Implementing Subprograms & Blocks

Semantics of Subprogram Calls and Returns

Subprogram Calls

- Pass parameters using parameter passing methods.
- Allocate storage space for local variables.
- Arrange to access nonlocal variables.
- Save the execution status of the caller.
- Save the return address.
- Transfer control to the callee.

Subprogram Returns

- Copy back using parameter passing methods if needed.
- Deallocate the storage used for locals.
- Restore the execution status of the caller.
- Return control to the caller.

Activation Record (AR)

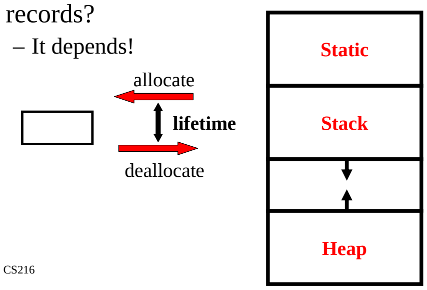
- The state info need for a subprogram call and return is stored in an **activation record** **(AR)**.
- In an activation record:
  - – Instruction part
    - A pointer to the instruction to be executed after the subprogram return (Return address)
  - – Environment part
    - The values of locals, nonlocals and parameters.

Subprogram, Call, Activation & Activation Record

- A subprogram
- A **call** to the subprogram
- An **activation** of the call
- An **activation record** for the activation

Storage for Activation Records

- Where do we allocate storage for the activation records?
  - It depends!



Two Types of Languages

- **FORTRAN-like languages**
  - No recursive subprograms
  - Static local variables
  - No nonlocal variables (Flat block structure)
- **Algol-like languages**
  - Recursive subprograms
  - Stack-dynamic local variables
  - Nonlocal variables (Nested block structure)

Storage for Activation Records

- FORTRAN-like languages
  - From **static** storage
- Algol-like languages
  - From **stack** storage

Implementing Subprogram Calls and Returns

- It depends on the type of the language!

1. Implementing FORTRAN77-like Subprograms

Activation Record

- The format or layout of the noncode part is called an **activation record**.

Functional Value

Local variables

Parameters

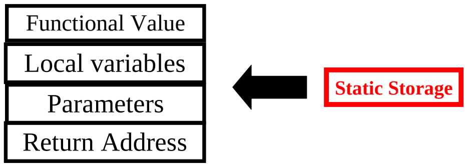
Return Address

Static Allocation for Activation Record

- A FORTRAN 77 subprogram can have **only one activation record instance** at any given time!
- Why?
  - – No recursive subprogram!

Static Allocation for Activation Record

- Statically allocate storage for Activation Record.
- Use it for each activation record instance.


Functional Value

Local variables

Parameters

Return Address

Static Storage

Example: Implementing A FORTRAN 77 Subprogram

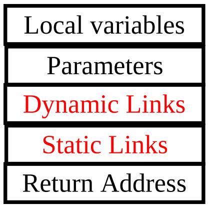
- A main program `MAIN`
- Three subprograms `A, B & C`
- The code and activation records:
  - – See Figure 10.2 (p. 400)

2. Implementing ALGOL-like Subprograms

- This is more complicated than implementing FORTRAN 77-like subprograms.
- Why?
  - – Local variables are often dynamically allocated.
  - – Recursion must be supported.
  - – Static scoping must be supported.
  - – More parameter passing methods

Activation Record

- A typical activation record for an ALGOL-like language:


Local variables

Parameters

Dynamic Links

Static Links

Return Address

Activation Record

- The activation record format is static, but its size may be dynamic.
- An activation record instance **must be created dynamically** when a subprogram is called.

