CS 314 Principles of Programming Languages

Lecture 15: Review and Functional Programming

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March 19, 2018

Class Information

- Midterm exam forum open in Sakai.
- HW4 and HW5 solutions posted in Sakai.
- This week's recitation is a review for midterm. Attendance is encouraged!
- Reminder: midterm exam 3/26, in class, closed book, closed notes.

Review: Lexical Scoping

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

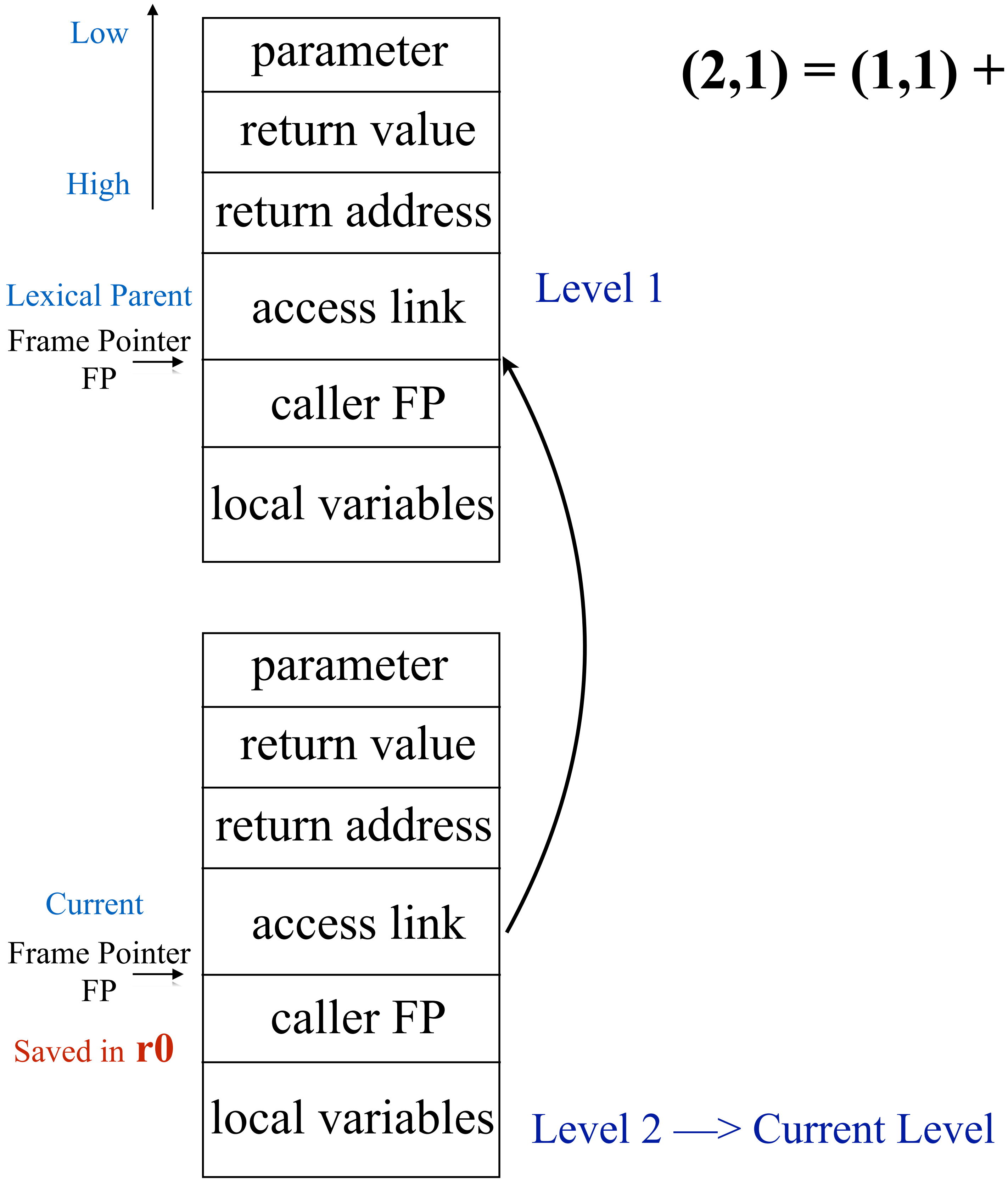
```
Program
  x, y: integer   // declarations of x and y
  Procedure B     // declaration of B
    y, z: real  // declaration of y and z
    begin
      ...
      y = x + z // occurrences of y, x, and z
      if (...) call B // occurrence of B
    end
  Procedure C     // declaration of C
    x: real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

