Chapter 10

Implementing Subprograms

Implementing Subprograms

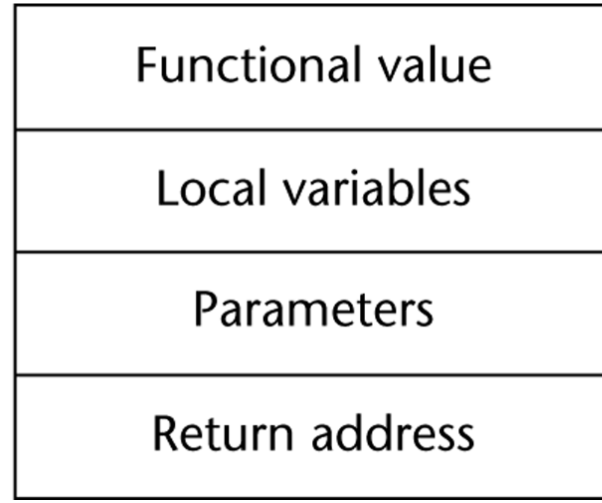
- The subprogram *call* and *return* operations are together called *subprogram linkage*
- Implementation of subprograms must be based on semantics of subprogram linkage
- Implementation:
  - Simple subprograms
    - no recursion, use only static local variables
  - Subprograms with stack-dynamic variables
  - Nested subprograms

Simple Subprograms

- Simple
  - subprograms are not nested and all local variables are static
  - Example: early versions of Fortran
- Call Semantics require the following actions:
  - Save execution status of current program unit
  - Carry out parameter passing process
  - Pass return address to the callee
  - Transfer control to the callee
- Return Semantics require the following actions:
  - If pass by value-result or out-mode, move values of those parameters to the corresponding actual parameters
  - If subprogram is a function, move return value of function to a place accessible to the caller
  - Restore execution status of caller
  - Transfer control back to caller

Simple Subprograms

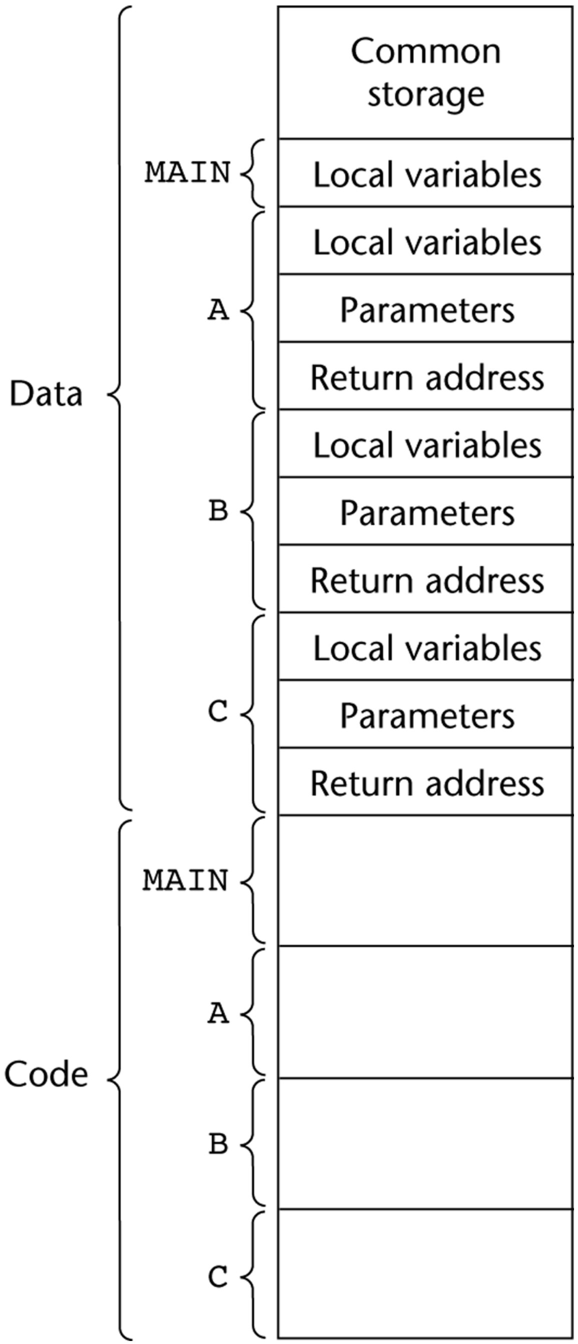
- Required Storage:
  - Status information of the caller
  - Parameters
  - return address
  - functional value (if it is a function)
- Subprogram consists of 2 parts:
  - Subprogram code
  - Subprogram data
    - The format, or layout, of the noncode part of an executing subprogram is called an *activation record*
    - An activation record instance is a concrete example of an activation record (the collection of data for a particular subprogram activation)



❖ Code and Activation record of a program with simple subprograms

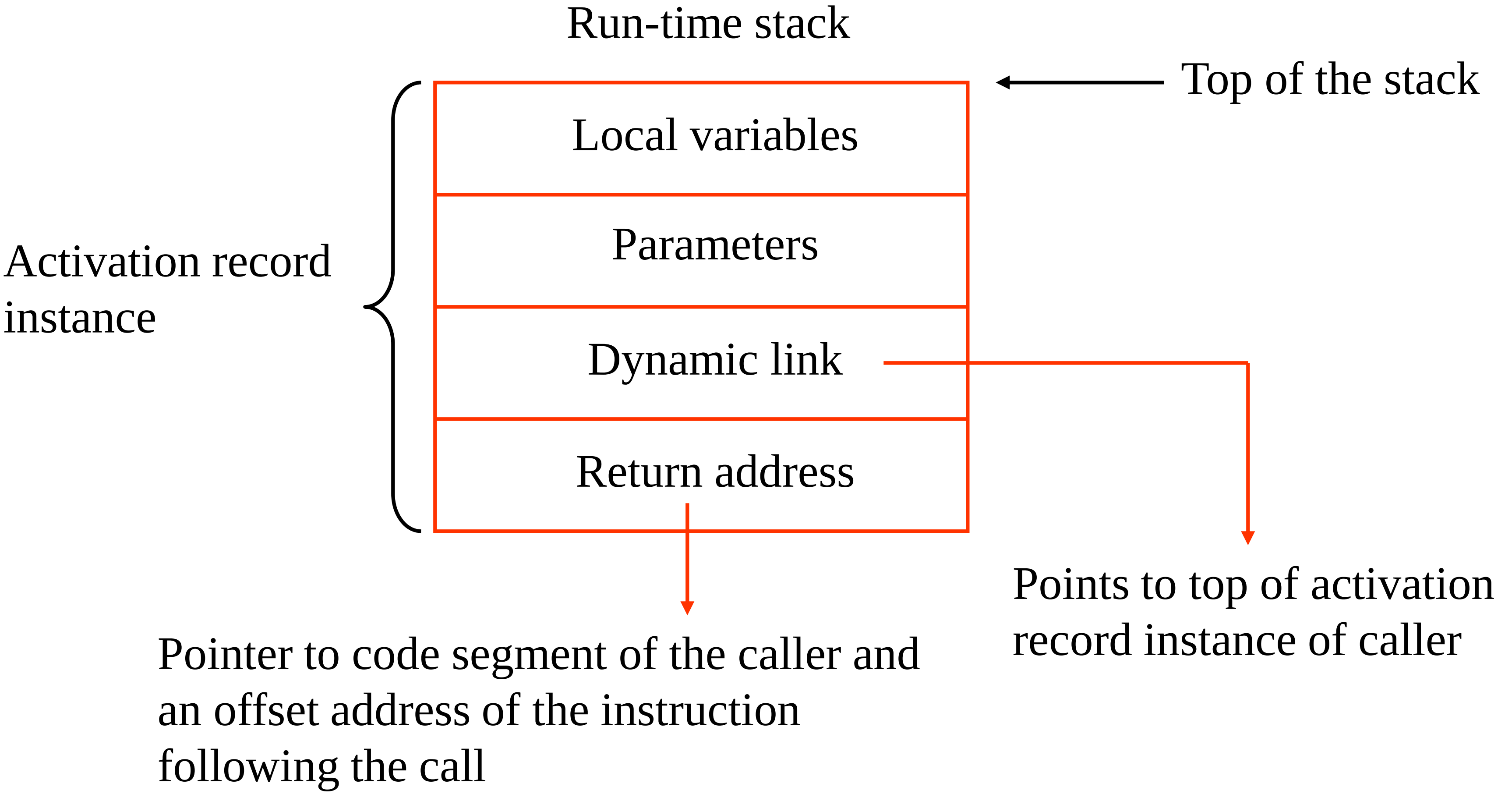
❖ Activation record instance for simple subprograms has fixed size. Therefore, it can be statically allocated

