CS 314 Principles of Programming Languages

Lecture 12: Names, Scopes and Bindings

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Class Information

- HW4 posted, due this Friday.
- Reminder: Project 1 due in about one week.

Names, Bindings and Memory

What's in a name? — Each name "means" something!

- Denotes a programming language construct
- Has associated "attributes"
  Examples: type, memory location, read/write permission, storage class, access restrictions.
- Has a meaning
  Examples: represents a semantic object, a type description, an integer value, a function value, a memory address.

Names, Bindings and Memory

$\boxed{\textbf{Bindings}}$ – association of a name with the thing it “names” (e.g., a name and a memory location, a function name and its “meaning”, a name and a value)

- **Compile time**: during compilation process - static (e.g.: macro expansion, type definition)
- **Link time**: separately compiled modules/files are joined together by the linker (e.g: adding the standard library routines for I/O (stdio.h), external variables)
- **Run time**: when program executes - dynamic

Compiler needs bindings to know meaning of names during translation (and execution).

Binding Time - Choices

- **Early binding** times — more efficient (faster) at run time
- **Late binding** times — more flexible (postpone binding decision until more "information" is available)
- Examples of static binding (early):
  - functions in C
  - types in C
- Examples of dynamic binding (late):
  - virtual methods in Java
  - dynamic typing in Javascript, Scheme

Note: dynamic linking is somewhat in between static and dynamic binding; the function signature has to be known (static), but the implementation is linked and loaded at run time (dynamic).

How to Maintain Bindings

- Symbol table: maintained by compiler during compilation

  names $\Rightarrow$ *attributes*
- Environment: maintained by compiler-generated-code during program execution

  names $\Rightarrow$ *memory locations*

Question:

- How long do bindings last for a name hold in a program?
- What initiates a binding?
- What ends a binding?

Scope Example

Nested Subroutines (Algol 60, Ada, ML, Common Lisp, Python, ….)

```
program L;
        var n: char;            {n declared in L}
        procedure W;
        begin
                write (n);      {n referenced in W}
        end;
        procedure D;
                var n: char;    {n declared in D}
        begin
                n := 'D';       {n referenced in D}
                W
        end;
begin
        n := 'L';               {n referenced in L}
        W;
        D
end
```

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Lexical Scope

- Non-local variables are associated with declarations at *compile* time
- Find the smallest block syntactically enclosing the reference and containing a declaration of the variable
- Example:
  - The reference to n in W is associated with two different declarations at two different times
  - The output is?

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Calling Chain:

$$L \Rightarrow W$$

$$L \Rightarrow D \Rightarrow W$$

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L

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end
```

Dynamic Scope

- Non-local variables are associated with declarations at *run* time
- Find the most recent, currently active run-time stack frame containing a declaration of the variable
- Example:
  - The reference to n in W is associated with two different declarations at two different times
  - The output is ?

L

D

Calling Chain:

$$L \Rightarrow W$$

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        procedure W;
        begin
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                n := 'D'; {n referenced in D}
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        n := 'L';   {n referenced in L}
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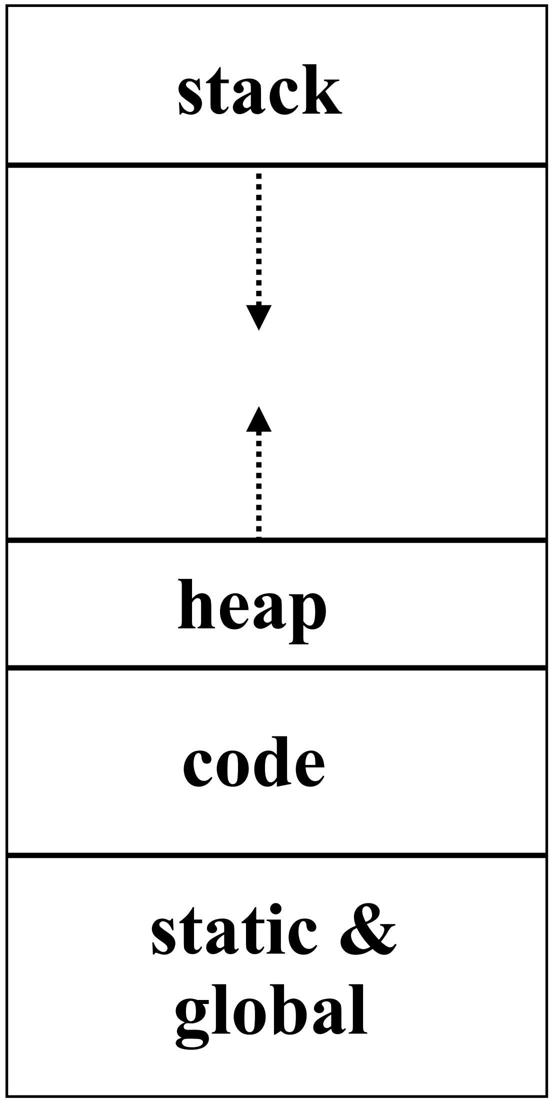
Review: Program Memory Layout

- Static objects are given an absolute address that is retained throughout the execution of the program
- Stack objects are allocated and deallocated in last-in, first-out order, usually in conjunction with subroutine calls and returns
- Heap objects are allocated and deallocated at any arbitrary time



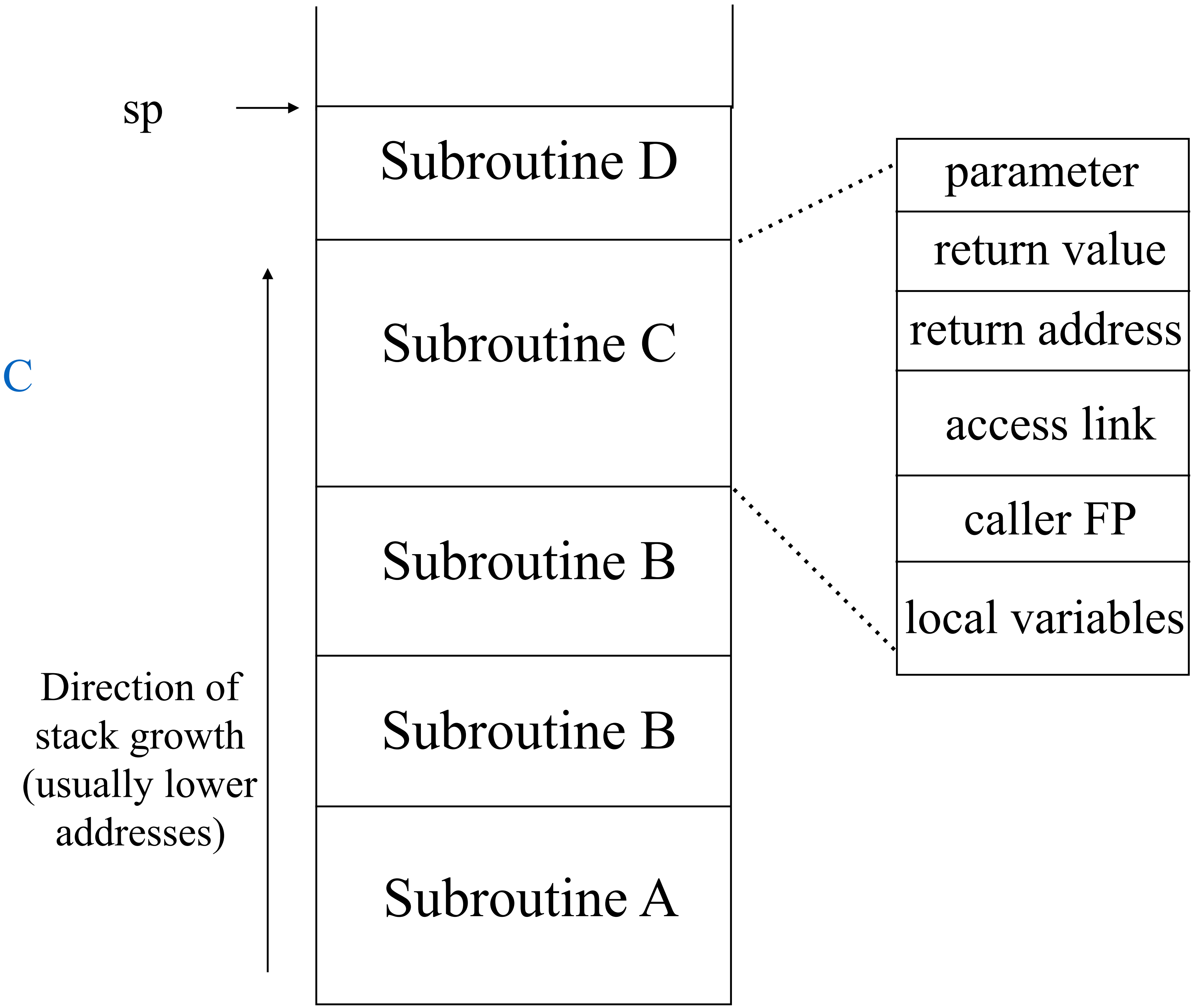
Procedure Activations

- Begins when control enters activation (call)
- Ends when control returns from call

Calling chain: $A \Rightarrow B \Rightarrow B \Rightarrow C \Rightarrow D$

Example:

procedure C:
    D
procedure B:
    if…then B else C
procedure A:
    B
main program:
    A



Procedure Activations

- Run-time stack contains frames from main program & active procedure
- Each stack frame includes:
  1. Pointer to stack frame of caller (**control link** for stack maintenance and dynamic scoping)
  2. Return address (within calling procedure)
  3. Mechanism to find non-local variables (**access link** for lexical scoping)
  4. Storage for parameters, local variables and final values

parameter
return value
return address
access link
caller FP
local variables

Lexical Scoping and Dynamic Scoping Example

How do we look for non-local variables?

```
Program
    x, y: integer   // declarations of x and y
    begin
        Procedure B    // declaration of B
            y, z: real  // declaration of y and z
            begin
                ...
                y = x + z // occurrences of y, x, and z
                if (...) call B // occurrence of B
            end
        Procedure C    // declaration of C
            x: real
            begin
                ...
                call B // occurrence of B
            end
        ...
        call C     // occurrence of C
        call B     // occurrence of B
    end
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```