```
Program
  (1,1), (1,2): integer   // declarations of x and y
  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
  begin
  ...
  call (1,4)     // occurrence of C
  call (1,3)     // occurrence of B
end
```

Review: Access to Non-Local Data(Lexical Scoping)

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

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



Assume “access link” field is 4 bytes.
Each unit offset corresponds to 4 bytes.

Access to Non-Local Data(Lexical Scoping)

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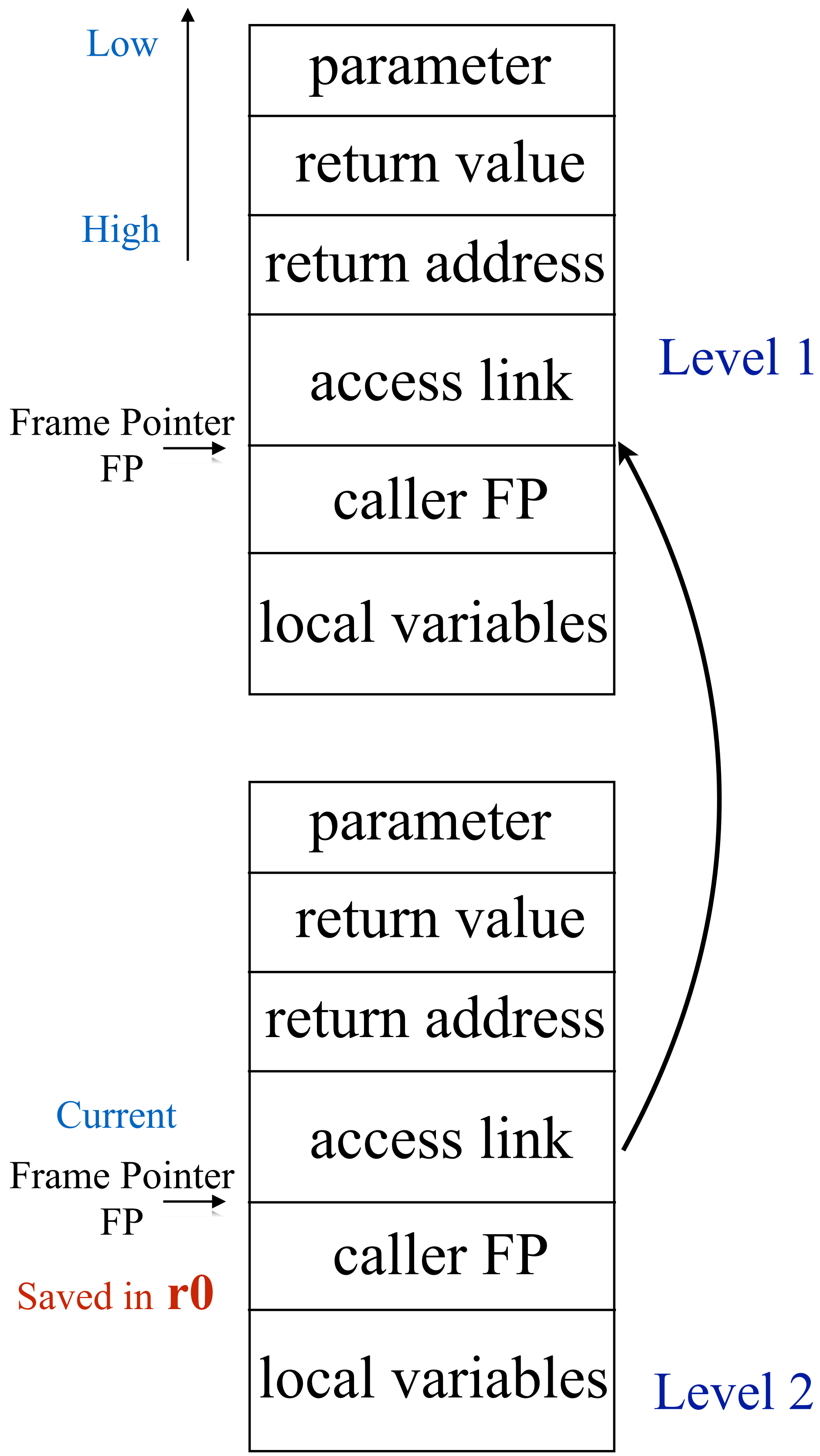

