the CVM "CALL" instruction, and they are restored by the CVM "RET" instruction.

©SoftMoore Consulting

Slide 23

23

### Local Variable Part of an Activation Record

- If local variables are declared in a subprogram, then space must be allocated on the runtime stack for those variables.
- The CVM instruction PROC (procedure) has an integer argument for the variable length of subprogram.
- Example
 

```
procedure P2 is
  var m, n : Integer;
  var b : Boolean;
begin
  ...
end P2;
```

©SoftMoore Consulting

Slide 24

24

### Local Variable Part of an Activation Record (continued)

- This procedure will need to allocate nine bytes for local variables. The instruction PROC 9 will be emitted to allocate the necessary space on the runtime stack.
- An instruction of the form PROC 0 is emitted whenever a subprogram does not have any local variables.

©SoftMoore Consulting

Slide 25

25

### Temporary Part of an Activation Record

- The temporary part of an activation record is analogous to the use of the run-time stack to hold temporary values as described in Section 10.4.
- As machine instructions for a subprogram are executed, the temporary part grows and shrinks.
- The temporary part of an activation record is empty at the start and end of each CPRL statement in the subprogram.

©SoftMoore Consulting

Slide 26

26

### Example: Temporary Part of an Activation Record

- Assume
  - register BP has the value 200
  - local integer variable x has relative address 8
  - local integer variable y has value 6 and relative address 12
- The CPRL assignment statement
 

```
x := y + 1;
```

 will compile to the following CVM instructions:
 

```
LDLADDR 8
LDLADDR 12
LOADW
LDCINT 1 ← will be optimized to LDCINT1
ADD
STOREW
```

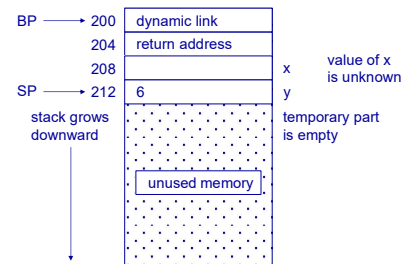
©SoftMoore Consulting

Slide 27

27

### Example: Temporary Part of an Activation Record (continued)

Temporary part is empty at the start of the CPRL statement.



