Overview of Course

- Names, References, Pointers
- Expressions, Control Flow
- Types
- Blocks, Procedures
- Exceptions
- Modularity
- Object-Oriented Programming
Next Few Sections

- block structure
  - procedures and parameter passing
  - dynamic versus static scoping
  - implementation of non-local access
  - downward/upward funarg
- exception handling – page ??
- modules – page ??
  - data abstraction
  - transparent versus opaque data types
- OO programming – page ??
Overview of Blocks Procedures

- Significance of blocks and scope
- Scope rules
- Dynamic versus static scoping
- Procedures and parameter passing
- Implementation of non-local access
- Downward/upward funarg
- Implications for programming language design
Abstraction

*Abstraction*: conceptualization without reference to specific instances. The act of determining the fundamental, essential, important, intrinsic properties disassociated from the specific details.

*Abstraction*: Any generalization technique that ignores or hides details to capture some kind of commonality between different instances for the purpose of controlling the intellectual complexity of engineered systems, particularly software systems.

Two kinds of abstraction: *process abstraction* and *data abstraction* (cf. modularity)
The fundamental difference between FORTRAN and ALGOL-like languages is the block. A *block* has two intertwined meanings. First, a block is the access-defining unit of the language. Second, a block is a sequence of executable statements that are treated as a unit. Subprocedures in most languages are blocks in both senses of the word. In Pascal the *only* access-defining unit is the procedure. In contrast, ALGOL and Ada have other access-defining constructs called blocks.

Blocks play a diminished role in OO languages like Java and C++. 
Blocks

```plaintext
declare  
    -- declarations
begin    
    -- executable code
end;
```
In Java declarations can appear anywhere in a block (syntactically like another form of statement, but declarations are not runtime actions). The Ada syntax is more explicit (and verbose).

/* Java */

int x;
x = 3;
int y=x+4;
y = 2*y;

-- Ada
declare
    X: Integer;
begin
    x := 3;
    declare
        Y: Integer := X+4;
    begin
        y := 2*y;
    end;
end;
Blocks can be nested in other blocks and in subprocedures. Blocks without names must be “called” or executed at the point in the program where they are defined. On the other hand, subprocedures (blocks with names) may be called from points in the program different from the point where they are defined.
Scope and extent

Recall . . .

Scope. The *scope* of a declaration is the portion of the program text in which the identifier introduced in the declaration is visible; i.e., has the attributes given to it by the declaration. We also speak of *visibility*. More about scope after introducing “block structure” . . .

Extent. The *extent* of a location in memory is the period of program execution in which the location can be accessed by some name or expression in the program.
From the perspective of some point in the program, the *local environment* is the collection of bindings declared in current block. The *nonlocal environment* is the collection of all the accessible variables not declared in the current block.
Blocks, Scope, and Complexity

Blocks are an important programming tool in managing the complexity of programs.

\textit{Localization of scope}. An important principle in making efficient, clear programs is \textit{localization of scope}. Identifiers should be declared in the smallest scope containing its uses.

Though not directly related to blocks, the following definition captures the essence of an additional technique to reduce the complexity of programs.

\textit{Single assignment style}. In single assignment style every variable is assigned exactly once. Such variables can be declared \texttt{final} in Java.
Here is an example of using single assignment style in Java to compute the month of Easter in the Gregorian calendar. Notice that it was deemed preferable to assign to the variable `epact` twice, and so it cannot be declared `final`. All the variables are declared just before they are needed.

```java
final int year = Integer.parseInt(args[0]);
final int golden = (year % 19) + 1;
final int century = (year / 100) + 1;
final int gregorian = (3*century / 4) - 12;
final int clavian = ((8*century + 5)/25) - 5;
int epact = (11*golden+20+clavian-gregorian)%30;
if (epact==24 || (epact==25&&golden==11)) epact ++;
final int moon = (44-epact<21 ? 74:44) - epact;
final int extra = (5*year / 4) - gregorian - 10;
final int sunday = moon + 7 - ((extra+moon)%7);
final String month = (sunday>31)?"April":"March";
```
The epact (Latin epactae, from Greek: epaktai hmerai = added days) has been described as the age of the moon in days on January 1, and occurs primarily in connection with tabular methods for determining the date of Easter. It varies (usually by 11 days) from year to year, because of the difference between the solar year of 365–366 days and the lunar year of 354–355 days.
Call graph