(2,1) = (1,1) + (2,2)

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(2,2)	LOADI r7 #8	// offset of local variable (2,2) in frame
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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)
=	STORE r12 r10	// (2,1) = (1,1) + (2,2)

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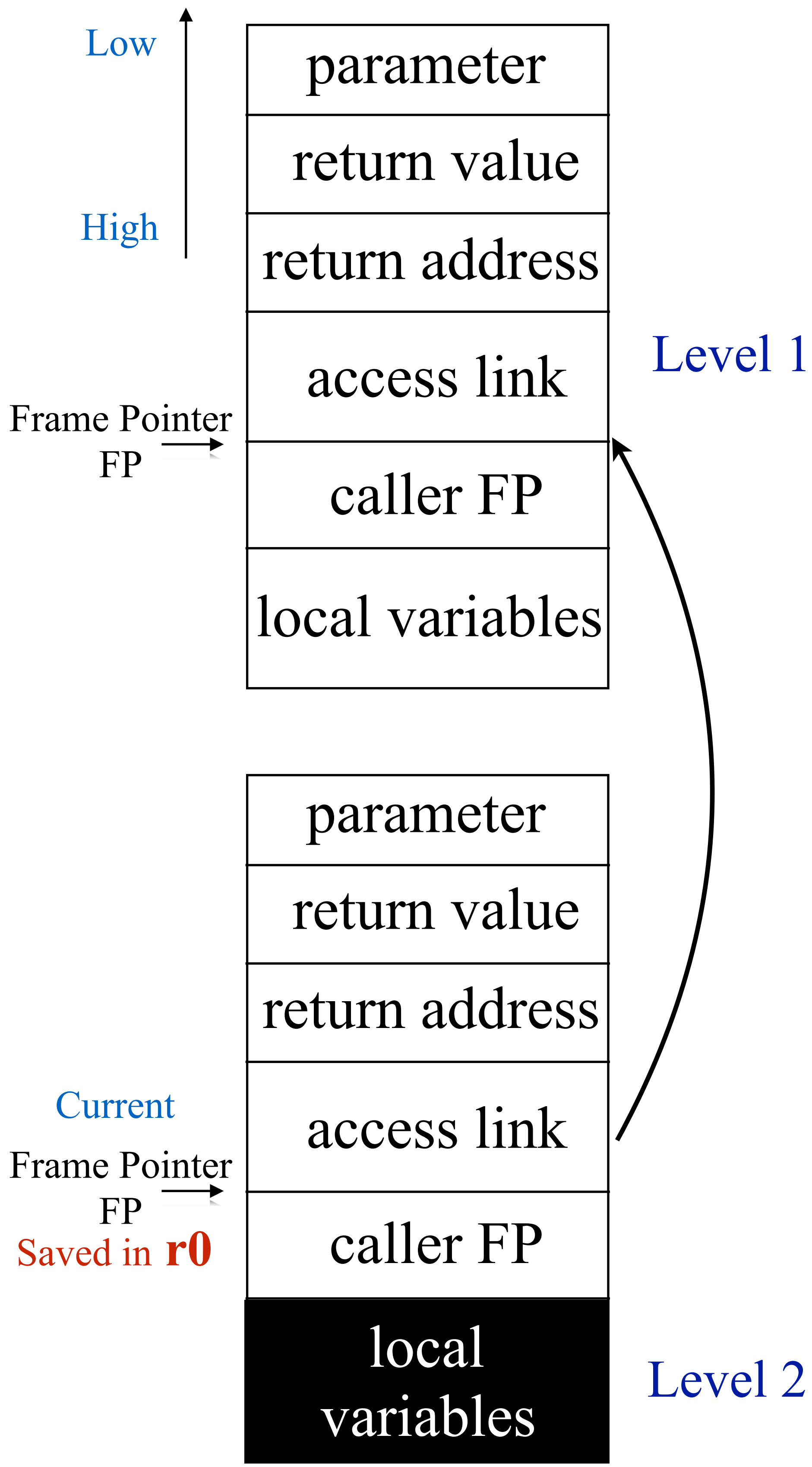

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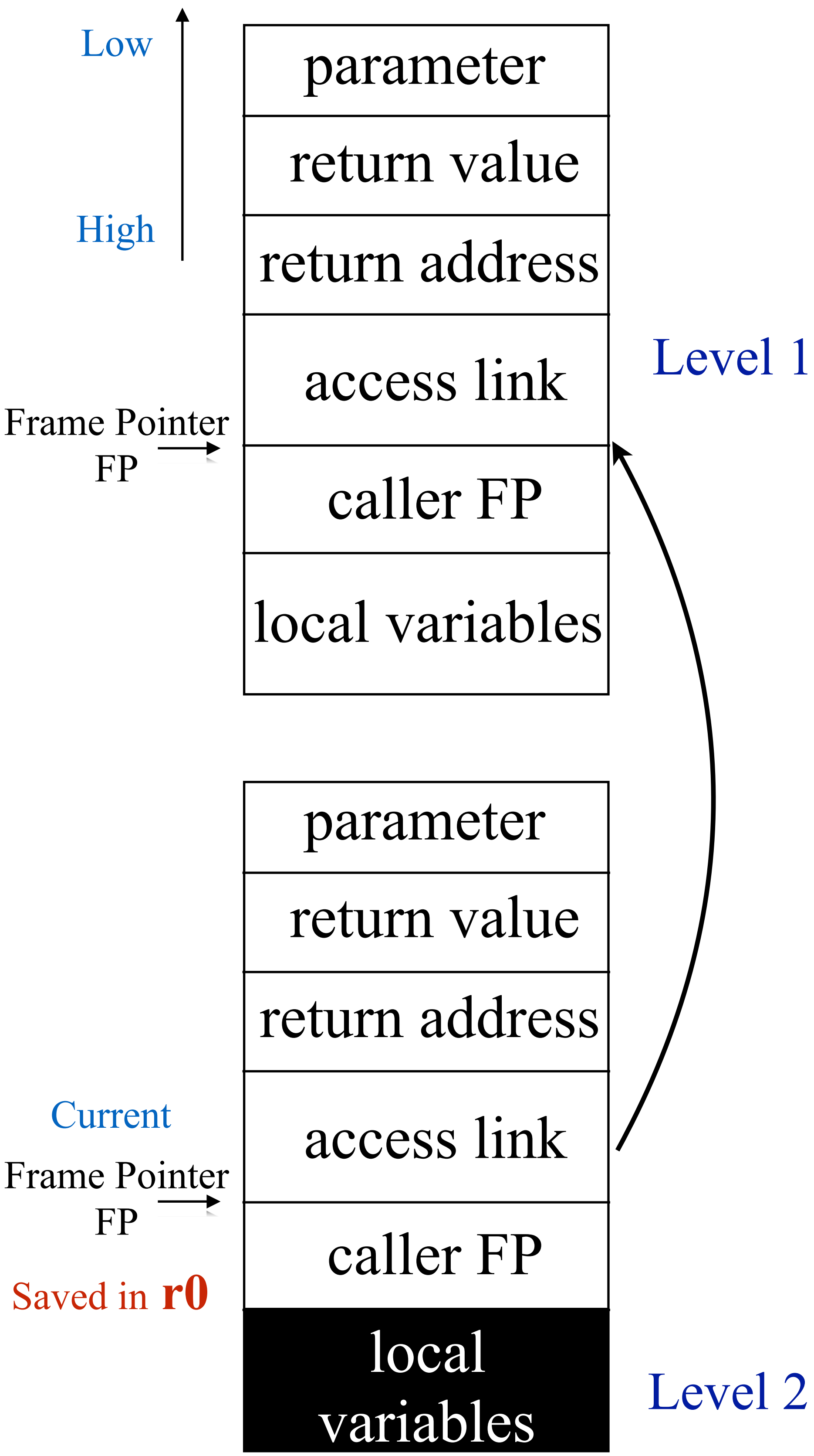