Lexical Scoping and Dynamic Scoping Example

Calling chain: MAIN⇒ C ⇒ B ⇒ B

```
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        x, y: integer   // declarations of x and y
        begin
          Procedure B    // declaration of B
                y, z: real  // declaration of y and z
                begin
                ...
                y = x + z // occurrences of y, x, and z
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                end
          Procedure C    // declaration of C
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                end
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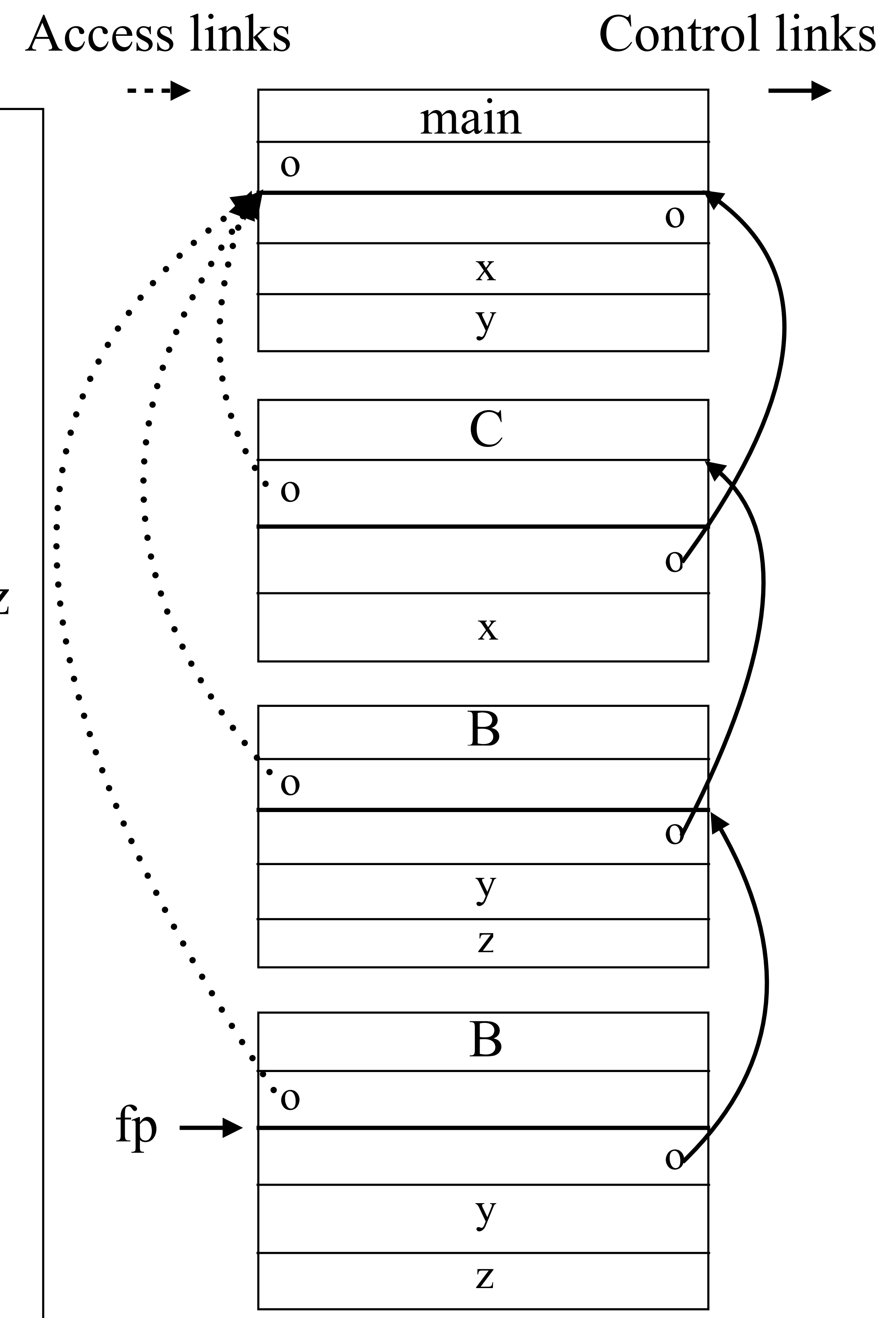
```



Look up Non - local Variable Reference

Access links and **control links** are used to look for non-local variable references.

Static Scope:

Access link points to the stack frame of the ***most recently*** *activated lexically enclosing procedure*

⇒ Non-local name binding is *determined* at *compile time*, and *implemented* at *run-time*

Dynamic Scope:

Control link points to the stack frame of ***caller***

⇒ Non-local name binding is *determined* and *implemented* at *run-time*

Access to Non-Local Data

How does the code find non-local data at run-time?

Real globals:

- visible everywhere
- translated into an address at compile time

Lexical scoping:

- view variables as (level, offset) pairs, (**compile-time symbol table**)
- use (level, offset) pair to get address by using chains of access link (at **run-time**)

Dynamic scoping:

- variable names are preserved
- look-up of variable name uses chains of control links (at **run-time**)

Lexical Scoping

Symbol table generated at compile time matches declarations and occurrences.
⇒ Each name can be represented as a pair (nesting_level, local_index).

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```
Program
  (1,1), (1,2): integer   // declarations of x and y
  begin
    Procedure (1,3)    // declaration of B
      (2,1), (2,2): real  // declaration of y and z
      begin
        ...
        (2,1) = (1,1) + (2,2) // occurrences of y, x, and z
        if (...) call (1,3) // occurrence of B
      end
    Procedure (1,4)    // declaration of C
      (2,1): real
      begin
        ...
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Lexical Scoping

Symbol table generated at compile time matches declarations and occurrences.
⇒ Each name can be represented as a pair (nesting_level, local_index).

```
Program
 x, y: integer   // declarations of x and y
 begin
  Procedure B    // declaration of B
   y, z: real  // declaration of y and z
   begin
    ...
    y = x + z // occurrences of y, x, and z
    if (...) call B // occurrence of B
   end
  Procedure C    // declaration of C
   x: real
   begin
    ...
    call B // occurrence of B
   end
 ...
 call C     // occurrence of C
 call B     // occurrence of B
end
```

```
Program
 (1,1), (1,2): integer   // declarations of x and y
 begin
  Procedure (1,3)    // declaration of B
   (2,1), (2,2): real  // declaration of y and z
   begin
    ...
    (2,1) = (1,1) + (2,2) // occurrences of y, x, and z
    if (...) call (1,3) // occurrence of B
   end
  Procedure (1,4)    // declaration of C
   (2,1): real
   begin
    ...
    call (1,3) // occurrence of B
   end
 ...
 call (1,4)     // occurrence of C
 call (1,3)     // occurrence of B
end
```