Dynamic and Static Links

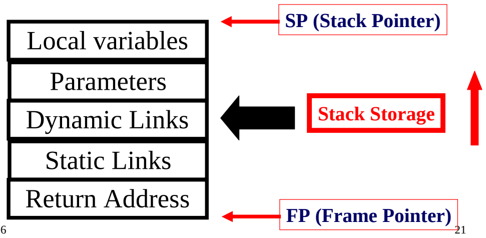
- The **dynamic link (DL)**
  - points to the top of an instance of the activation record of the caller.
- The **static link (SL)**
  - points to the bottom of the activation record instance of an activation of the static parent (to be used for access to nonlocal variables).

Activation Record

- An Algol-like subprogram can have **more than one activation record instance** at any given time!
- Why?
  - Recursive subprogram!

Dynamic Allocation for Activation Record

- Dynamically allocate storage for Activation Record.



SP (Stack Pointer)

Local variables

Parameters

Dynamic Links

Static Links

Return Address

Stack Storage

FP (Frame Pointer)

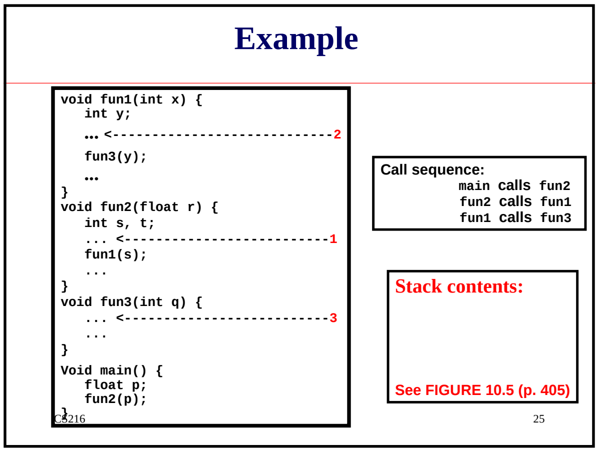
Example: Activation Record

```
procedure sub(var total: real; part: integer);
var list: array[1..2] of integer;
    sum: real;
begin
…
end
```

Example: Activation Record

sum	Local
list[3]	Local
list[2]	Local
list[1]	Local
part	Parameter
total	Parameter
	DL
	SL
	RA

(1) Without Recursion and Nonlocal References



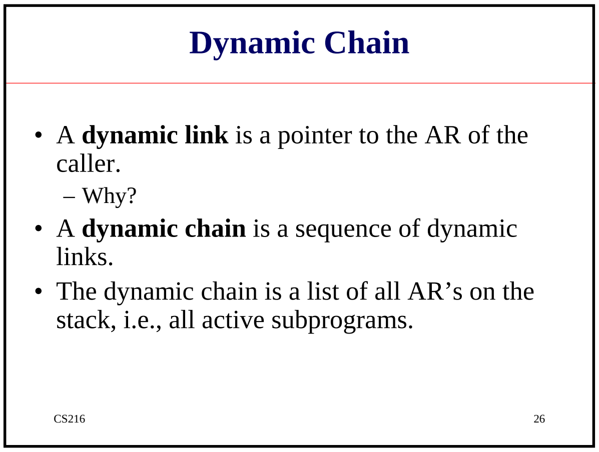
Example

```
void fun1(int x) {
   int y;
   ... <---------------------------2
   fun3(y);
   ...
}
void fun2(float r) {
   int s, t;
   ... <-------------------------1
   fun1(s);
   ...
}
void fun3(int q) {
   ... <-------------------------3
   ...
}
Void main() {
   float p;
   fun2(p);
}
```

Call sequence:
`main` calls `fun2`
`fun2` calls `fun1`
`fun1` calls `fun3`

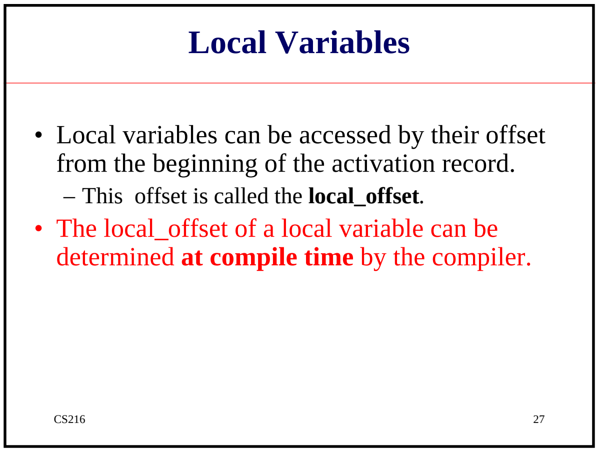
Stack contents:

See FIGURE 10.5 (p. 405)



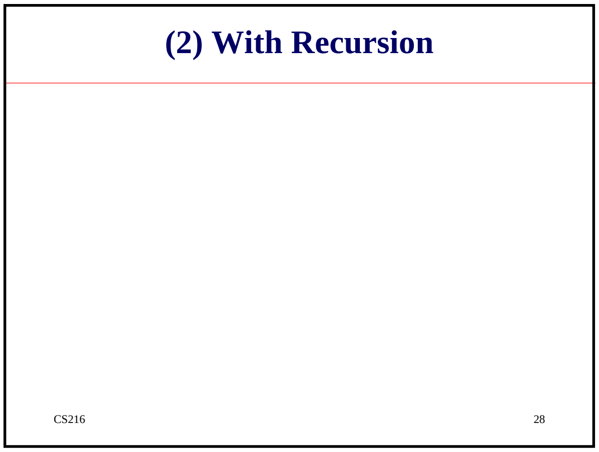
Dynamic Chain

- A **dynamic link** is a pointer to the AR of the caller.
  - Why?
- A **dynamic chain** is a sequence of dynamic links.
- The dynamic chain is a list of all AR's on the stack, i.e., all active subprograms.

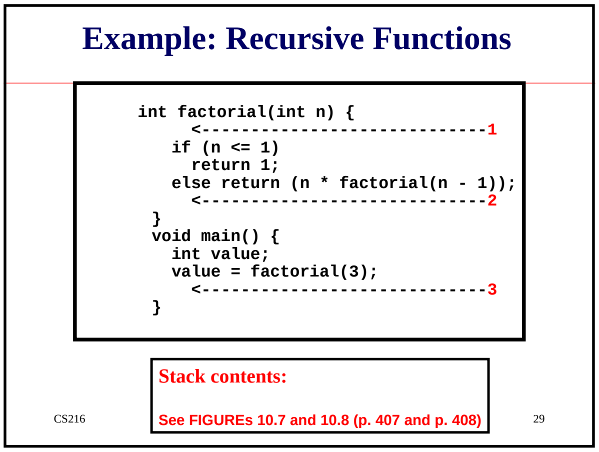


Local Variables

- Local variables can be accessed by their offset from the beginning of the activation record.
  - This offset is called the **local_offset**.
- The local_offset of a local variable can be determined **at compile time** by the compiler.



(2) With Recursion

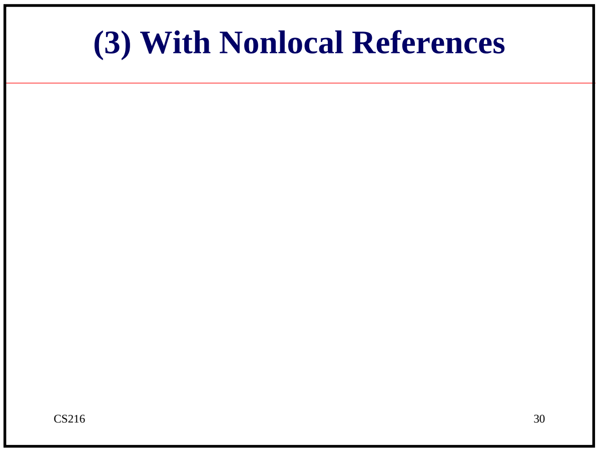


Example: Recursive Functions

```
int factorial(int n) {
     <------------------------------1
   if (n <= 1)
     return 1;
   else return (n * factorial(n - 1));
     <------------------------------2
 }
 void main() {
   int value;
   value = factorial(3);
     <------------------------------3
 }
```