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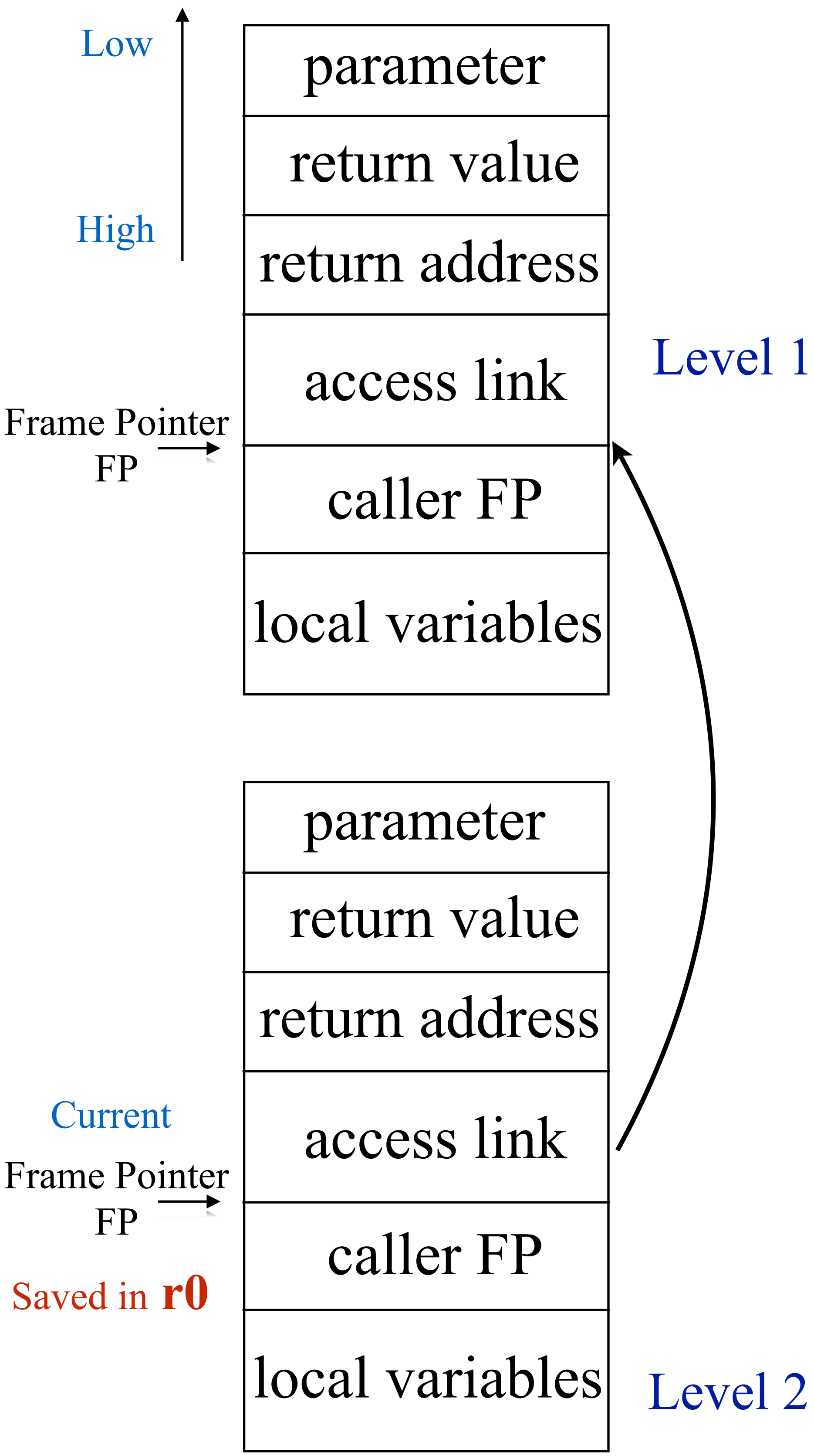

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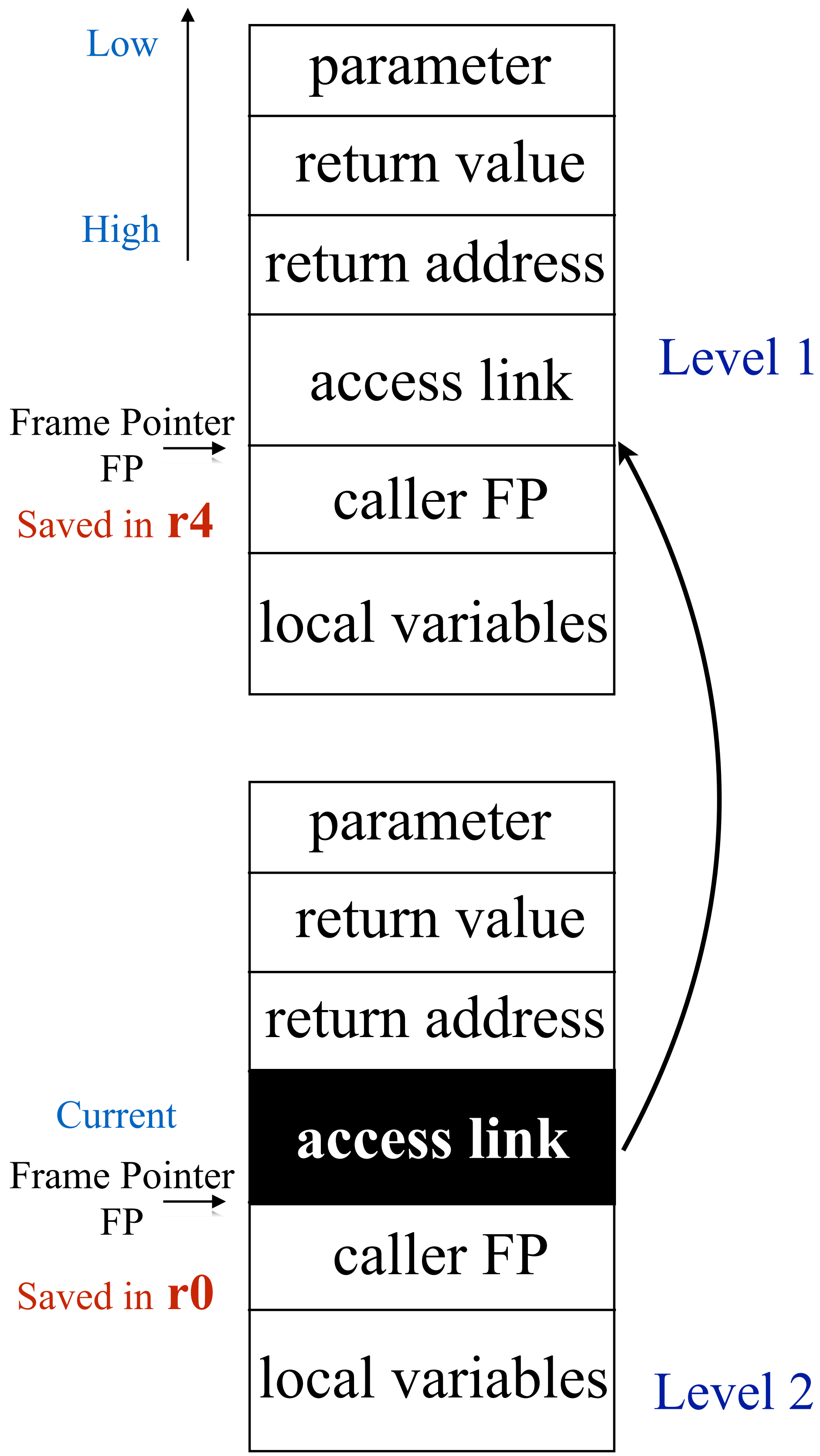

Level 2 —> Current Level

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```
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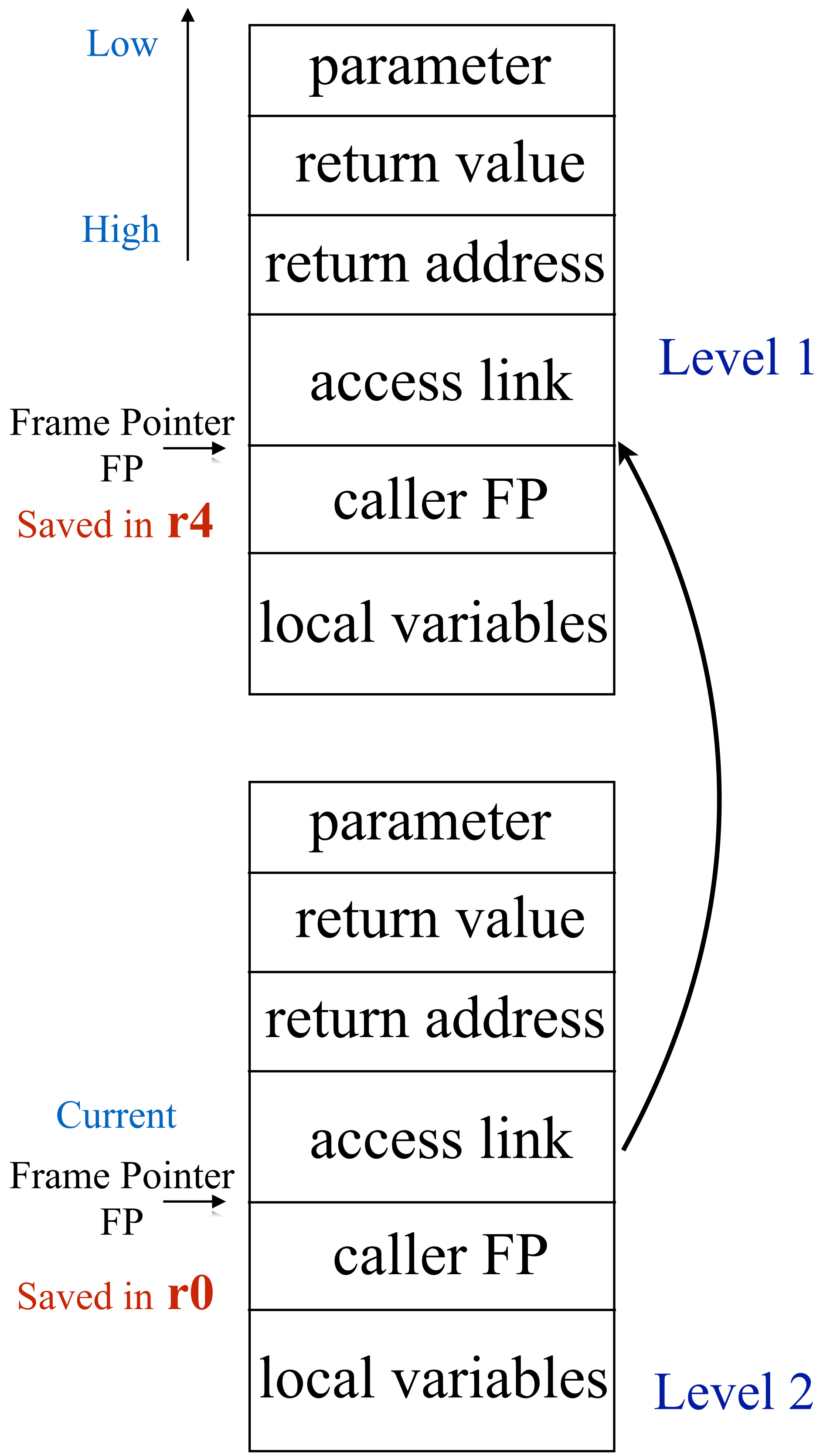

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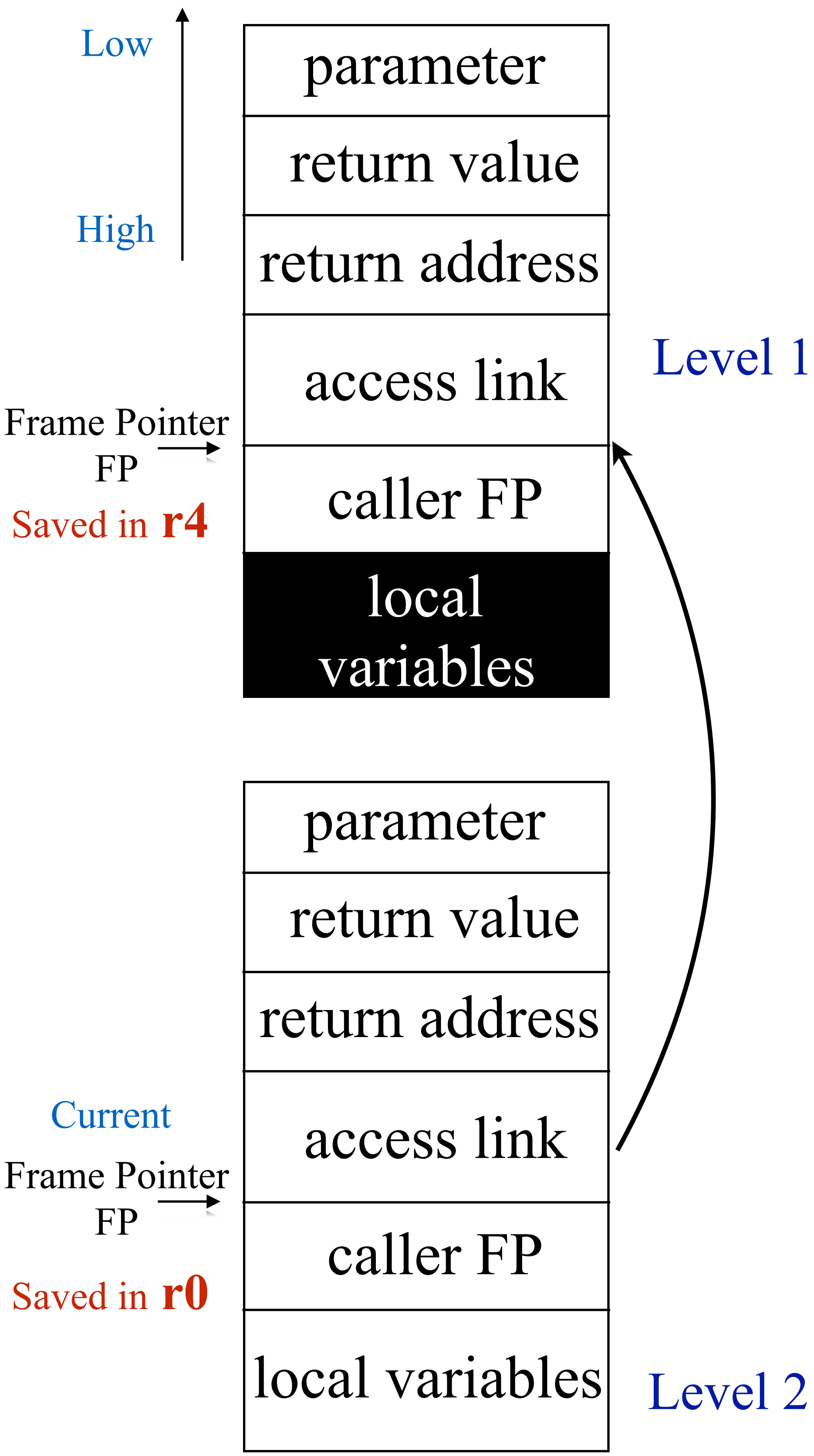

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```

Level 2 —> Current Level

Assume “access link” field is 4 bytes.
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Procedures

- Modularize program structure
  - Actual parameter: information passed from caller to callee (*Argument*)
    Appears in caller code.
  - Formal parameter: <u>local</u> variable whose <u>value</u> (usually) is received from caller
    Appears in callee declaration
- Procedure declaration
  - Procedure names, formal parameters, procedure body with formal local declarations and statement lists, optional result type

    Example: void translate(point *p, int dx)

Parameters

Parameter Association

- Positional association: Arguments associated with formals one-by-one; Example: C, Pascal, Java, Scheme
- Keyword association: formal/actual pairs; mix of positional and keyword possible;
  Example: Ada

  procedure plot(x, y: in real; z: in boolean)

  … plot (0.0, 0.0, z ⇒ true)

  … plot (z ⇒ true, x ⇒ 0.0, y ⇒ 0.0)

Parameter Passing Modes

- Pass-by-value: C/C++, Pascal, Java/C# (value types), Scheme
- Pass-by-result: Ada, Algol W
- Pass-by-value-result: Ada, Swift
- Pass-by-reference: Fortran, Pascal, C++, Ruby, ML

Pass-by-value