❖ Since simple subprograms do not support recursion, there can be only one active version of a given subprogram



Subprograms with Stack-Dynamic Variables

- Compiler must generate code to cause implicit allocation and deallocation of local variables



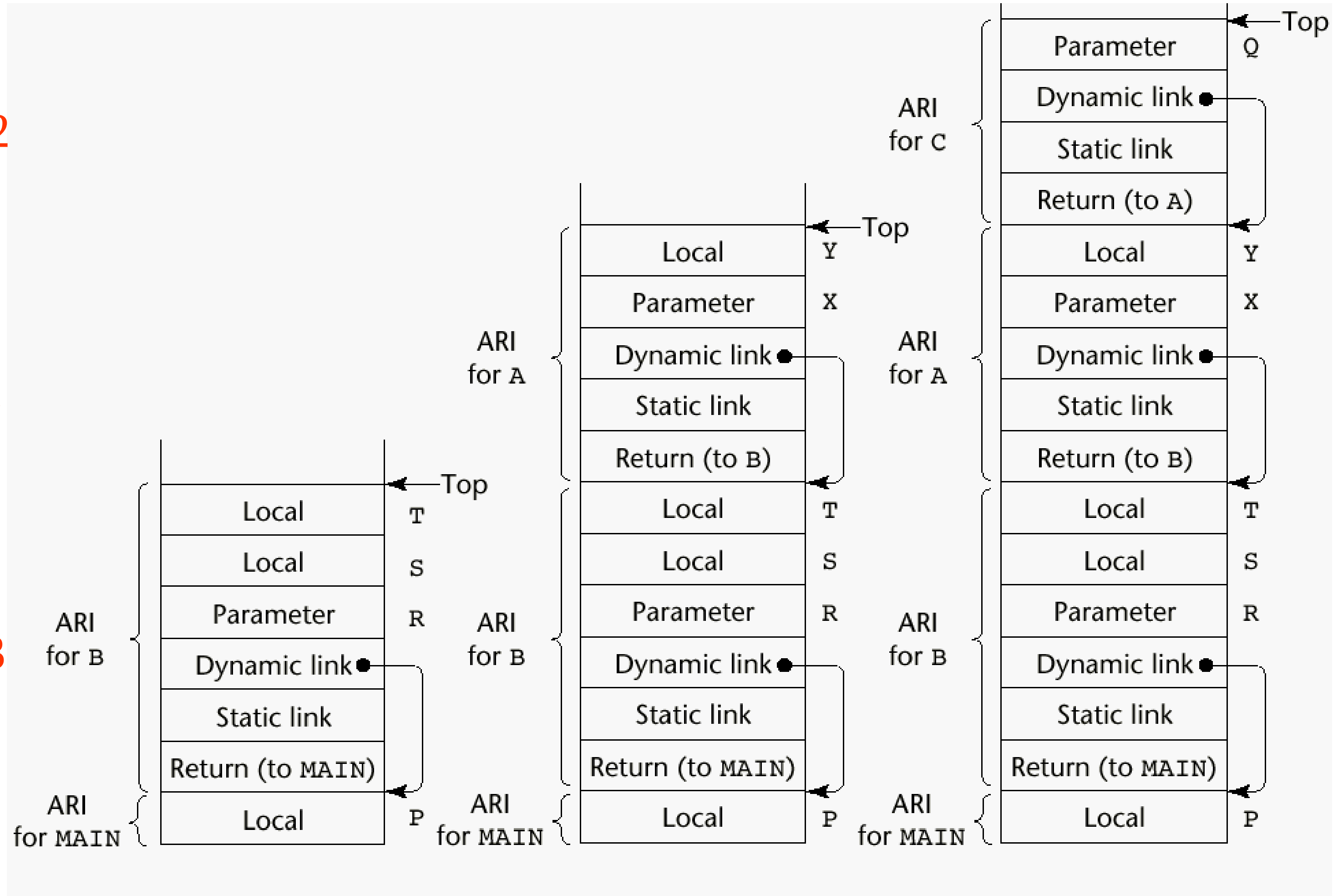
Subprograms with Stack-Dynamic Variables

```
void sub(float total, int part) {
    int list[4];
    float sum;
    …
}
```

Local variable	sum
Local variable	list[3]
Local variable	list[2]
Local variable	list[1]
Local variable	list[0]
Parameter	part
Parameter	total
Dynamic link	
Return address	

Example: without Recursion

```
void A(int X) {
    int Y;
    …            ← 2
    C(Y);
}
void B(float R) {
    int S, T;
    …            ← 1
    A(S);
    …
}
void C(int Q) {
    …            ← 3
}
void main() {
    float P;
    …
    B(P);
    …
}
```