Stack contents:

See FIGUREs 10.7 and 10.8 (p. 407 and p. 408)



(3) With Nonlocal References

Nonlocal References with Static Scoping Rule

- Observation:
  - All variables that can be nonlocally accessed reside in some activation record instance in the stack.
- The process of locating a nonlocal reference:
  1. **Find the correct activation record instance in which the variable is allocated.**
  2. **Use the local offset within that activation record instance to access it.**

How to Find the Correct Activation Record Instance?

- Find the innermost enclosing block containing the applied occurrence and a binding occurrence.

Implementing Nonlocal References with Static Scoping Rule

- Using **static chains**
- Using **display**

1. Static Chain

- The **static link** in an activation record instance for a subprogram S points to an activation record instances of S's static parent (enclosing subprogram).
  - The **most recent ARI** of the static parent!

Static Chain

- A **static chain** is a chain of static links.
- The static chain from an activation record instance for a subprogram S links all the static ancestors of S.

How to Find the Correct Activation Record Instance Using Static Chain?

- To find the declaration for a reference to a nonlocal variable?
  - Search the static chain until the activation record instance that contains the variable (as a local variable) is found!
- How many static links to be followed?
  - Can be determined at compile time!

Static Depth of A Subprogram

- Given a subprogram S,
- The **static_depth** of S is an integer associated with the subprogram:
  - How deeply it is nested in the outmost program!
  - 0 (the outmost), 1, 2, …
  - Also called SNL **(Static Nesting Level)**

Example: Static Depth

```
program A;
var x: int;
   procedure B;
      procedure C;
       …
       x:=x+1;
       …
      end;{C}
      …
      x:=x+1;
      …
   end;{B}
   …
   x:=x+1;
   …
end;{A}
```

A ----- static_depth = 0

B ----- static_depth = 1

C ----- static_depth = 2

Nesting Depth of A Nonlocal Reference

- Given a nonlocal reference to a variable X,
- The **nesting_depth** or **chain_offset** of the nonlocal reference is

  (The static_depth of the the subprogram containing the reference to X)

  MINUS

  (The static_depth of the the subprogram containing the declaration for X)
  - Also called SD **(Static Distance)**

Example: Nesting Depth

```
program A;
var x: int;
   procedure B;
      procedure C;
       …
       x:=x+1;
       …
      end;{C}
      …
      x:=x+1;
      …
   end;{B}
   …
   x:=x+1;
   …
end;{A}
```

A ----- static_depth = 0
B ----- static_depth = 1
C ----- static_depth = 2

SD Nesting depth of X in C: 2

SD Nesting depth of X in B: 1

SD Nesting depth of X in A: 0

How to Access Nonlocal Variables Using Static Chain?

- A reference to a nonlocal variable X can be represented by the pair **(chain_offset, local_offset)** where
  - **chain_offset** = The number of static links to the correct ARI.
  - **local_offset** = The offset from the beginning of the AR of the subprogram containing the declaration for X.

Example: Nonlocal Variable Access Using Static Chain

```
program A;
var x: int;
   procedure B;
      procedure C;
       …
       x:=x+1;
       …
      end;{C}
      …
      x:=x+1;
      …
   end;{B}
   …
   x:=x+1;
   …
end;{A}
```

A ----- static_depth = 0
B ----- static_depth = 1
C ----- static_depth = 2

Nesting depth of X in C: 2
Nesting depth of X in B: 1
Nesting depth of X in A: 0

Reference to X in C: (2, local-offset)

Reference to X in B: (1, local-offset)

Reference to X in A: (0, local-offset)