```
begin
    c: array[1...10] of integer;
    m, n: integer;
    procedure r(k, j: integer)
    begin
        k := k + 1;
        j := j + 2;
    end r;
  ...
  m := 5;
  n := 3;
  r(m, n);
  write m,n;
end
```

Output:

5 3

Advantage: Argument protected from changes in callee.
Disadvantage: Copying of values takes execution time and space, especially for aggregate values (e.g.: structs, arrays)

Pass-by-reference

```
begin
        c: array[1...10] of integer;
        m, n: integer;
        procedure r(k,j: integer)
        begin
                k := k + 1;
                j := j + 2;
        end r;
  ...
  m := 5;
  n := 3;
  r(m, n);
  write m, n;
end
```

Output:

6 5

Advantage: more efficient than copying
Disadvantage: leads to aliasing, there are two or more names for the storage location; hard to track side effects

Aliasing

Aliasing:

More than two ways to name the same object within a scope

Even without pointers, you can have aliasing through (global ⟷ formal) and (formal ⟷ formal) parameter passing.

```
begin
      j, k, m: integer;
      procedure r(a, b: integer)
      begin
            b := 3;
            m := m * a;
      end
      ...
      q(m, k);   → global/formal <m,a> ALIAS PAIR
      q(j, j);   → formal/formal <a,b> ALIAS PAIR
      write y;
end
```

Pass-by-result