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for this statement:

$$(2,1) = (1,1) + (2,2)$$

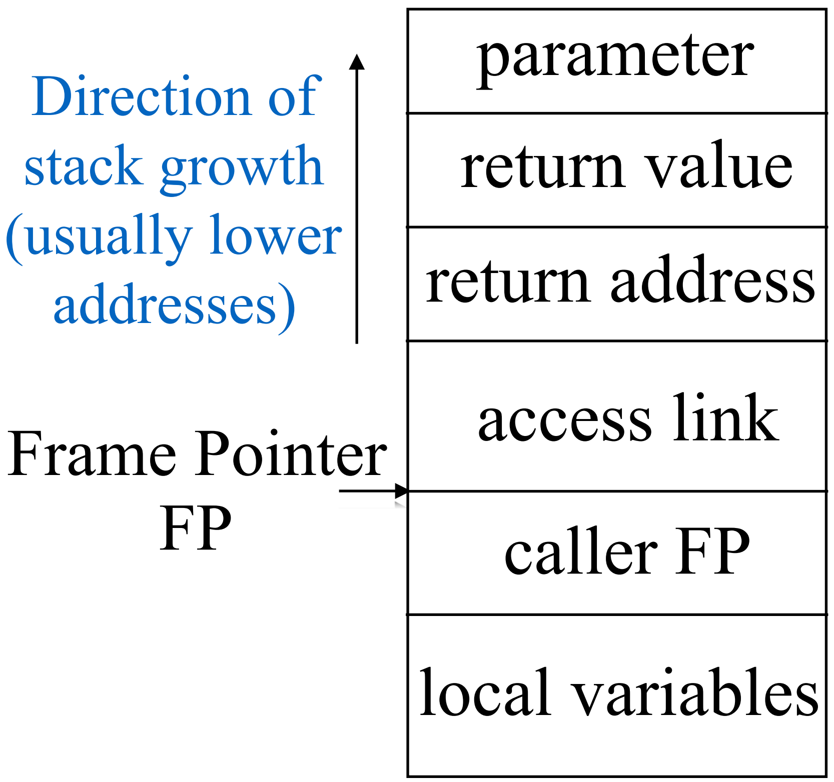
What do we know?

- Assume the nesting level of the statement is **level 2**
- Register r_0 contains the current FP (frame pointer)
- **(2, 1) and (2, 2) are local variables**, so they are allocated in the activation record that current FP points to.
  (1, 1) is an non-local variable.
- Two new instructions:
  LOAD R_x, R_y means $R_x \leftarrow MEM(R_y)$
  STORE R_x, R_y means $MEM(R_x) \leftarrow R_y$

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

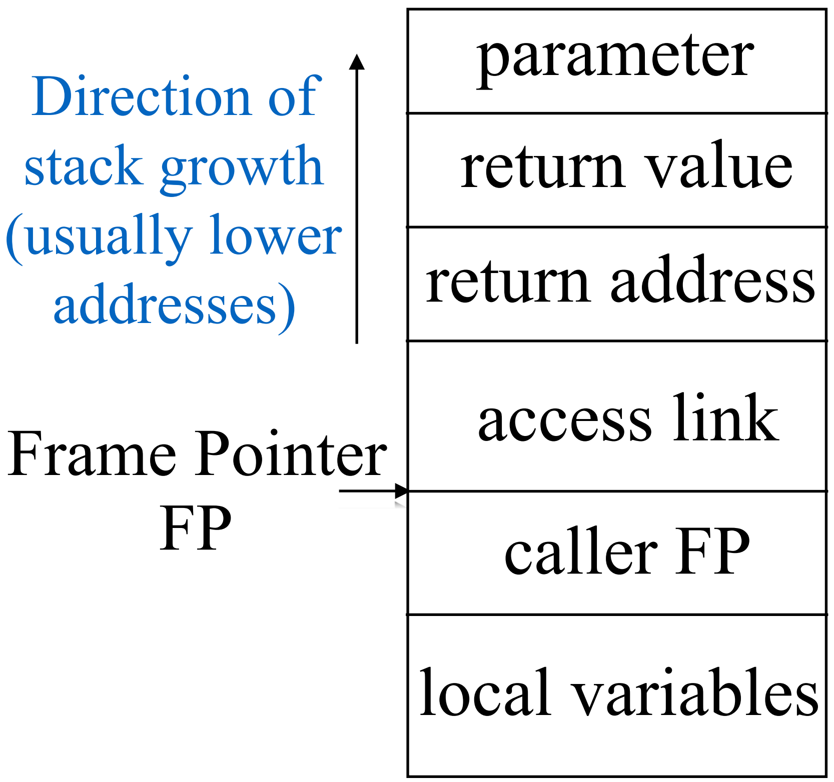



```
(1,1)  LOADI r1, #4      // offset of local variable (1,1) in frame
       LOADI r2, #-4     // offset of access link in frame (bytes)
       ADD r3 r0 r2      // address of access link
       LOAD r4 r3        // get access link
       ADD r5 r4 r1      // address of local variable (1,1) in frame
       LOAD r6 r5        // get content of variable (1,1)
```

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

(2,1) = (1,1) + (2,2)

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```

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

Direction of stack growth (usually lower addresses)