Example

```
program MAIN_2;
  var X : integer;
  procedure BIGSUB;
    var A, B, C : integer;
    procedure SUB1;
      var A, D : integer;
      begin { SUB1 }
      A := B + C;  <-----------------------1
      end;  { SUB1 }
    procedure SUB2(X : integer);
      var B, E : integer;
      procedure SUB3;
        var C, E : integer;
        begin { SUB3 }
        SUB1;
        E := B + A:   <-------------------2
        end; { SUB3 }
      begin { SUB2 }
      SUB3;
      A := D + E;  <-----------------------3
      end; { SUB2 }
    begin { BIGSUB }
    SUB2(7);
    end; { BIGSUB }
  begin
  BIGSUB;
  end. { MAIN_2 }
```

Call sequence:

MAIN_2 calls BIGSUB
BIGSUB calls SUB2
SUB2 calls SUB3
SUB3 calls SUB1

Example

```
program MAIN_2;
  var X : integer;
  procedure BIGSUB;
    var A, B, C : integer;
    procedure SUB1;
      var A, D : integer;
      begin { SUB1 }
      A := B + C;  <-----------------------1
      end;  { SUB1 }
    procedure SUB2(X : integer);
      var B, E : integer;
      procedure SUB3;
        var C, E : integer;
        begin { SUB3 }
        SUB1;
        E := B + A:   <-------------------2
        end; { SUB3 }
      begin { SUB2 }
      SUB3;
      A := D + E;  <-----------------------3
      end; { SUB2 }
    begin { BIGSUB }
    SUB2(7);
    end; { BIGSUB }
  begin
  BIGSUB;
  end. { MAIN_2 }
```

Stack contents at position 1:

See FIGURE 10.9 (p. 414)

Example

```
program MAIN_2;
  var X : integer;
  procedure BIGSUB;
    var A, B, C : integer;
    procedure SUB1;
      var A, D : integer;
      begin { SUB1 }
      A := B + C;  <-----------------------1
      end;  { SUB1 }
    procedure SUB2(X : integer);
      var B, E : integer;
      procedure SUB3;
        var C, E : integer;
        begin { SUB3 }
        SUB1;
        E := B + A:   <-------------------2
        end; { SUB3 }
      begin { SUB2 }
      SUB3;
      A := D + E;  <-----------------------3
      end; { SUB2 }
    begin { BIGSUB }
    SUB2(7);
    end; { BIGSUB }
  begin
  BIGSUB;
  end. { MAIN_2 }
```

Nonlocal references:

At position 1 in SUB1:
A - (0, 3)
B - (1, 4)
C - (1, 5)

At position 2 in SUB3:
E - (0, 4)
B - (1, 4)
A - (2, 3)

At position 3 in SUB2:
A - (1, 3)
D - an error
E - (0, 5)

QUIZ: Static Chain

```
program MAIN_2;
  var X : integer;
  procedure BIGSUB;
    var A, B, C : integer;
    procedure SUB1;
      var A, D : integer;
      begin { SUB1 }
      A := B + C;  <-----------------------1
      end;  { SUB1 }
    procedure SUB2(X : integer);
      var B, E : integer;
      procedure SUB3;
        var C, E : integer;
        begin { SUB3 }
        SUB1;
        E := B + A:   <-------------------2
        end; { SUB3 }
      begin { SUB2 }
      SUB3;
      A := D + E;  <-----------------------3
      end; { SUB2 }
    begin { BIGSUB }
    SUB2(7);
    end; { BIGSUB }
  begin
  BIGSUB;
  end. { MAIN_2 }
```

Stack contents?
(1) At position 2
(2) At position 3

Static Chain - Evaluation

- A nonlocal reference is slow.
  - **(Nesting-Depth or SD + 1)** memory references!
- It is difficult to estimate the costs of nonlocal references for time-critical (real-time) programs.

2. Display

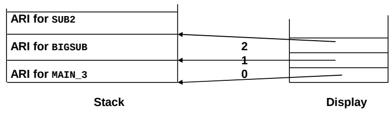
- The idea:
  - Put the static links in an array called a **display**.
  - Rather than being stored in the activation records.