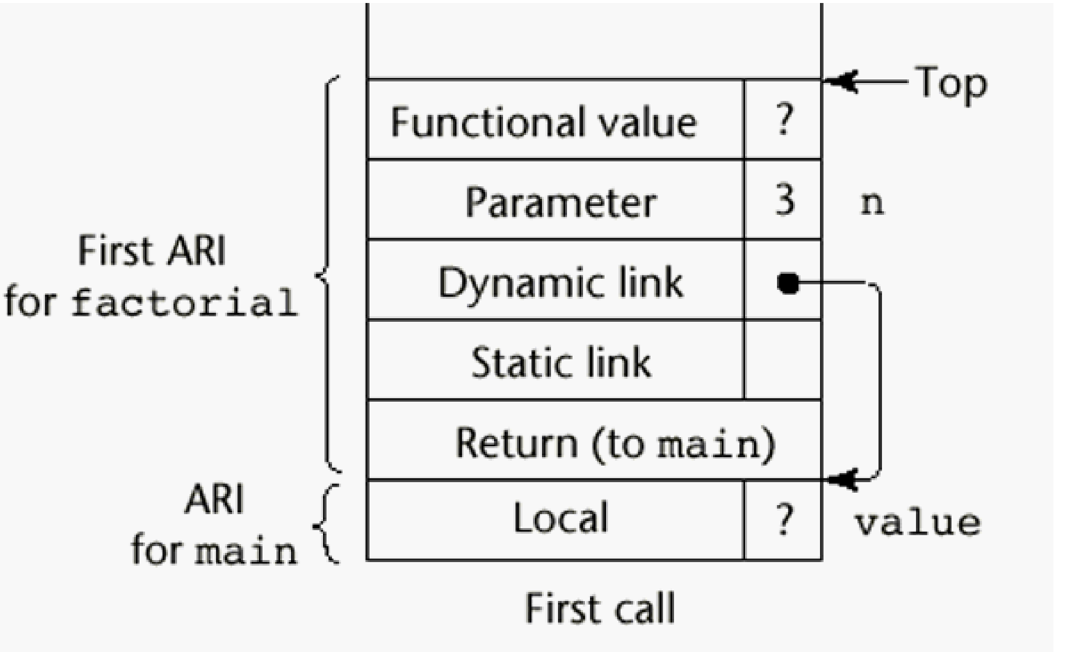
Collection of dynamic links present in the stack at any given time is called the dynamic chain

Subprograms with Stack-Dynamic Variables

- Recursion adds possibility of multiple simultaneous activations of a subprogram
  - Each activation requires its own copy of formal parameters and dynamically allocated local variables, along with return address

Subprograms with Recursion

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



Subprograms with Recursion

```
int factorial (int n) {
    …
    if (n <= 1)
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void main() {
    int value;
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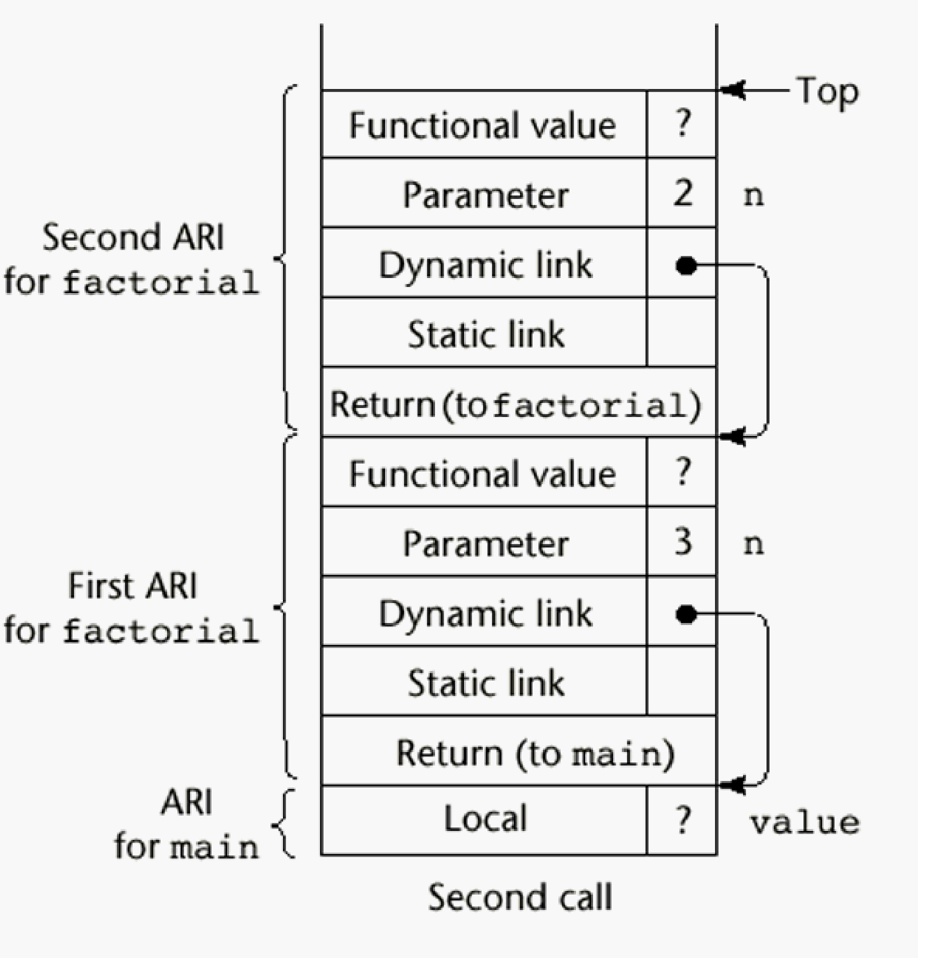
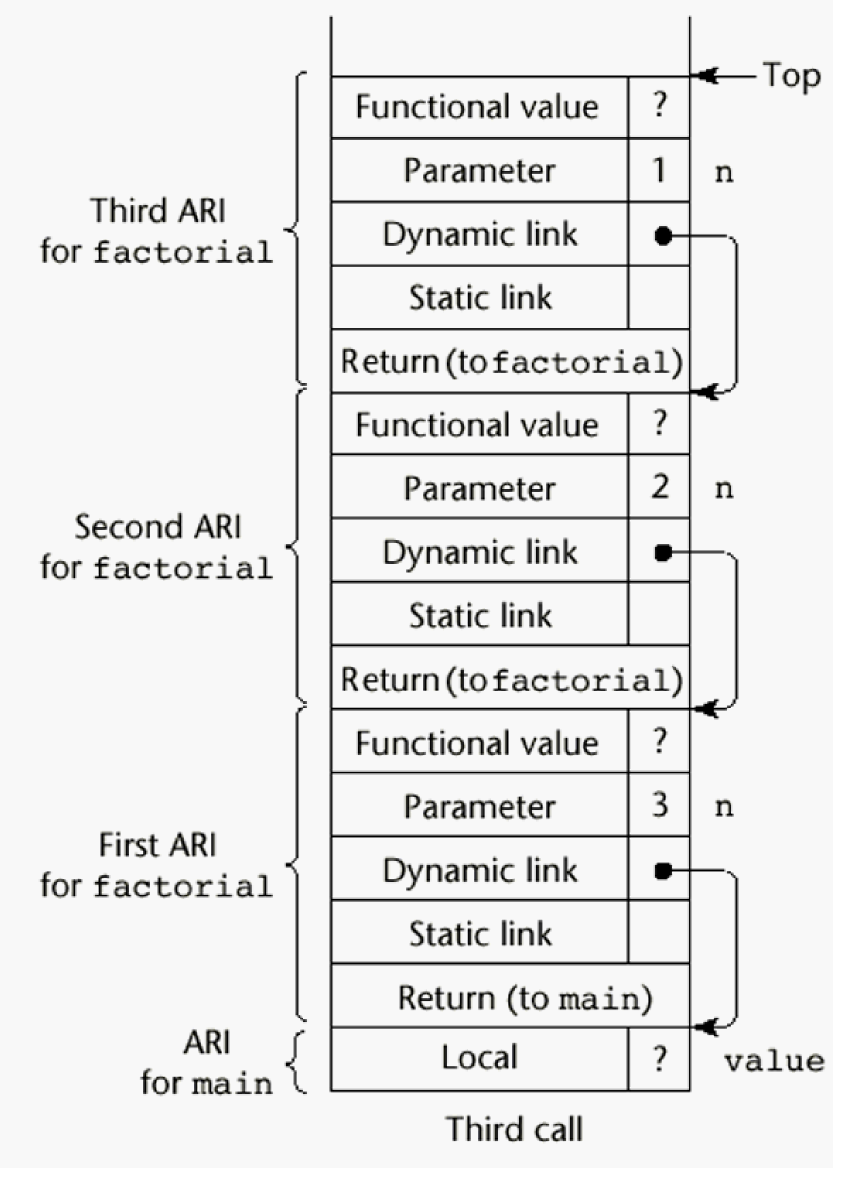
    …
}
```