parameter
return value
return address
access link
caller FP
local variables

Frame Pointer FP

```
(1,1)  LOADI r1, #4      // offset of local variable (1,1) in frame
       LOADI r2, #-4     // offset of access link in frame (bytes)
       ADD r3 r0 r2      // address of access link
       LOAD r4 r3        // get access link
       ADD r5 r4 r1      // address of local variable (1,1) in frame
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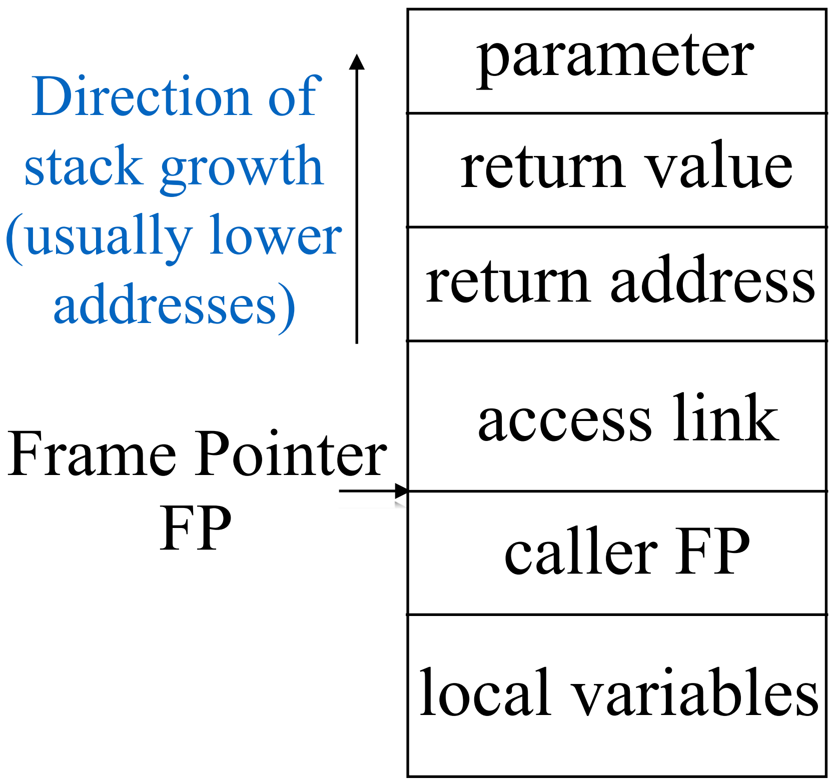
Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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       LOAD r4 r3       // get access link
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       LOAD r6 r5       // get content of variable (1,1)
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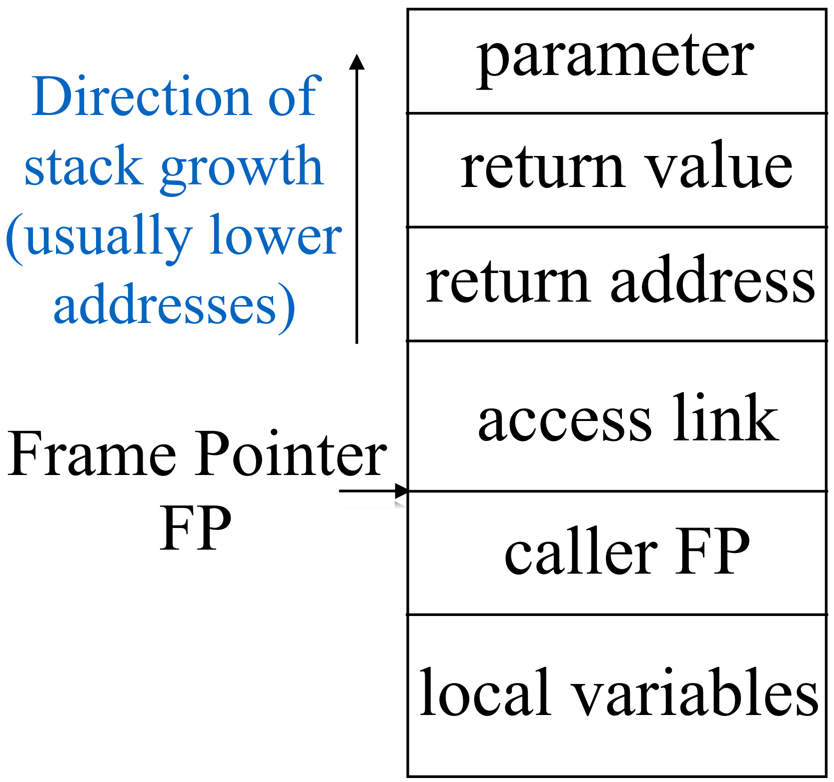
Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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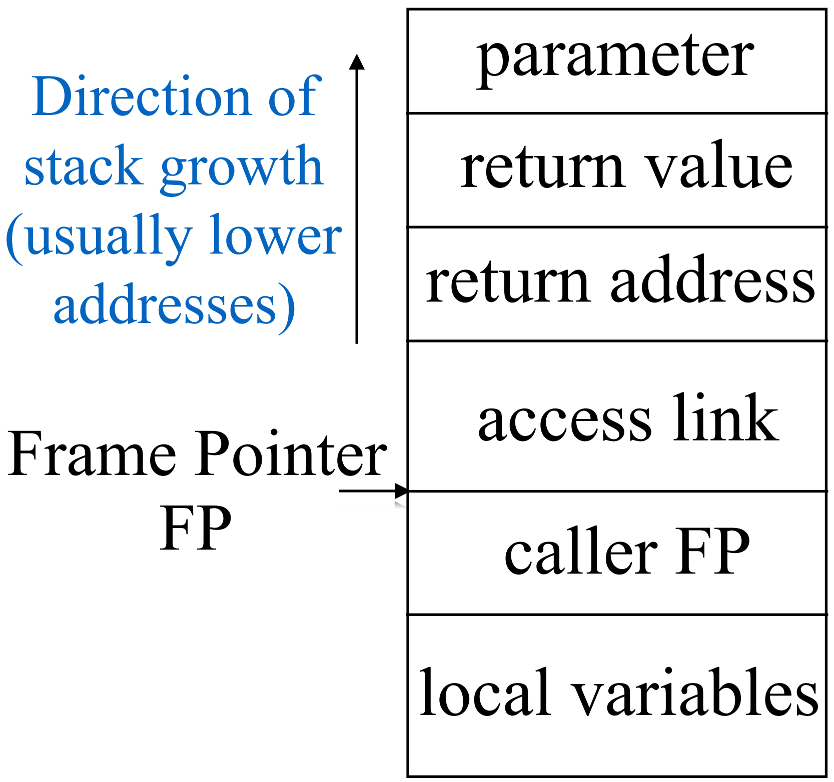
Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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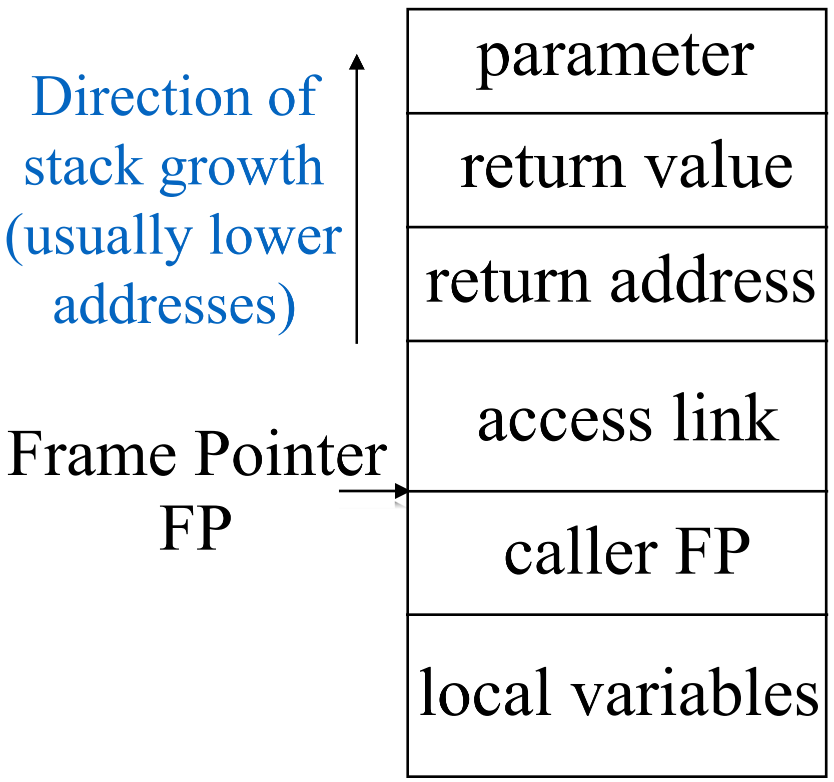
       LOAD r6 r5       // get content of variable (1,1)
```