Display

- The display contains a list of pointers to ARIs in the stack.
  - **One for each active static depth (static nesting level)!**
  - **Display[i]** = The **most recent** ARI of a subprogram with static depth (SNL) **i**
    - There are k+1 entries in the display where k is the static depth of the currently executing subprogram units.
    - k=0 is for the main program unit.

Example: Display

```
program MAIN_3;
  procedure BIGSUB;
    procedure SUB1;
       …
    end; {SUB1}
    procedure SUB2;
        procedure SUB3;
          …
        end; {SUB3}
      …
    end; {SUB2}
   SUB2;
  end; {BIGSUB}
BIGSUB;
end. {MAIN_3}
```



How to Access Nonlocal Variables Using Display

- A reference to a nonlocal variable X can be represented by the pair **(display_offset, local_offset)** where
  - **display_offset** = The same as **chain_offset**.
  - **local_offset** = The offset from the beginning of the AR of the subprogram containing the declaration for X.

How to Access Nonlocal Variables Using Display

- Use the **display_offset** to get the pointer to the correct ARI with the variable.
  - Display[display-offset]
- Use the **local_offset** to get to the variable within the ARI.
  - **Two memory references** for any nonlocal reference!

How to Maintain the Display?

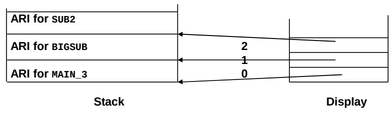
- During program execution!
- At a subprogram call:
  - Maintain the display condition:
  - **Display[i]** = The **most recent** ARI of a subprogram with static depth (SNL) **i**
- At a subprogram return:
  - Maintain the display condition:
  - **Display[i]** = The **most recent** ARI of a subprogram with static depth (SNL) **i**

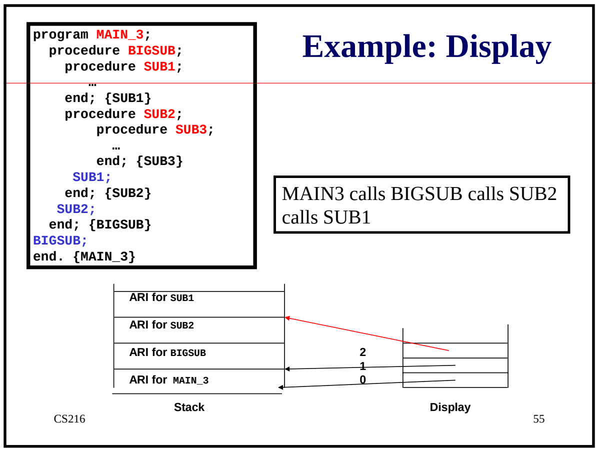
Example: Display

```
program MAIN_3;
  procedure BIGSUB;
    procedure SUB1;
       …
    end; {SUB1}
    procedure SUB2;
        procedure SUB3;
          …
        end; {SUB3}
       SUB1;
    end; {SUB2}
   SUB2;
  end; {BIGSUB}
BIGSUB;
end. {MAIN_3}
```

MAIN3 calls BIGSUB calls SUB2

Calls SUB1?





Example: Display

```
program MAIN_3;
  procedure BIGSUB;
    procedure SUB1;
    …
    end; {SUB1}
    procedure SUB2;
        procedure SUB3;
        …
        end; {SUB3}
      SUB1;
    end; {SUB2}
   SUB2;
  end; {BIGSUB}
BIGSUB;
end. {MAIN_3}
```