Call graph of

ada/programs/funarg/main.adb
funarg/main.adb

See also Sebesta, 8e, Figure 5.3, page 230.
Since the execution of a subroutine continues until all subroutines it has called have returned, calls behave in a LIFO (stack) order. The static enclosing block is always (usually) in the stack of activation records making it possible to find a block’s nonlocal variables by skipping through the stack.

Interplay of static and dynamic factors.

runtime/calls.adb
runtime/nested.adb
runtime/blocks.adb
runtime/var_access.adb
Scope Rules

The nested structure of scoping can be represented pictorially via contour diagrams or nested boxes. The local environment of every block appears in a box. The nonlocal environment comprises all the variables in surrounding boxes. This rule corresponds to implicit inheritance, i.e., variables declared in outer blocks are visible to inner blocks. Variables declared in inner blocks are not visible. If a nested block introduces an identifier declared in an outer block, then the outer declaration is eclipsed and there is a hole in its scope for the scope of the inner block. Almost all languages use implicit inheritance, although Euclid does not.
Scope Rules

Static scoping or lexical scoping means that a procedure is called in the environment of its definition. A procedure is defined in one place in the program, but may well be called in an entirely different environment or environments. If a procedure is called in the environment of its caller, then we have dynamic scoping sometimes known as dynamic binding, or fluid binding. This is the most recently occurring and still-active binding of a variable.
Static versus Dynamic

Outer: declare
  b: Boolean := true; -- 1st decl of variable b
procedure P is
begin
  print (b); -- variable b not local to P
end P;
begin
  Inner: declare
    b: Boolean := false; -- 2nd decl of b
  begin
    P; -- call procedure P
  end Inner;
end Outer;
Static versus Dynamic

```python
x = 0
def outer():
    x = 1
def inner():
    x = 2  # a 2nd, new declaration of 'x'
    print("inner:", x)
inner()  # call inner is same env as def
print("outer:", x)
outer()
print("global:", x)
```
Write a simple, Algol-like program that distinguishes dynamic scoping from static scoping. Explain.

[See previous program.]

In dynamic scoping “false” is printed because the environment of the caller (“Inner” block) is used; in static scoping the environment in which the procedure is defined is used (“Outer” block), so “true” is printed.
Grading Exam Question

10  obviously correct, exemplary explanation
9   -1 for absurd syntax, but clear explanation
8   -1 for too many declarations
7   -1 for too many blocks
6   clearly different behavior
5   separate environment for call site; weak explanation
4   a non-local variable
3   
2   two declarations, same variable
1   
0   blank sheet
A procedure is a block with a name so that it can be called many times, perhaps in different contexts. The subprocedure is an important building block in writing complex programs, because the details of a subprocedure can be ignored. Caller needs to know what it does; not how it does it. If you find yourself writing the “same” code again and again, it is time for a subprocedure.
Interface. In general, an interface is the boundary between distinct systems. Specifically, the specification or protocol governing their interaction.

Procedure specification. A procedure specification describes the interface between the procedure and the caller of the procedure. This may include the number, mode, default values and type of the procedure’s parameters, and, if a function, the return type. Many different terms are in use for this concept: parameter profile, profile, protocol, prototype, type.

Side effect. A side effect is some action or effect that a subprocedure has on the caller that is not advertised through the procedure specification. For example, a change to a non-local variable is a side effect. Even the use of a non-local may effect the outcome of a procedure call.
Procedures

*Actual argument*. An expression supplied as an argument in the procedure call is said to be an *actual argument*.

*Formal parameter*. The name used within the subroutine or function to refer to the actual argument supplied when the subroutine is called is said to be *formal parameter*. The actual arguments may vary every time the subroutine is called in the program, but the names of the formal parameters are given once in the definition of the subroutine. These names are picked by the programmer when the subroutine is written. Usually, the formal parameters and their types are introduced at the beginning of the subroutine’s definition.