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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(1,1)  LOADI r1, #4     // offset of local variable (1,1) in frame
       LOADI r2, #-4    // offset of access link in frame (bytes)
       ADD r3 r0 r2     // address of access link
       LOAD r4 r3       // get access link
       ADD r5 r4 r1     // address of local variable (1,1) in frame
       LOAD r6 r5       // get content of variable (1,1)
(2,2)  LOADI r7 #8      // offset of local variable (2,2) in frame
       ADD r8 r0 r7     // address of local variable (2,2)
       LOAD r9 r8       // get content of variable (2, 2)
```
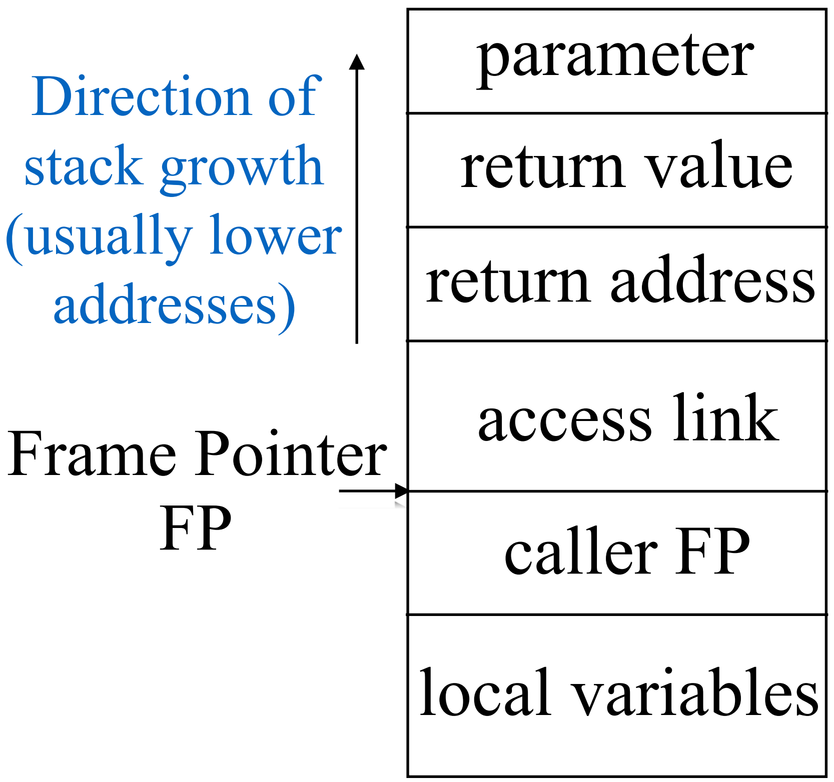

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (∗)?

$$(2,1) = (1,1) + (2,2)$$

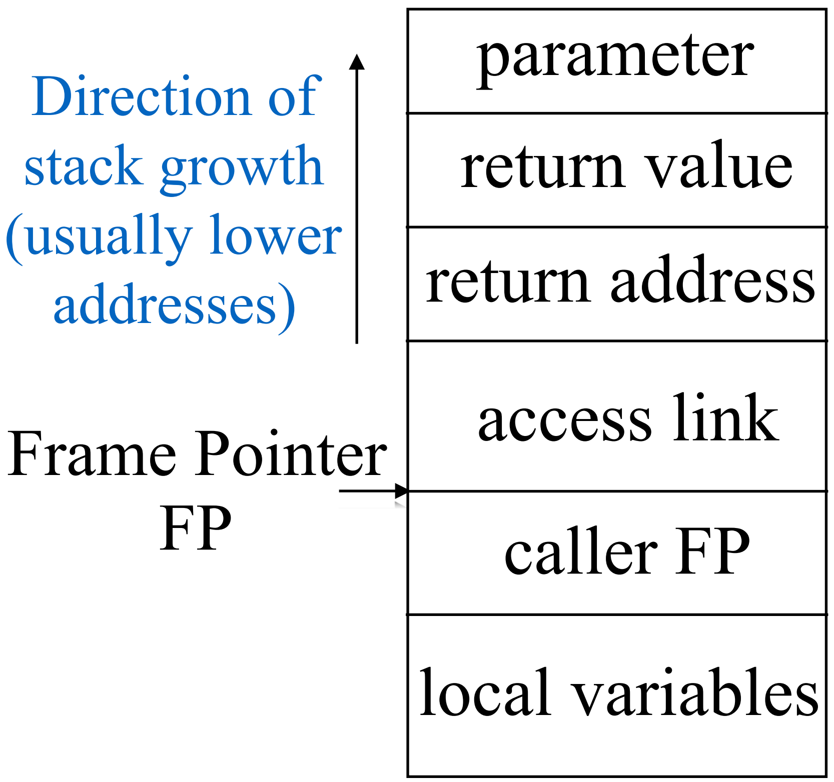