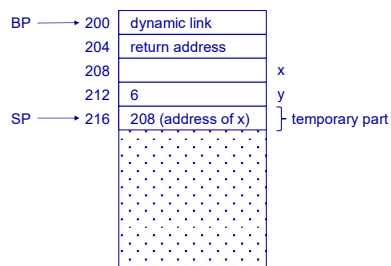
©SoftMoore Consulting

Slide 28

28

### Example: Temporary Part of an Activation Record (continued)

After execution of LDLADDR 8



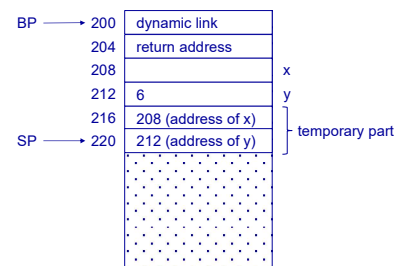
©SoftMoore Consulting

Slide 29

29

### Example: Temporary Part of an Activation Record (continued)

After execution of LDLADDR 12



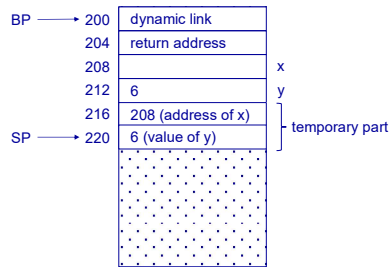
©SoftMoore Consulting

Slide 30

30

### Example: Temporary Part of an Activation Record (continued)

After execution of LOADW



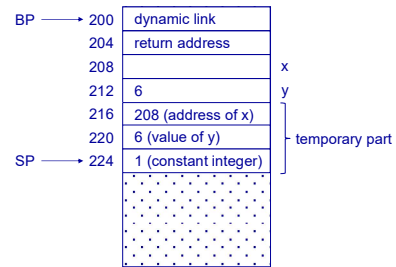
©SoftMoore Consulting

Slide 31

31

### Example: Temporary Part of an Activation Record (continued)

After execution of LDCINT1



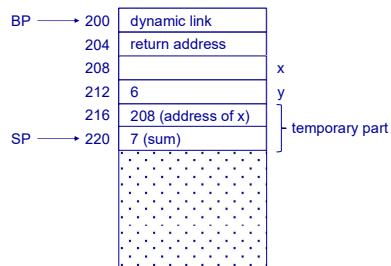
©SoftMoore Consulting

Slide 32

32

### Example: Temporary Part of an Activation Record (continued)

After execution of ADD



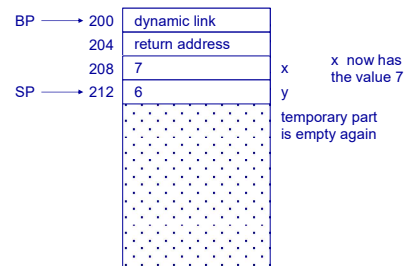
©SoftMoore Consulting

Slide 33

33

### Example: Temporary Part of an Activation Record (continued)

After execution of STOREW



©SoftMoore Consulting

Slide 34

34

### Example: Subprogram with Parameters

```
var x : Integer;

procedure P3(a : Integer, b : Integer) is
  var n : Integer;
begin
  ...
end P3;

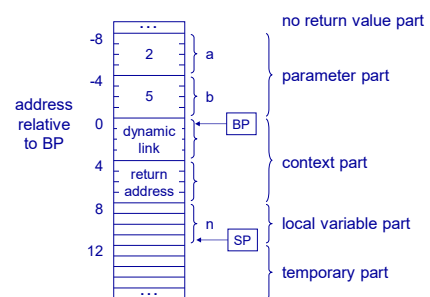
begin
  ...
  P3(2, 5);
  ...
end.
```

©SoftMoore Consulting

Slide 35

35

### Activation Record for Procedure P3



©SoftMoore Consulting

Slide 36

36

### Supporting Recursion

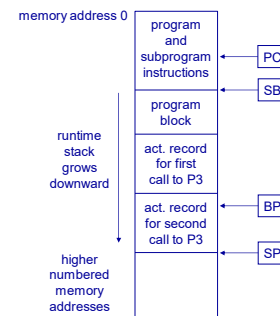
- Since a new activation record is created every time a subprogram is called, CPRL supports recursive calls.
- To illustrate, suppose that a program calls procedure P3, and then P3 makes a recursive call to itself. Each call to P3 has its own activation record, which means each call has its own copy of parameters, locally declared variables, etc.
- The diagram on the next page illustrates this situation.

©SoftMoore Consulting

Slide 37

37

### Supporting Recursion (continued)



©SoftMoore Consulting

Slide 38

38

### Loading a Program

- The object code is loaded into the beginning of memory starting at address 0.
- Register PC is initialized to 0, the address of the first instruction.
- Register SB is initialized to the address following the last instruction (i.e., the first free byte in memory).
- Register BP is initialized to the address of the byte following the last instruction (i.e., the same as SB).
- Register SP is initialized to BP – 1 since the runtime stack is empty.

©SoftMoore Consulting

Slide 39

39

### General Discussion of Parameters

- Functions can have only value parameters, but procedures can have both variable (var) and value parameters.
- The code to handle the passing of these two kinds of parameters as part of a procedure call is somewhat analogous to how you handle an assignment statement of the form "x := y", where you generate different code for the left and right sides.
  - Left side: generate code to leave the **address** on the stack.
  - Right side: generate code to leave the **value** on the stack.