*Positional association* of parameters.

*Named association* of parameters.

*Default parameters*

Sebesta, 8, 9.2.3 Parameters, page 388 (formal parameters, positional parameters, keyword parameters, default values)
Default Parameters in Python

```python
def f(a, L=[]):
    L.append(a)
    return L

print(f(4, [1, 2, 3]), f(1), f(2), f(3))

def g(a, L=None):
    if L is None:
        L = []
    L.append(a)
    return L

print(g(4, [1, 2, 3]), g(1), g(2), g(3))
```

The output:

```
[1, 2, 3, 4] [1] [1, 2] [1, 2, 3]
[1, 2, 3, 4] [1] [2] [3]
```
Parameter Passing

A *parameter passing mechanism* is a facility provided by a programming language to pass data between the caller and the callee.

Webber, Chapter 18 Parameters, page 350. Sebesta, 8e, Section 9.5 Parameter Passing Methods.

- call by reference – pass l-value
- call by value – pass r-value to local variable
- copy-out – local variable, initially undefined, copied back
- copy-in/copy-out – previous two mechanisms combined
- text substitution
- call by name
- call by need
Parameter Passing

Many programs pass data to subroutines using non-local variables. In the past FORTRAN’s COMMON block was used in this way. And today this is common in the instance variables of OO languages like Java. Because this reliance on non-local or external data sources is not described in the subprocedure specification, this practice leads to programs that are difficult to understand.
Call-By-Reference

Pass the l-value of actual to the procedure. Hence, the formal refers directly to same location as the actual argument.

figures / cbr.fig
procedure P (x, y: Integer) is
    t: Integer := y;
begin
    x := y + 2;
    if y = t then
        Put ("no aliasing");
    else
        Put ("aliasing");
    end if;
end P;
Allocate local storage for each formal parameter. Copy the r-value of each actual argument at the beginning of the call.

figures / cbv.fig
Case of C and Java

C uses only call-by-value. How is the possible? Programmer can create call-by-reference using pointers.
Java uses only call-by-value. For primitive types this can be annoying. Everything else is an object. A pointer is passed as the “value” of an object.
declare
  A: array 1..10 of Integer;
i: Integer := 1;
procedure P (x: out Integer) is
begin
  i := 2;  x := 3;
end P;
begin
  -- L-value computed just before call
  P (A[i]);
end;
Parameter Passing

Copy-in/copy-out is not the same as call by reference.

```
declare
  G: Integer := 1;
procedure P (X: Integer) is
  -- reference ** copy-in/copy-out
  begin
    -- ** X:=G:=1
    X := 6;  -- ** G:=X:=6 ** X:=6
    G := 9;  -- ** G:=9 ** G:=9
  end P;
begin
  P (G);  -- call P
end;
```
Parameter Passing

Parameter passing defined by the method of implementation of the formal/actual association (call-by-reference, call-by-value, copy-in/copy-out).
Parameter passing defined by the intent of programmer in using the parameters: in, out, in/out.
Parameter passing defined by the outcome of the procedure call with the actuals substituted for the formals. Might be considered the correct way, but implementation issues. (Text substitution, call-by-name, call-by-need.)
**Text Substitution**

TeX and C/C++.

```c
#define P(x,y) temp=x;x=y;y=temp

main () {
    int temp, a=1, b=2;
    P(a,b);   /* Produces legal code */
    P(2*a,2); /* Produces illegal code */
}
```

After the macro \( P \) is expanded we get:

```c
main () {
    int temp, a=1, b=2;
    temp=a;a=b;b=temp ;
    temp=2*a;2*a=2;2=temp ;
}
```
Macros are different from function calls.

```c
#define min(x, y) ((x)<(y)?(x):(y))

main () {
    int a=1, b=2, c=3;
    a = min (b, c);
    // b==2
    a = min (b++, c);
    // b==4!
}

After the macro min is expanded we get:

a = ((b++)<(c)?(b++):(c))
```
Jensen’s Device

real procedure Sum (index, ub, x);
value ub;
integer index, ub; real x;
begin real temp; temp := 0;
for index:=1 step 1 until ub do
  temp := temp + x;
Sum := temp;
end;