```
(1,1)  LOADI r1, #4      // offset of local variable (1,1) in frame
       LOADI r2, #-4     // offset of access link in frame (bytes)
       ADD r3 r0 r2      // address of access link
       LOAD r4 r3        // get access link
       ADD r5 r4 r1      // address of local variable (1,1) in frame
       LOAD r6 r5        // get content of variable (1,1)
(2,2)  LOADI r7 #8       // offset of local variable (2,2) in frame
       ADD r8 r0 r7      // address of local variable (2,2)
       LOAD r9 r8        // get content of variable (2, 2)
```

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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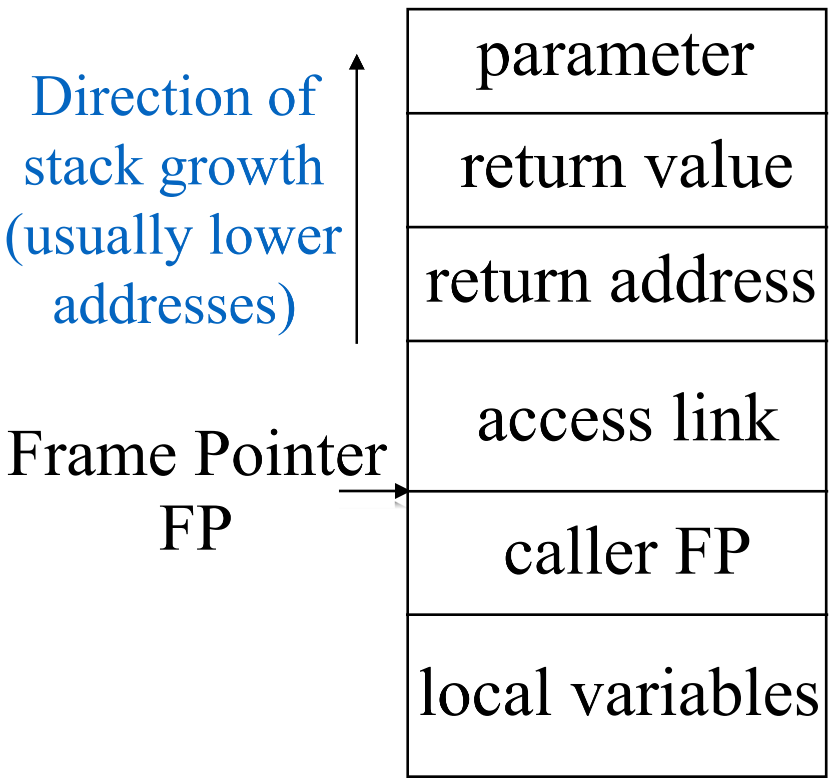
       ADD r3 r0 r2     // address of access link
       LOAD r4 r3       // get access link
       ADD r5 r4 r1     // address of local variable (1,1) in frame
       LOAD r6 r5       // get content of variable (1,1)
(2,2)  LOADI r7 #8      // offset of local variable (2,2) in frame
       ADD r8 r0 r7     // address of local variable (2,2)
       LOAD r9 r8       // get content of variable (2, 2)
```

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$




```
(1,1)  LOADI r1, #4      // offset of local variable (1,1) in frame
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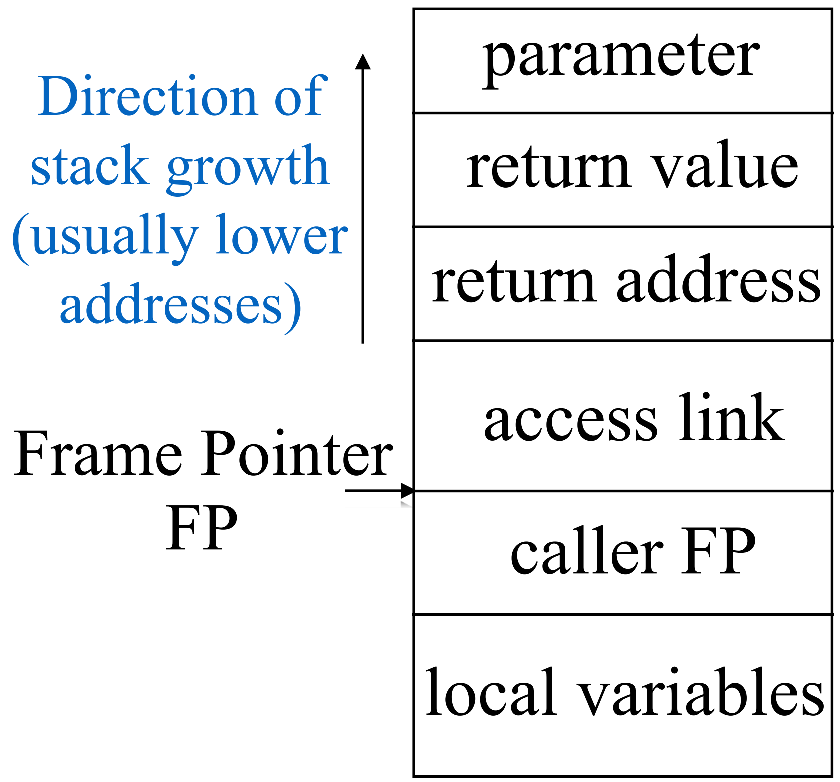
       LOAD r4 r3        // get access link
       ADD r5 r4 r1      // address of local variable (1,1) in frame
       LOAD r6 r5        // get content of variable (1,1)
(2,2)  LOADI r7 #8       // offset of local variable (2,2) in frame
       ADD r8 r0 r7      // address of local variable (2,2)
       LOAD r9 r8        // get content of variable (2, 2)
  +    ADD r10 r6 r9     // (1,1) + (2,2)
```