MAIN3 calls BIGSUB calls SUB2 calls SUB1

ARI for SUB1

ARI for SUB2

ARI for BIGSUB

ARI for MAIN_3

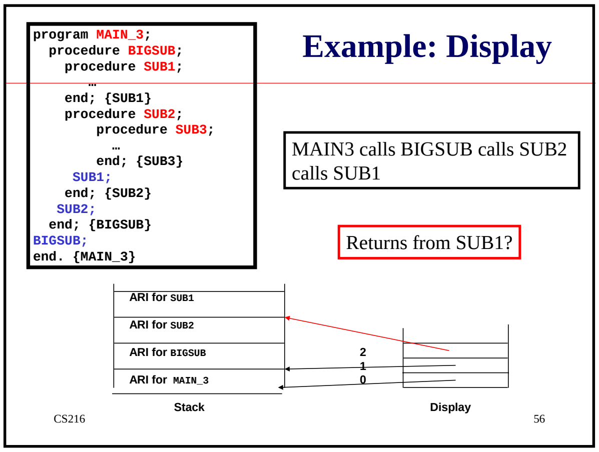
Stack

2

1

0

Display



Example: Display

```
program MAIN_3;
  procedure BIGSUB;
    procedure SUB1;
    …
    end; {SUB1}
    procedure SUB2;
        procedure SUB3;
        …
        end; {SUB3}
      SUB1;
    end; {SUB2}
   SUB2;
  end; {BIGSUB}
BIGSUB;
end. {MAIN_3}
```

MAIN3 calls BIGSUB calls SUB2 calls SUB1

Returns from SUB1?

ARI for SUB1

ARI for SUB2

ARI for BIGSUB

ARI for MAIN_3

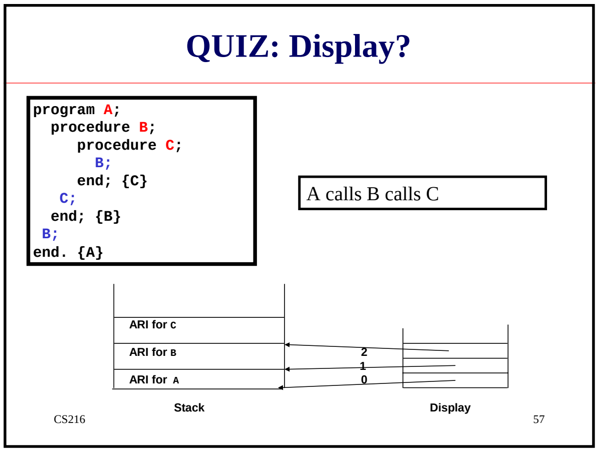
Stack

2

1

0

Display



QUIZ: Display?

```
program A;
  procedure B;
     procedure C;
       B;
     end; {C}
   C;
  end; {B}
 B;
end. {A}
```

A calls B calls C

ARI for C

ARI for B

ARI for A

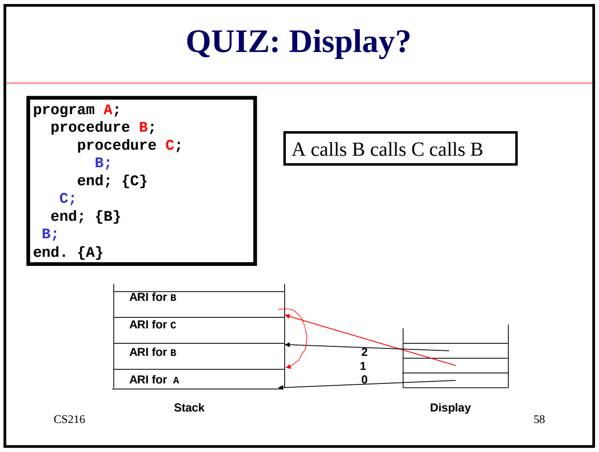
Stack

2

1

0

Display



QUIZ: Display?

```
program A;
  procedure B;
     procedure C;
       B;
     end; {C}
   C;
  end; {B}
 B;
end. {A}
```