Consider an actual argument for $x$ that contains the actual argument for $index$.

\[
\sum_{i=1}^{n} A[i] \quad \text{Sum}(i,n,A[i])
\]
\[
\sum_{i=1}^{n} B[i,i] \quad \text{Sum}(i,n,B[i,i])
\]
\[
\sum_{i=1}^{m} \sum_{j=1}^{i} j \times B[j,i] \quad \text{Sum}(i,m,j*\text{Sum}(j,i,B[j,i]))
\]
Call-By-Name

A procedure can be replaced by its body with the actuals substituted for the formals (just like text-substitution). If necessary, variables must be renamed. There are two types of clashes that require renaming.

1. If an actual argument uses an identifier that is also used locally to the subprocedure, then the local identifier must be consistently renamed to something else.

2. Identifiers that are defined in the context in which the subprocedure is called and are also free identifiers in the body of the subprocedure must be renamed throughout that context to something else.
Call-By-Name

Definition of procedure Roots:

procedure Roots (a: Float) is
    d: Float;
begin
    d := Discr (a,a,a);
end Roots;

A call to Roots in this context:

Context: begin
    Roots (2.3); -- call Roots
end Context;

is equivalent to

Context: begin
    Roots: declare
        d: Float;
    begin
        d := Discr (2.3, 2.3, 2.3);
    end Roots;
end Context;
* Call-By-Name

The invocation \texttt{Roots}(d) in the context:

Context: declare
d: Float;
function \texttt{Discr}(x,y,z: Float) return Float ...
begin
 Roots (d);
end Context;

without the proper identifier substitutions:

Context: declare
d: Float;
function \texttt{Discr}(x,y,z: Float) return Float ...
begin
 Roots: declare
d: Float;
begin
 d := \texttt{Discr} (d,d,d);
end Roots;
end Context;
* Call-By-Name

With the proper identifier substitutions

Context: declare
d: Float;
function Discr_1(x,y,z: Float) return Float ...
begin
Roots: declare
d_1: Float;
begin
d_1 := Discr (d,d,d);
end Roots;
-- Any calls to Discr in the block but outside
-- Roots would have to be renamed to Discr_1.
end Context;
Call-By-Need

An “optimization” of call-by-name in which the name is evaluated once and then kept for later use.
Implementing Block-Structured Languages

During the running of the program every subprocedure needs to know where the code is to execute next (a subprocedure is not always called from the same point in the program). In the absence of recursion, a global place for each subprocedure’s return address could be allotted. However, in the present of recursion, it seems necessary and advantageous for the runtime system of a language to keep (during execution) a stack of addresses for all the pending subprocedure calls in order that each subprocedure can continue execution at the point in was suspending in order to execute another subroutine.
Implementing Block-Structured Languages

As a matter of fact, this can be extended to a structured record of a subprocedure's invocation that includes not only the return address but arguments and local variables as well. The LIFO order makes it very efficient to reuse the space allocated to local variables. And, and . . ., the nonlocal variables seem to be in some other subprocedure's (or block's) local variables.
Implementing Block-Structured Languages

Activating a subprocedure requires the dynamic creation of an instance of the activation records for the subprogram. This activation record is a data structure providing parameters, local variables, the non-local environment, and the return address of each invocation of a subprocedure. Because of the nature of subprocedure call and return (LIFO), it is reasonable to create instances of these activation records on a stack. This stack, part of the runtime system and is called the run-time stack or simply *the stack*.
Static, hierarchical structure of `runtime/nested.adb` and dynamic, run-time behavior of the program.

```
begin  == time ==>  end
```

```
R
Q Q Q R
P P P P P Q Q Q
N N N N N N N N N N N N N N
```
Non-Local Variable Access

The tricky part about implementing the run-time behavior of the program correctly is non-local variable access. Decisions about how to implement this access have a profound impact on programming language design as we shall see.
procedure Access is