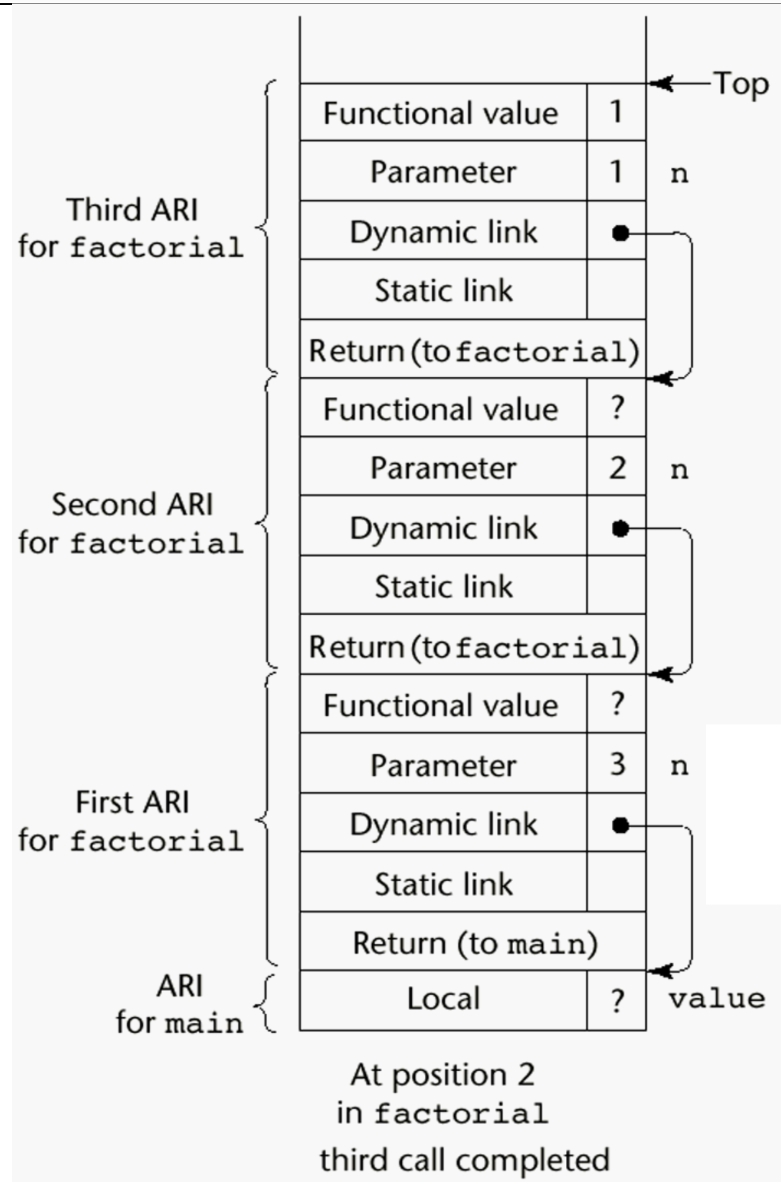
Subprograms with Recursion

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



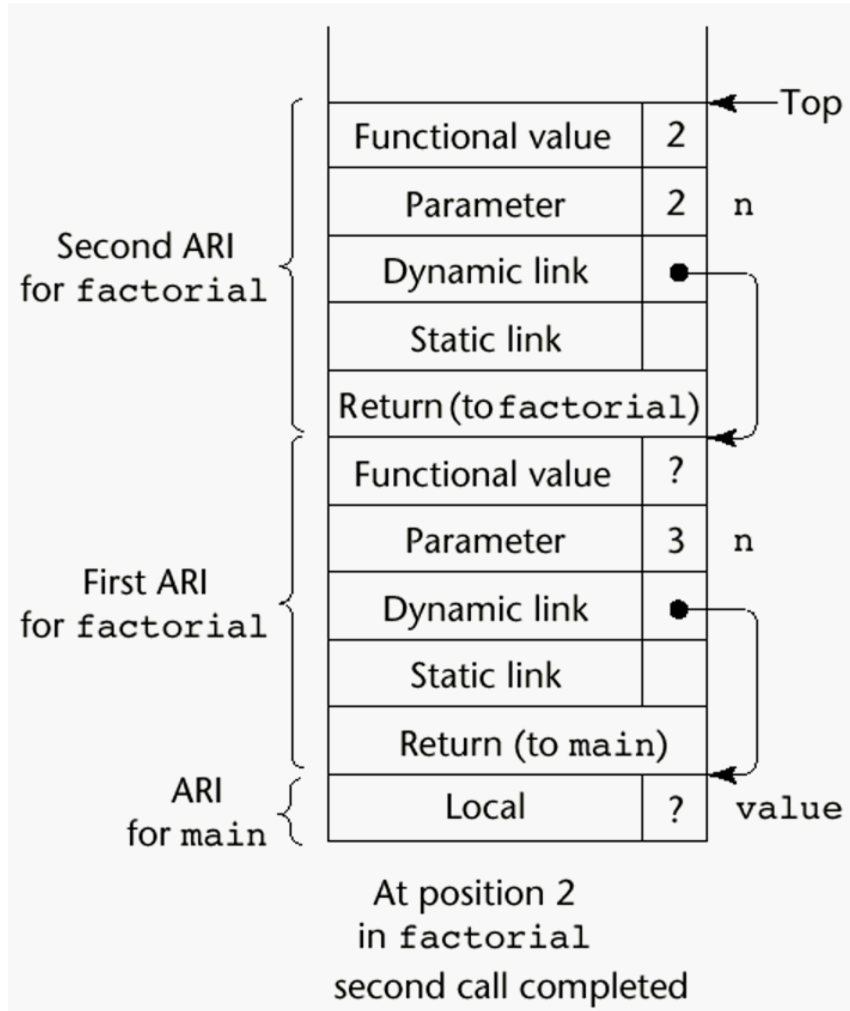
Subprograms with Recursion

```
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
}
```