©SoftMoore Consulting

Slide 40

40

### General Discussion of Parameters (continued)

- Analogy for parameters
  - Variable (var) parameters: Generate code similar to the way you handle the left side of an assignment statement.
  - Value parameters: Generate code similar to the way you handle the right side of the assignment.
- When parsing the code for actual parameters, by default we always call `parseExpression()`.
  - generates code to leave the value of the expression on the stack
  - correct for a value parameter but not for a variable parameter
- Note that the code for class `Variable` contains a constructor that takes a single `NamedValue` object and uses it to construct a `Variable` object.

©SoftMoore Consulting

Slide 41

41

### Converting NamedValue to Variable

- When you have a `NamedValue` expression corresponding to a variable parameter, you need to convert it to a `Variable`.
- One possible approach: In the `checkConstraints()` method of class `ProcedureCall`, when iterating through and comparing the list of formal parameters and actual parameters,
  - If the formal parameter is a variable parameter and the actual parameter is not a `NamedValue`, generate an error message (can't pass an arbitrary expression to a variable parameter).
  - If the formal parameter is a variable parameter and the actual parameter is a `NamedValue`, convert the `NamedValue` to a `Variable`.

©SoftMoore Consulting

Slide 42

42

### Converting NamedValue to Variable (continued)

```
for (i in actualParams.indices)
{
    var expr = actualParams[i]
    val param = formalParams[i]

    ... // check that types match

    ... // check that named values are being passed
        // for var parameters (see next slide)
}
```

(in method checkConstraints() of ProcedureCallStmt)

©SoftMoore Consulting

Slide 43

43

### Converting NamedValue to Variable (continued)

```
// check that named values are being passed for var parameters
if (param.isVarParam)
{
    if (expr is NamedValue)
    {
        // replace named value by a variable
        expr = Variable(expr)
        actualParams[i] = expr
    }
    else
    {
        val errMsg = "Expression for a var parameter must " +
            "be a variable."
        throw error(expr.position, errMsg)
    }
}
```

(in method checkConstraints() of ProcedureCallStmt)

©SoftMoore Consulting

Slide 44

44

### Calling a Subprogram

When a subprogram is called

- For a function, space is allocated on the stack for the return value.
- The actual parameters are pushed onto the stack.
  - expression values for value parameters
  - addresses for variable parameters
- The CALL instruction pushes the context part onto the stack.
- The PROC instruction of the subprogram allocates space on the stack for the subprogram's local variables.

©SoftMoore Consulting

Slide 45

45

### PROC Instruction versus ALLOC Instruction

- For CVM, the PROC instruction and the ALLOC instruction are equivalent and can be used interchangeably.
- Both instructions simply move SP to allocate space on the stack; e.g., for a function return value or a subprogram's local variable.

©SoftMoore Consulting

Slide 46

46

### Return Instruction

- The CVM return instruction indicates the number of bytes used by the subprogram parameters so that they can be removed from the stack
- Example
 

```
ret 8
```

©SoftMoore Consulting

Slide 47

47

### Returning from a Subprogram

When a return instruction is executed

- BP is set to the dynamic link.
  - restores BP to the caller's activation record
- PC is set to the return address.
  - restores PC to the caller's instructions
- SP is set so as to restore the stack to its state before the call instruction was executed.
  - For procedures, SP is set to the memory address before the activation record.
  - For functions, SP is set to the memory address of the last byte of the return value. The return value remains on the stack.

©SoftMoore Consulting

Slide 48

48



### Referencing Local Variables and Parameters

The LDLADDR instruction is used to reference subprogram parameters and variables that are local to the subprogram.

- Computes the absolute address of a local variable from its relative address with respect to BP and pushes the absolute address onto the stack
- Use with subprograms is similar to the use of LDGADDR for program variables except that the relative address of the first local variable is 8 instead of 0 since there are 8 bytes in the context part of the activation record.
- Relative addresses can be negative to load the address of a parameter.