```
begin
        c: array[1...10] of integer;
        m, n: integer;
        procedure r(k, j: integer)
        begin
                k := 1;
                j := 2;
        end r;
      ...
      m := 5;
      n := 3;
      r(m, m);→ NOTE: CHANGE THE CALL
      write m, n;
end
```

Output: 1 or 2 for m?

Problem: order of copy back makes a difference;
implementation dependent.

Pass-by-value-result

```
begin
      c: array[1...10] of integer;
      m, n: integer;
      procedure r(k, j: integer)
      begin
            k := k + 1;
            j := j + 2;
      end r;
     ...
     m := 5;
     n := 3;
     r(m, n);
     write m, n;
end
```

Output: 6 5

Problem: order of copy back makes a difference;
implementation dependent.

Pass-by-value-result

```
begin
    c: array[1...10] of integer;
    m, n: integer;
    procedure r(k, j: integer)
    begin
        k := k + 1;
        j := j + 2;
    end r;
   ...
   /* set c[m] = m */
   m := 2;
   r(m,c[m]);→  WHAT ELEMENT OF "c" IS ASSIGNED TO?
   write c[1], c[2], c[3], ... c[10];
end
```

Output:

Pass-by-value-result

```
begin
    c: array[1...10] of integer;
    m, n: integer;
    procedure r(k, j: integer)
    begin
        k := k + 1;
        j := j + 2;
    end r;
   ...
   /* set c[m] = m */
   m := 2;
   r(m,c[m]);→  WHAT ELEMENT OF "c" IS ASSIGNED TO?
   write c[1], c[2], c[3], ... c[10];
end
```

Output:

Problem: When is the address computed for the copy-back operation? At procedure call (procedure entry), just before procedure exit, or somewhere in between? (Example: ADA on entry)

Pass-by-value-result

```
begin
      c: array[1...10] of integer;
      m, n: integer;
      procedure r(k, j: integer)
      begin
            k := k + 1;
            j := j + 2;
      end r;
     ...
     /* set c[m] = m */
     m := 2;
     r(m,c[m]);→  WHAT ELEMENT OF "c" IS ASSIGNED TO?
     write c[1], c[2], c[3], ... c[10];
end
```

Output:

1 4 3 4 5 … 10 on entry

1 2 4 4 5 … 10 on exit

Problem: When is the address computed for the copy-back operation? At procedure call (procedure entry), just before procedure exit, or somewhere in between? (Example: ADA on entry)

Pass-by-value-result

```
begin
      c: array[1...10] of integer;
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      begin
            k := k + 1;
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      end r;
    ...
    /* set c[m] = m */
    m := 2;
    r(m,c[m]);
    write c[1], c[2], c[3], ... c[10];
end
```

WHAT ELEMENT OF "c" IS ASSIGNED TO?

Output:

1 4 3 4 5 … 10 on entry ← Applicative order

1 2 4 4 5 … 10 on exit ← Normal order

Problem: When is the address computed for the copy-back operation? At procedure call (procedure entry), just before procedure exit, or somewhere in between? (Example: ADA on entry)

Comparison: by-value-result vs. by-reference

Actual parameters need to evaluate to L-values (addresses).

```
begin
        y: integer;
        procedure p(x: integer)
        begin
                x := x + 1      → ref: x and y are ALIASED
                x := x + y      → val-res: x and y are NOT ALIASED
        end
        ...
        y := 2;
        p(y);
        write y;
end
```

Output:

- pass-by-reference: 6
- pass-by-value-result: 5

Note: *by-value-result*: Requires copying of parameter values (expansive for aggregate values); does not have aliasing, but copy-back order dependence.

Review: Computational Paradigms

Imperative:

Sequence of state-changing actions.

- Manipulate an abstract machine with:
  1. Variables naming memory locations
  2. Arithmetic and logical operations
  3. Reference, evaluate, assign operations
  4. Explicit control flow statements
- Fits the *von Neumann architecture* closely
- Key operations: *Assignment* and *Control Flow*

Review: Computation Paradigms

Functional:

Composition of operations on data.

- No named memory locations
- Value binding through parameter passing
- Key operations: *Function application* and *Function abstraction*
- Basis in *lambda calculus*

Pure Functional Languages

Fundamental concept: **application** of (mathematical) functions to values

1. **Referential transparency**: the value of a function application is independent of the context in which it occurs

   - value of *foo(a, b, c)* depends only on the values of *foo*, *a*, *b* and *c*
   - it does not depend on the global state of the computation

   $\Rightarrow$ all vars in function must be local (or parameters)

2. The concept of assignment is NOT part of function programming

   - no explicit assignment statements
   - variables bound to values only through the association of actual parameters to formal parameters in function calls
   - function calls have no side effects
   - thus no need to consider global states

Pure Functional Languages

3. Control flow is governed by function calls and conditional expressions

   $\Rightarrow$ no iteration

   $\Rightarrow$ recursion is widely used

4. All storage management is implicit
   - needs garbage collection

5. Functions are *First Class Values*
   - can be returned as the value of an expression
   - can be passed as an argument
   - can be put in a data structure as a value
   - (unnamed) function exists as a value

Pure Functional Languages

A program includes:

1. A set of function definitions
2. An expression to be evaluated

E.g. in scheme,

```
> (define length
          (lambda (x)
               (if (null? x)
                    0
                    (+ 1 (length (rest x))))))

> (length '(A LIST OF 5 THINGS))
  5
```

LISP

- Functional language developed by John McCarthy in the mid 50's
- Semantics based on *Lambda Calculus*
- All functions operate on lists or symbols called: "S-expression"
- Only five basic functions:
  list functions ***con***, ***car***, ***cdr***, ***equal***, ***atom***,
  and one conditional construct: ***cond***
- Useful for list-processing applications
- Program and data have the same syntactic form "S-expression"
- Originally used in Artificial Intelligence

SCHEME

- Developed in 1975 by G. Sussman and G. Steele
- A dialect of LISP
- Simple syntax, small language
- Closer to initial semantics of LISP as compared to COMMON LISP
- Provide basic list processing tools
- Allows functions to be first class objects

Next Lecture

Things to do:

- Read Scott, Chapter 9.1 - 9.3 (4th Edition) or Chapter 8.1 - 8.3 (3rd Edition), Chapter 11.1 - 11.3 (4th Edition) or Chapter 10.1 - 10.3 (3rd Edition)