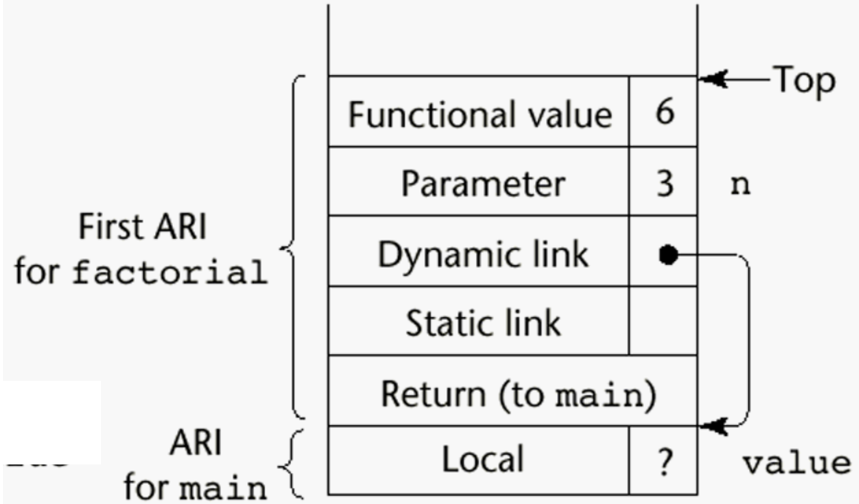
Subprograms with Recursion

```
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
}
```



Subprograms with Recursion

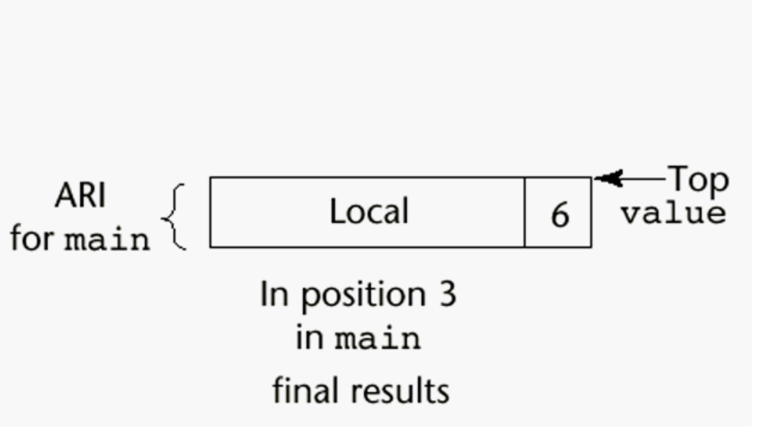
```
int factorial (int n) {
    …          ← 1
    if (n <= 1)
       return 1;
    else
       return n*factorial(n-1);
    …          ← 2
}
void main() {
    int value;
    value = factorial(3);
    …          ← 3
}
```



At position 2
in factorial
first call completed

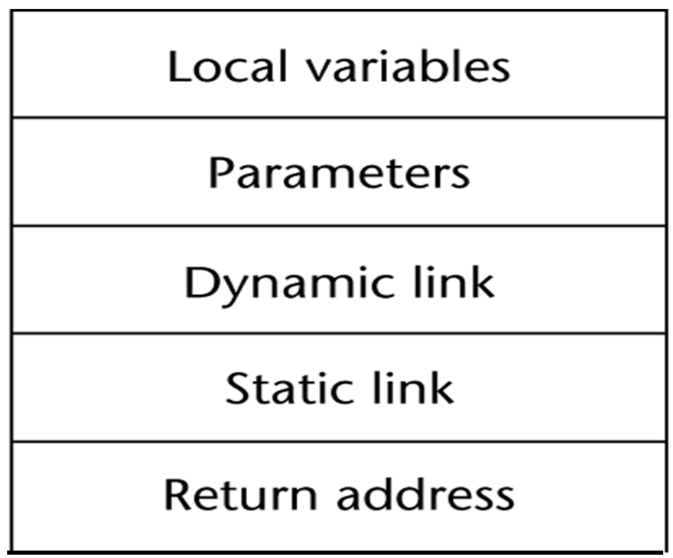
Subprograms with Recursion

```
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
}
```



Nested Subprograms

- Support for static scoping
  - Implemented using static link (also called static scope pointer), which points to the bottom of the activation record instance of its static parent



Nested Subprograms

- Static chain
  - links all static ancestors of executing subprogram
- Static_depth
  - an integer associated with static scope that indicates how deeply it is nested in outermost scope
- Chain offset
  - Difference between static_depth of procedure containing reference to variable x and static_depth of procedure containing declaration of x

```
procedure A is
    procedure B is
        procedure C is
                …
        end;    -- of C
        …
    end;   -- of B
    …
end;     -- of A
```

- Static_depths of A, B, and C are 0, 1, and 2, respectively
- If procedure C references a variable declared in A, the chain_offset of that reference is 2

Nested Subprograms

```
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 }
```

Calling sequence:

Main_2 calls Bigsub

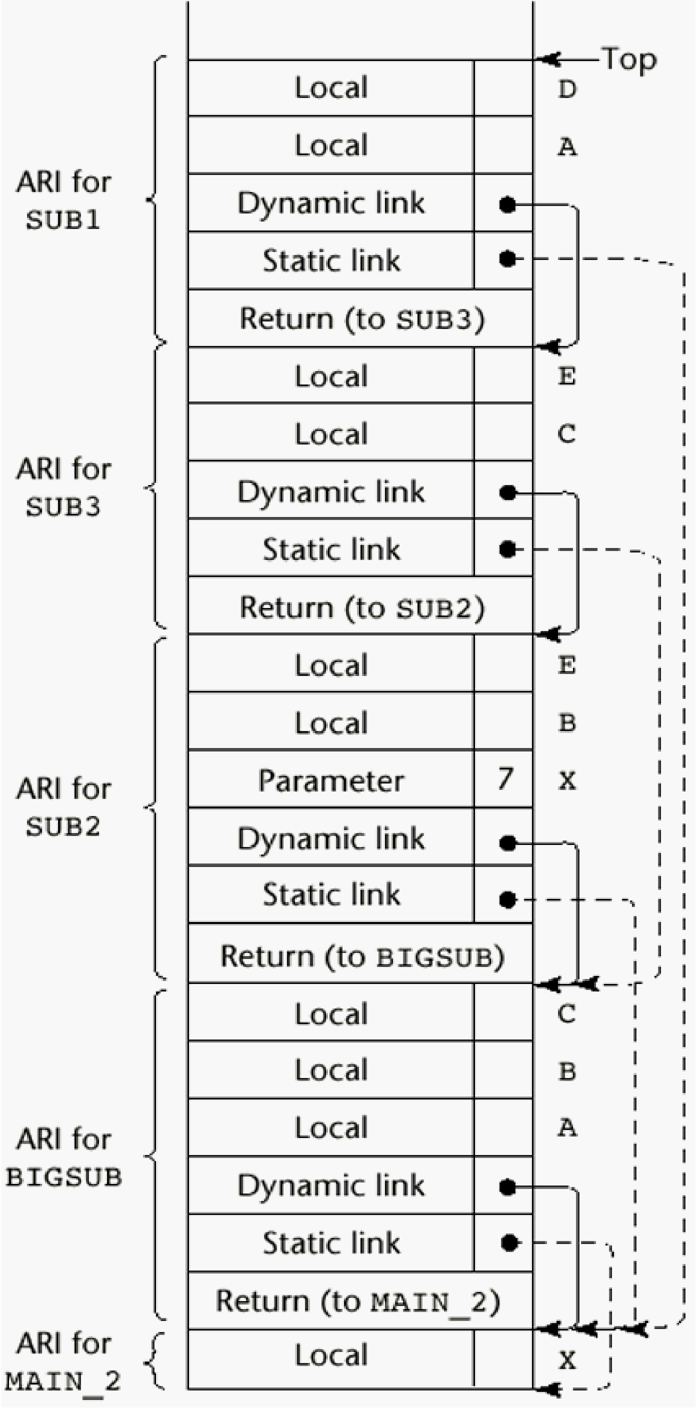
Bigsub calls Sub2

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 }
```



Nested Subprograms

- At position 1 in SUB1:
  - A - (0, 3)   =============> (chain_offset, local_offset)
  - 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)

Nested Subprograms

- Drawbacks
  - A nonlocal reference is slow if the number of scopes between the reference and the declaration of the referenced variable is large
  - Time-critical code is difficult, because the costs of nonlocal references are hard to estimate

- Displays
  - Alternative to static chains
  - Store static links in a single array called display, instead of storing in the activation records
  - Accesses to nonlocals require exactly two steps for every access, regardless of the number of scope levels
    - Link to correct activation record is found using a statically computed value called the display_offset
    - Compute local_offset within activation record instance

Blocks

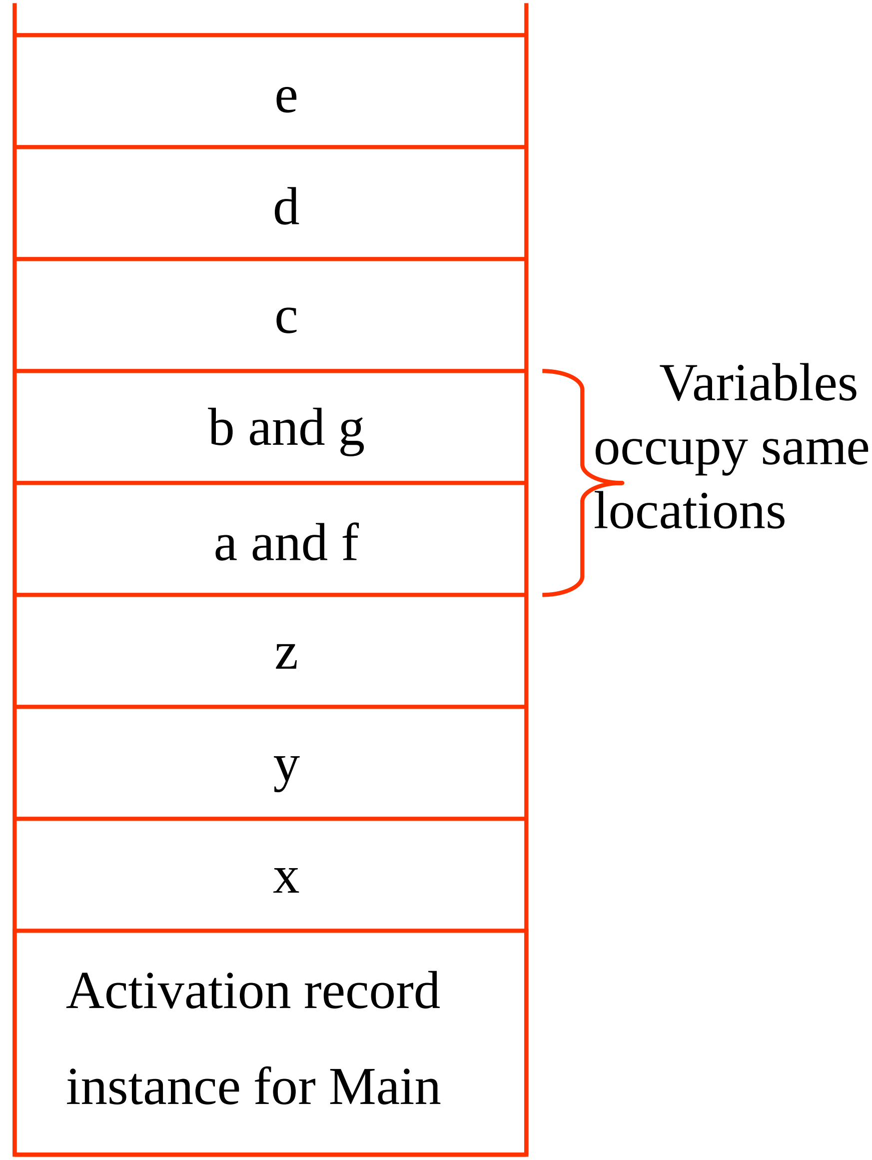
- User-specified local scope for variables

```
{
        int temp;
        temp = list[upper];
        list[upper] = list[lower];
        list[lower] = temp;
}
```

- Blocks can be implemented using static chain
- Blocks are treated as parameterless subprograms that are always called from same place in the program
  - Every block has an activation record
  - An instance is created every time a block is executed
- Alternative implementation
  - Amount of space can be allocated statically
  - Offsets of all block variables can be statically computed, so block variables can be addressed exactly as if they were local variables

Blocks