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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       LOAD r6 r5        // get content of variable (1,1)
(2,2)  LOADI r7 #8       // offset of local variable (2,2) in frame
       ADD r8 r0 r7      // address of local variable (2,2)
       LOAD r9 r8        // get content of variable (2, 2)
  +    ADD r10 r6 r9     // (1,1) + (2,2)
(2,1)  LOADI r11 #4      // offset of local variable (2,1) in frame
       ADD r12 r0 r11    // address of local variable (2,1)
```
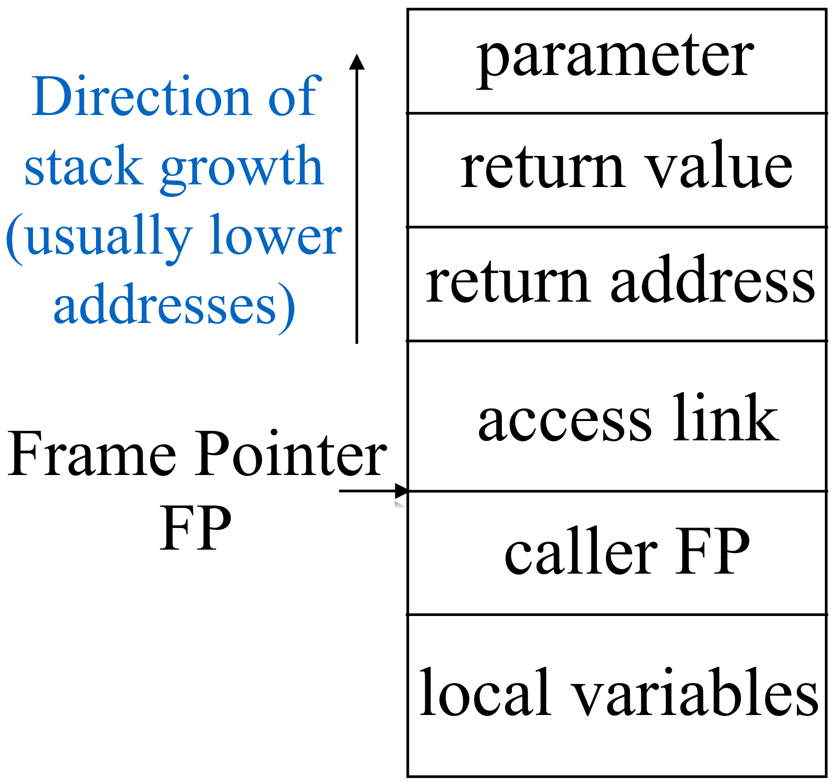

Access to Non-Local Data(Lexical Scoping)

What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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(2,2)  LOADI r7 #8       // offset of local variable (2,2) in frame
       ADD r8 r0 r7      // address of local variable (2,2)
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  +    ADD r10 r6 r9     // (1,1) + (2,2)
(2,1)  LOADI r11 #4      // offset of local variable (2,1) in frame
       ADD r12 r0 r11    // address of local variable (2,1)
```

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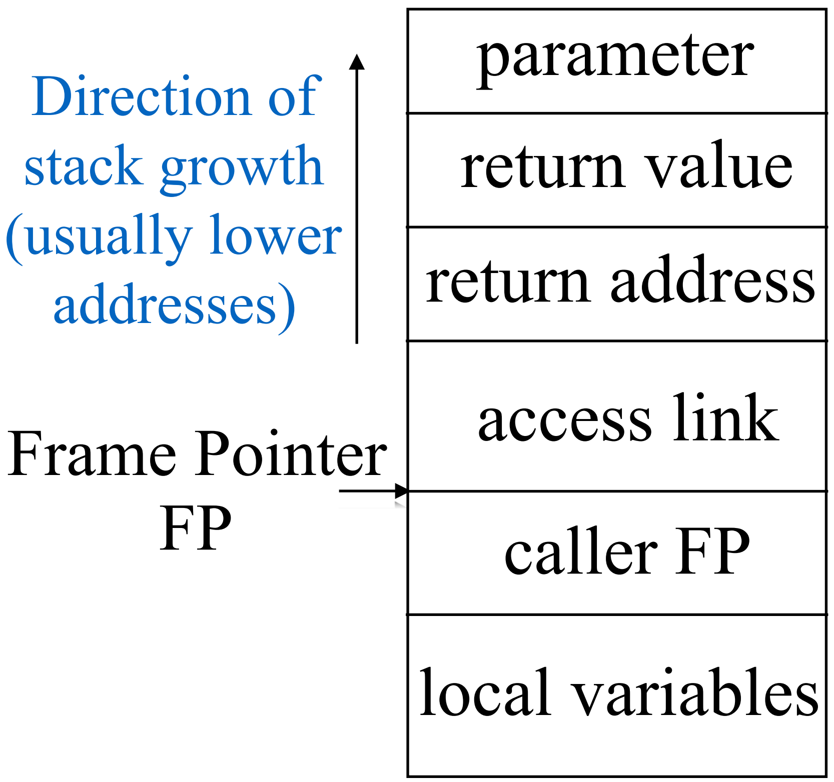
What code do we need to generate for statement (*)?

$$(2,1) = (1,1) + (2,2)$$

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       LOAD r6 r5        // get content of variable (1,1)
(2,2)  LOADI r7 #8       // offset of local variable (2,2) in frame
       ADD r8 r0 r7      // address of local variable (2,2)
       LOAD r9 r8        // get content of variable (2, 2)
  +    ADD r10 r6 r9     // (1,1) + (2,2)
(2,1)  LOADI r11 #4      // offset of local variable (2,1) in frame
       ADD r12 r0 r11    // address of local variable (2,1)
  =    STORE r12 r10     // (2,1) = (1,1) + (2,2)
```

Next Lecture

Things to do:

- Read Scott, Chapter 3.1 - 3.4, Chapter 9.1 - 9.3 (4th Edition) or Chapter 8.1 - 8.3 (3rd Edition)
- Read ALSU, Chapter 7.1 - 7.3 (2nd Edition).