  G: Integer := 2;

procedure Q is

  H: Integer := 3;

procedure R is

  L: Integer := 5;
  begin
    G := 3+L; -- access G, L
  end R;

  begin
    R;
  end Q;

procedure P is

  begin
    Q;
  end P;

begin

  P; -- call subprocedure "P"

  Q; -- call subprocedure "Q"

end Access;
procedure Access is

G: Integer := 2;

procedure Q is
  N: Integer := 3;

procedure R is
  L: Integer := 5;
  begin
  G := 3+L;   -- access G, L
  end R;

begin
  R;
  end Q;

procedure P is
  begin
  Q;
  end P;

begin
  -- call subprocedure "P"
  P;
  -- call subprocedure "Q"
  Q;
end Access;
procedure Access is
  G: Integer := 7;

procedure Q is
  N: Integer := 3;

procedure R is
  L: Integer := 5;
  begin
    G := 3+L;  -- access G, L
  end R;

begin
  R;
end Q;

procedure P is
begin
  Q;
end P;

begin
  P;  -- call subprocedure "P"
  Q;  -- call subprocedure "Q"
end Access;
Non-Local Variable Access

A key observation about the stack implementation of the run-time environment is that two values pinpoint a variable in static binding. One, the *static distance* is the difference in static nesting between a variable use and its declaration. The *static nesting* is how deeply nested a declaration or variable use is. Two, *offset* is a more or less arbitrary displacement within an activation record locating where the variable is stored. At compile time this information can easily be stored in the symbol table and used to generate code to access the local or nonlocal variable. A local variable (static distance equal zero) is located in the current activation record. A nonlocal variable is located $n$ hops (where $n$ is the static distance) along the static chain. This fetch can be done in constant time if the static links are kept in an array.
The static link is a pointer (during the execution of the program) to the activation record of the *statically* enclosing procedure or block. The static chain of the currently active procedure is the sequence of activation records representing the statically enclosing procedure or blocks. This static link must be maintained at runtime.
Implementing Variable Access

fetch M[EP + offset(v)] ; local variable

AR := M[EP].SL ; activation record of parent
fetch M[AR + offset(v)] ;

AR := M[EP].SL ; activation record of parent
AR := M[AR].SL ; traverse second static link :
AR := M[AR].SL ; traverse last static link
fetch M[AR + offset(v)] ;
Subprogram Call

When the compiler encounters a subprogram call it determines the subprogram that declared the called subprogram, which must be a static ancestor of the calling routine. It then computes the number of enclosing scopes between the caller and the subprogram that declared the called subprogram. This information is stored and can be accessed by the subprogram call during execution. At the time of the call, the static link of the called subprogram’s activation record instance is determined by moving down the static chain of the caller the number of links equal to the nesting depth computed at compile time.

Sebesta, 7th, section 10.4.2 Static Chains, page 446
Calling A Procedure

; transmit parameters
M[SP].PAR[1] := evaluation of parameter 1
M[SP].PAR[n] := evaluation of parameter n
M[EP].IP := resume ; save resume location

AR := M[EP].SL ; static parent, and so on
AR := M[AR].SL ;
M[SP].SL := AR ; set static link
EP := SP ; push new activation record
; callee should increment stack size
; SP := SP + size(callee’s activation record)
goto entry(callee)
resume:
OK, fine. The program of non-local variable access is marvelously solved. Let us push the boundaries.

“First-class subroutines in a language with nested scopes introduce an additional level of complexity: they raise the possibility that a reference to a subroutine may outlive the execution of the scope in which that routine was declared.”

Scott, page 144.
Passing Procedures

Consider programs in which procedure pass other procedures around as arguments.
Passing Procedures

1. What gets passed to $Q$ to represent $P$ or $T$?
2. What code must be emitted to implement the call $f_P(5)$?

For any procedure call we must:

1. transmit the parameters,
2. save the return address,
3. set the dynamic link,
4. start the execution of the new procedure,
5. set the static link.

Closure. The value of a procedure is a closure—an ep, ip pair: environment pointer and code (instruction) pointer.
A closure is a program and the referencing environment where it was defined.

Sebesta, 11th, page 406.