```
void main() {
    int x, y, z;
    while (…) {
        int a, b, c;
        …
        while (…) {
            int d, e;
            …
        }
    }
    while (…) {
        int f, g;
        …
    }
    …
}
```



Subprogram Implementation

- Activation record on the stack
  - Parameters
  - Return address
  - Local variables
  - Static link
  - Dynamic link

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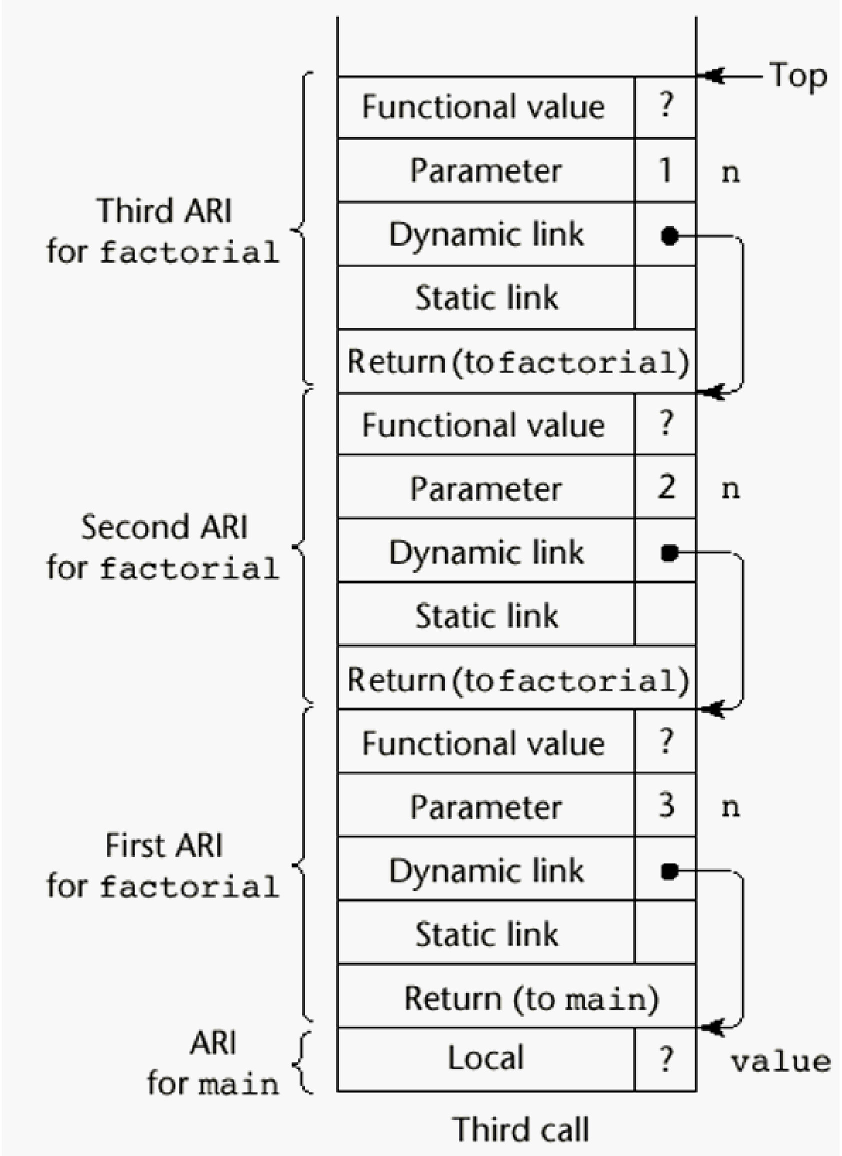


Subprogram Implementation

- Bad design of subprogram implementation may result in network security problems

- Buffer overflow attack
  - A type of vulnerability used by hackers to compromise the integrity of a system
  - Problem is due to
    - Lack of safety feature in language design
    - bad coding by programmers

Buffer overflow attack

- The effectiveness of the buffer overflow attack has been common knowledge in software circles since the 1980’s
- The Internet Worm used it in November 1988 to gain unauthorized access to many networks and systems nationwide
- Still used today by hacking tools to gain “root” access to otherwise protected computers
- The fix is a very simple change in the way we write array accesses; unfortunately, once code that has this vulnerability is deployed in the field, it is nearly impossible to stop a buffer overflow attack

Overview of Buffer Overflow Attacks

- The buffer overflow attack exploits a common problem in many programs.
- In several high-level programming languages such as C, "boundary checking", i.e. checking to see if the length of a variable you are copying is what you were expecting, is not done.

```
void main(){
    char bufferA[256];
    myFunction(bufferA);
}
```

```
void myFunction(char *str)
{
    char bufferB[16];
     strcpy(bufferB, str);
}
```

Overview of Buffer Overflow Attacks

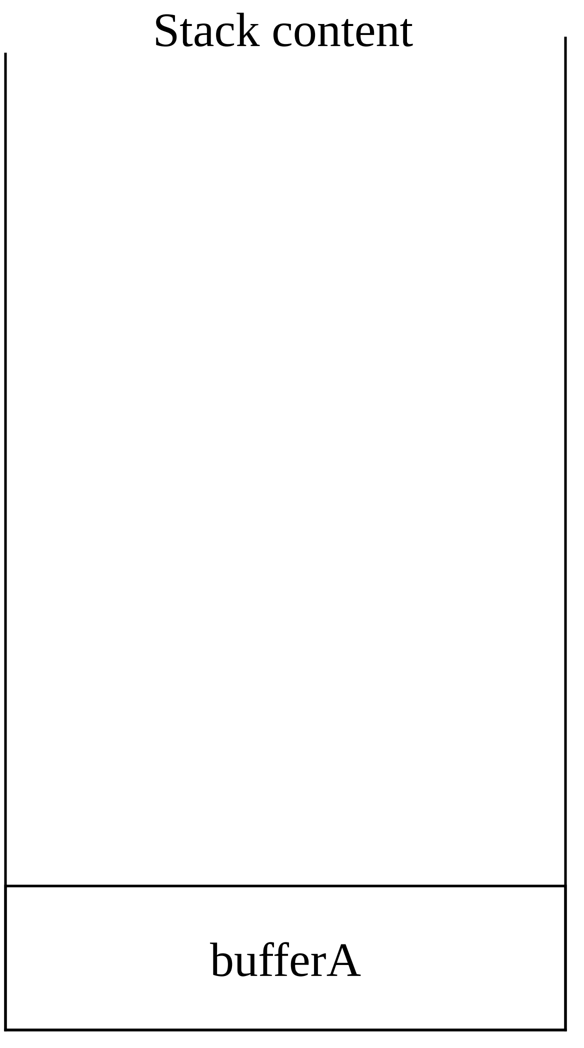
```
void main(){
    char bufferA[256];
    myFunction(bufferA);
}
```

```
void myFunction(char *str)
{
    char bufferB[16];
    strcpy(bufferB, str);
}
```

- main() passes a 256 byte array to myFunction(), and myFunction() copies it into a 16 byte array!
- Since there is no check on whether bufferB is big enough, the extra data overwrites other unknown space in memory.
- This vulnerability is the basis of buffer overflow attacks
- How is it used to harm a system?
  - It modifies the system stack

Overview of Buffer Overflow Attacks