©SoftMoore Consulting

Slide 49

49

### Referencing Global Variables

The LDGADDR instruction is used within a subprogram to reference global variables; i.e., variables declared at the program level.

- Computes the absolute address of a global variable from its relative address with respect to SB and pushes the absolute address onto the stack.
- Note that LDGADDR is used the same way in subprograms as it is in the main program.

©SoftMoore Consulting

Slide 50

50

### Example: Activation Record

```
var x : Integer;

procedure P3(a : Integer, b : Integer) is
  var n : Integer;
begin
  ...
end P3;

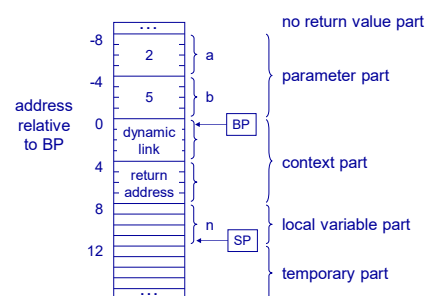
begin
  ...
  P3(2, 5);
  ...
end.
```

©SoftMoore Consulting

Slide 51

51

### Activation Record for Procedure P3



©SoftMoore Consulting

Slide 52

52

### Referencing Variables and Parameters for P3

- LDLADDR -8 loads (pushes) the address of parameter a onto the stack
- LDLADDR -4 loads (pushes) the address of parameter b onto the stack
- LDLADDR 8 loads (pushes) the address of local variable n onto the stack
- LDGADDR 0 loads (pushes) the address of global variable x onto the stack

©SoftMoore Consulting

Slide 53

53

### Variable (var) Parameters

- For variable (var) parameters, the address of the actual parameter is passed; i.e., the value contained in the formal parameter is the address of the actual parameter.
- We need to use two instructions to load (push) the address of actual parameter onto the stack.

©SoftMoore Consulting

Slide 54

54

### Example: Activation Record

```

var x : Integer;

procedure p4(var a : Integer, b : Integer) is
  var n : Integer;
begin
  ...
end p4;

begin
  x := 5;
  p(x, 6);
end.

```

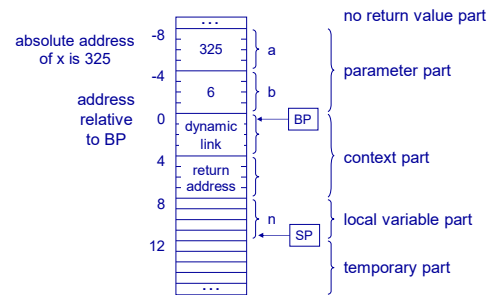
Note that parameter a is a variable parameter.

©SoftMoore Consulting

Slide 55

55

### Activation Record for Procedure P4 (after call p(x, 6))



©SoftMoore Consulting

Slide 56

56

### Referencing Variables and Parameters for P4

- **LDLADDR -8**    loads (pushes) the address of the actual parameter x onto the run-time stack
- **LDLADDR -4**    loads (pushes) the address of parameter b onto the stack
- **LDLADDR 8**    loads (pushes) the address of local variable n onto the stack
- **LDGADDR 0**    loads (pushes) the address of global variable x onto the stack

©SoftMoore Consulting

Slide 57

57

### Method emit() for Class Variable (Loads the address of the variable onto the stack)

```

override fun emit()
{
  if (decl is ParameterDecl && decl.isVarParam)
  {
    // address of actual parameter is value of var parameter
    emit("LDLADDR ${decl.relAddr}")
    emit("LOADW")
  }
  else if (decl.scopeLevel == ScopeLevel.PROGRAM)
    emit("LDGADDR ${decl.relAddr}")
  else
    emit("LDLADDR ${decl.relAddr}")
}

```

We will extend this method again when we consider the topic of arrays in CPRL.

©SoftMoore Consulting

Slide 58

58