In a language with first-class functions and static scope, a function value is generally represented by a closure, which is a pair consisting of a pointer to function code and a pointer to an activation record.

Mitchell, page 182.
Calling A Formal Procedure

; transmit parameters
M[SP].PAR[1] := evaluation of parameter 1

; 
M[SP].PAR[n] := evaluation of parameter n

M[EP].IP := resume ; save resume location

M[SP].SL := fp.EP ; set static link
EP := SP ; push new activation record
; callee should increment stack size
; SP := SP + size(callee’s activation record)
goto fp.IP
resume:
Ada Program Examples

1. funarg/main.adb – nested blocks, non-local variables
2. funarg/pass.adb – passing procedures
3. funarg/diff.adb – procedures with different environment pointers
4. funarg/down.adb – again passing procedures, but trouble
5. funarg/ret.adb – returning procedures with different environment pointers
6. funarg/up.adb – trouble with returning procedures
7. funarg/abuse.adb – slipping closure out of its environment
Ada Program Examples

1. funarg/accessibility.adb – illustrate dynamic accessibility check
Passing a procedure down is not a problem; set the ep to the correct parent. Here is the stack of the program `funarg/down.adb` at different times during the execution of the program.
Passing a procedure up is a problem; the ep is set to an activation record that is popped off the stack. Here is the stack of the program `funarg/up.adb` at different times during the execution of the program.
Upward Funarg Problem

So, what is the conclusion? Either

1. Forbid returning and assigning subprocedures. E.g., Pascal.
2. Fine print with pointer types. E.g., Ada.
3. Restrict all local procedures. E.g., Modula-3. Even though downward funargs would be quite safe. Assigning procedure values makes it impossible to know if its use is upward or downward. Modula-3 encourages a “flat” structure.
4. No local procedures. E.g., C, C++, Java.
5. Throw out the stack-based implementation. E.g., functional languages (discussed later).
Here are the details from the Ada reference manual:

3.10.2 Operations of Access Types ¶24 X’Access

The view denoted by the prefix X shall satisfy the following additional requirements, presuming the expected type for X’Access is the general access type A:

¶29 b A check is made that the accessibility level of X is not deeper than that of the access type A. If this check fails, Program_Error is raised.

In general, this is determined statically, but access parameters and generics require dynamic checks. We saw this error in the program funarg/up.adb
procedure Up is

  type F is access procedure (X: Integer);

  procedure P (X: Integer) is begin null; end P;

  function R (B: Boolean) return F is
    N: Integer;
    procedure T (X: Integer) is begin N:=X; end T;
    begin
      if B then
        return P'Access;  -- no problem
      else
        return T'Access;  -- subprogram "T" deeper than access type "F"
      end if;
    end R;
2.3.1 Assignment An expression e is assignable to a variable v if:

- the type of e is assignable to the type of v, and
- the value of e is a member of the type of v, is not a local procedure, and if it is an array, then it has the same shape as v.

The first point can be checked statically; the others generally require runtime checks. Since there is no way to determine statically whether the value of a procedure parameter is local or global, assigning a local procedure is a runtime rather than a static error.

and ...
... return is handled like an assignment ...

2.3.11 Return A RETURN statement for a function procedure has the form:

\[
\text{RETURN Expr}
\]

where \( \text{Expr} \) is an expression assignable to the result type of the procedure

funarg/Down.m3
funarg/Up.m3
C And Procedures

The programming language C has no nested procedures, so a closure need only contain a pointer to the code. No restrictions on passing procedure pointers are needed. In C++ and Java you can pass subprocedures only inside classes. Pointers to instances of classes are “closures;” they point to all the instance variables and all the methods. Passing subprocedures in C++ and Java is clumsy.

inner/Searcher.java
member/function.cc
Summary

1. Block-structured languages required the development of new run-time techniques
2. An activation record represents the state of a procedure
3. Activation records contain the local variables
4. Instruction counter represents the site of control; the environment pointer represents the context
5. A static link points to the activation record of the lexical parent
6. Variables are addressed by two coordinates: static distance and offset
7. Accessing a variable requires two steps; can be done in one machine instruction