A calls B calls C calls B

ARI for B

ARI for C

ARI for B

ARI for A

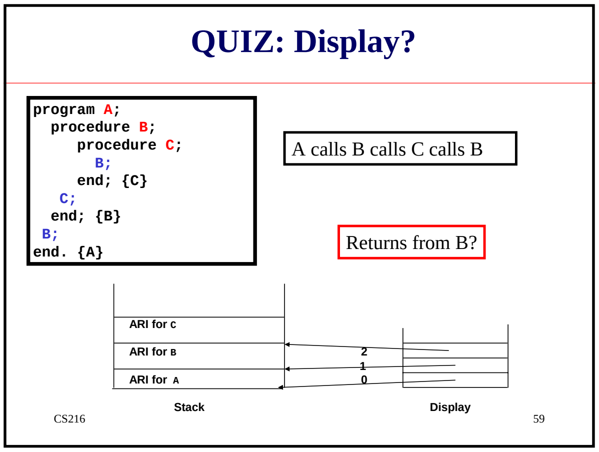
Stack

2

1

0

Display



QUIZ: Display?

```
program A;
  procedure B;
     procedure C;
       B;
     end; {C}
   C;
  end; {B}
 B;
end. {A}
```

A calls B calls C calls B

Returns from B?

ARI for C

ARI for B

ARI for A

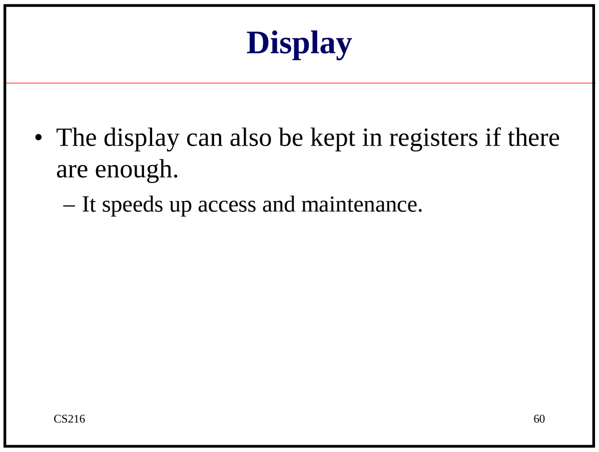
Stack

2

1

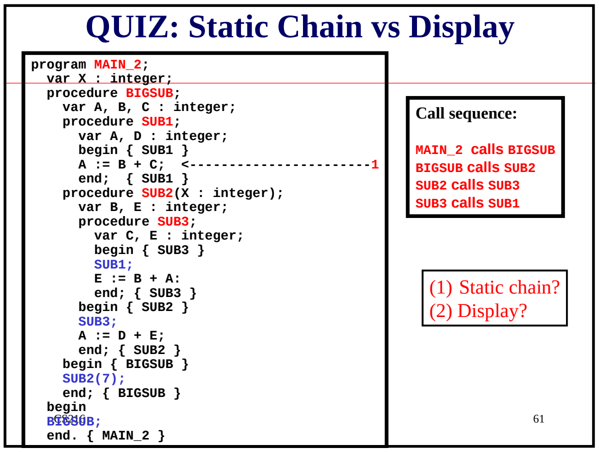
0

Display



Display

- The display can also be kept in registers if there are enough.
  - It speeds up access and maintenance.



QUIZ: Static Chain vs Display

```
program MAIN_2;
  var X : integer;
  procedure BIGSUB;
    var A, B, C : integer;
    procedure SUB1;
      var A, D : integer;
      begin { SUB1 }
      A := B + C;  <-------------------------1
      end;  { SUB1 }
    procedure SUB2(X : integer);
      var B, E : integer;
      procedure SUB3;
        var C, E : integer;
        begin { SUB3 }
        SUB1;
        E := B + A:
        end; { SUB3 }
      begin { SUB2 }
      SUB3;
      A := D + E;
      end; { SUB2 }
    begin { BIGSUB }
    SUB2(7);
    end; { BIGSUB }
  begin
  BIGSUB;
  end. { MAIN_2 }
```

Call sequence:

MAIN_2 calls BIGSUB
BIGSUB calls SUB2
SUB2 calls SUB3
SUB3 calls SUB1

(1) Static chain?
(2) Display?