```
void main(){
    char bufferA[256];
    myFunction(bufferA);
}
```



Overview of Buffer Overflow Attacks

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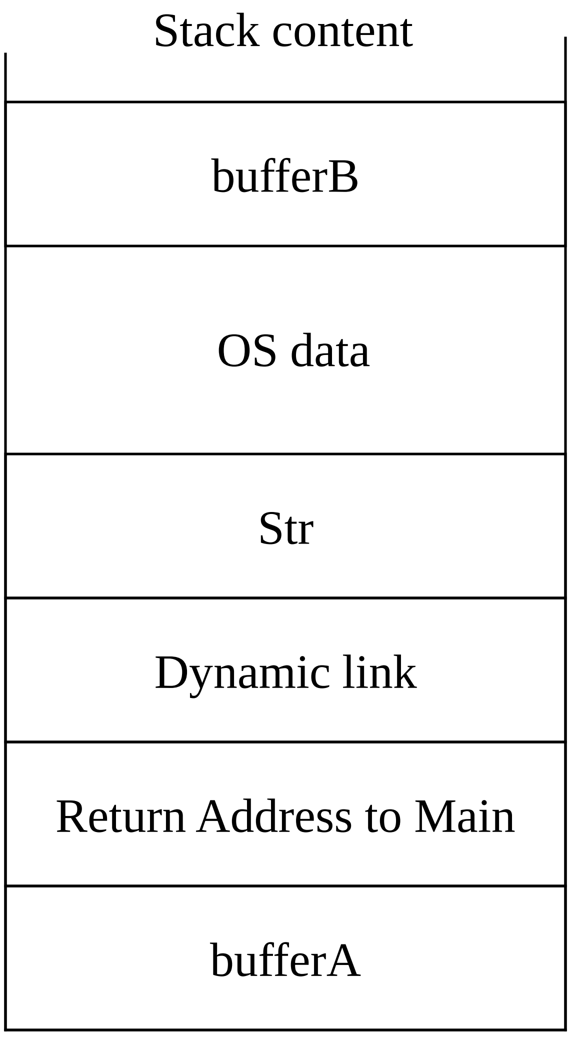

Overview of Buffer Overflow Attacks

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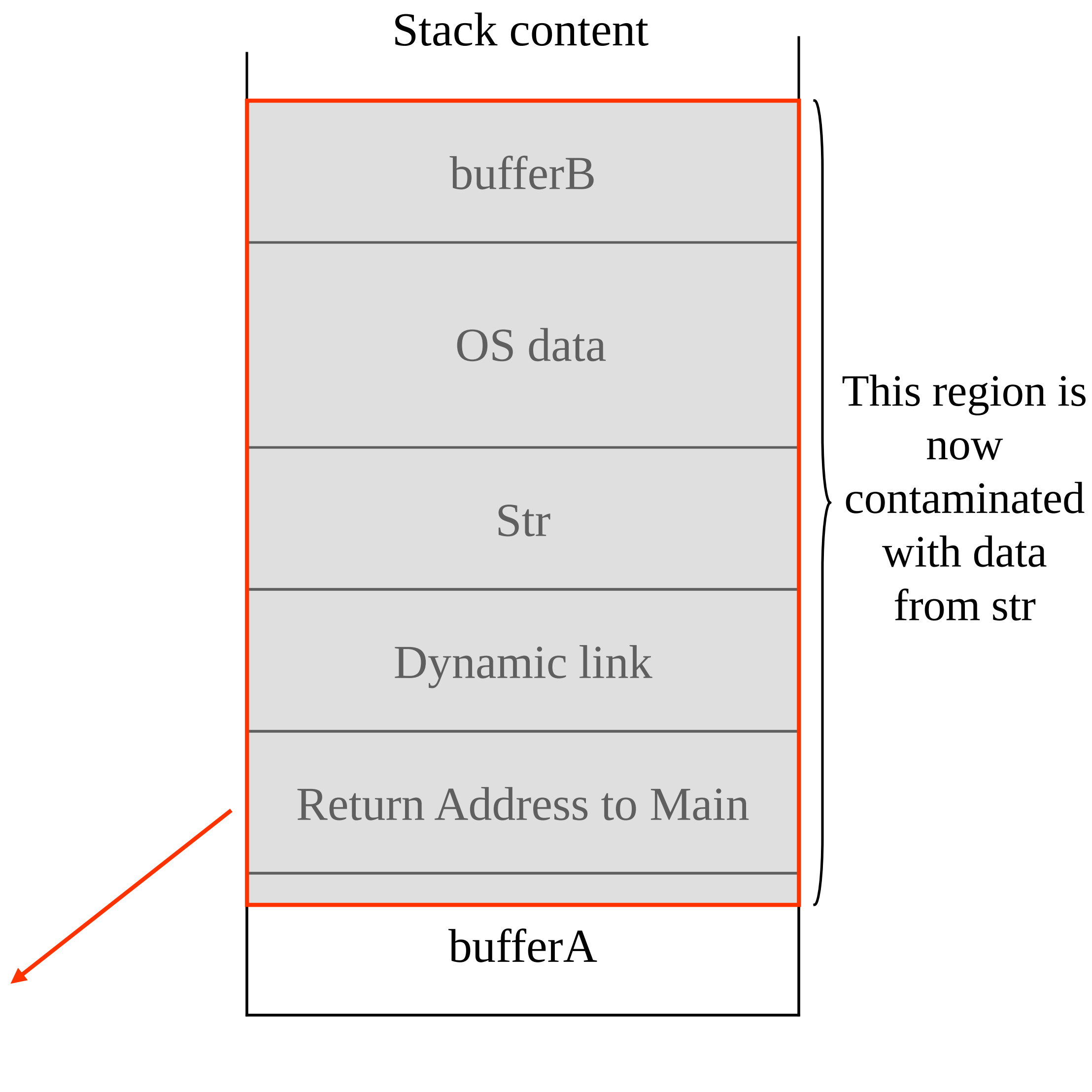
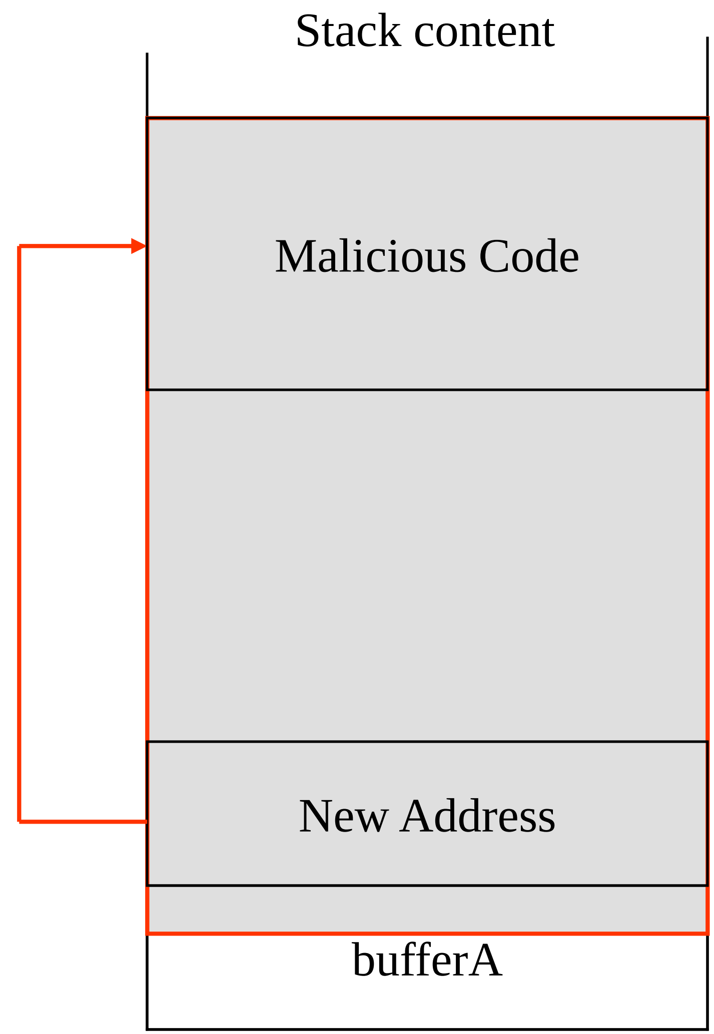


Overview of Buffer Overflow Attacks

- If the content of str is carefully selected, we can point the return address to a piece of code we have written
- When the system returns from the function call, it will begin executing the malicious code



A Possible Solution

```
void main(){
    char bufferA[256];
    myFunction(bufferA, 256);
}


void myFunction(char *str, int len)
{
    char bufferB[16];
    if (len <= 16)
            strcpy(bufferB, str);
}
```

Buffer Overflow Attack