Runtime Support

CMPT 379: Compilers
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anoopsarkar.github.io/compilers-class

Runtime Support

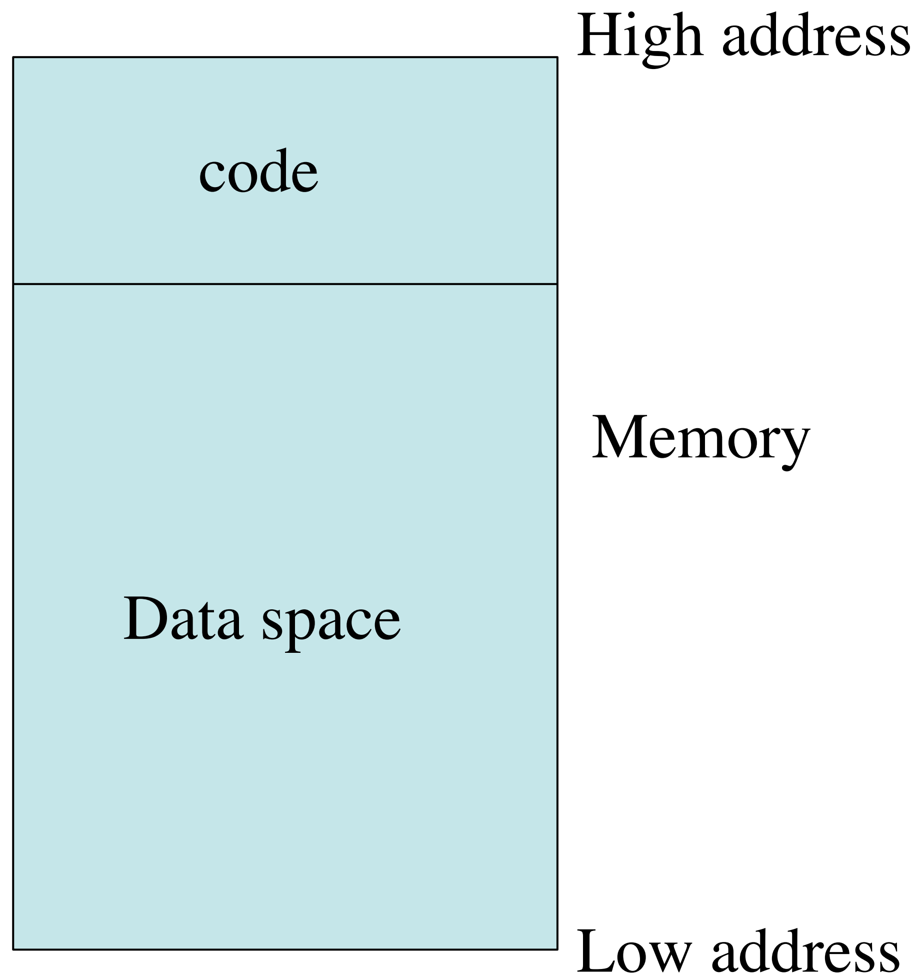
- Management of runtime resources
- Correspondence between:
  - Static (compile-time) structures
  - Dynamic (run-time) structures
- Storage organization
  - Using memory to store data structures of the executing program

Invoke the Program

- Execution of the program is initially under the control of the operating system
- When program is invoked:
  - The OS allocates space for the program
  - The code is loaded into part of the memory
  - The OS jumps to the entry point (i.e., main)

Memory

- Compiler is responsible for:
  - Generating code
  - Orchestrating use of the data area



Procedure Activation

- Two assumptions about programming languages
  - Execution is sequential; control moves from one point in a program to another in a well-defined order
    - Violated by concurrency
  - When a procedure is called, control always returns to the point immediately after the call
    - Violated by exceptions

Procedure Activation

- An invocation of procedure P is an *activation of P*
- The lifetime of an activation of P is
  - All the steps to execute P
  - Including all the steps in procedures P calls

Procedure Activation

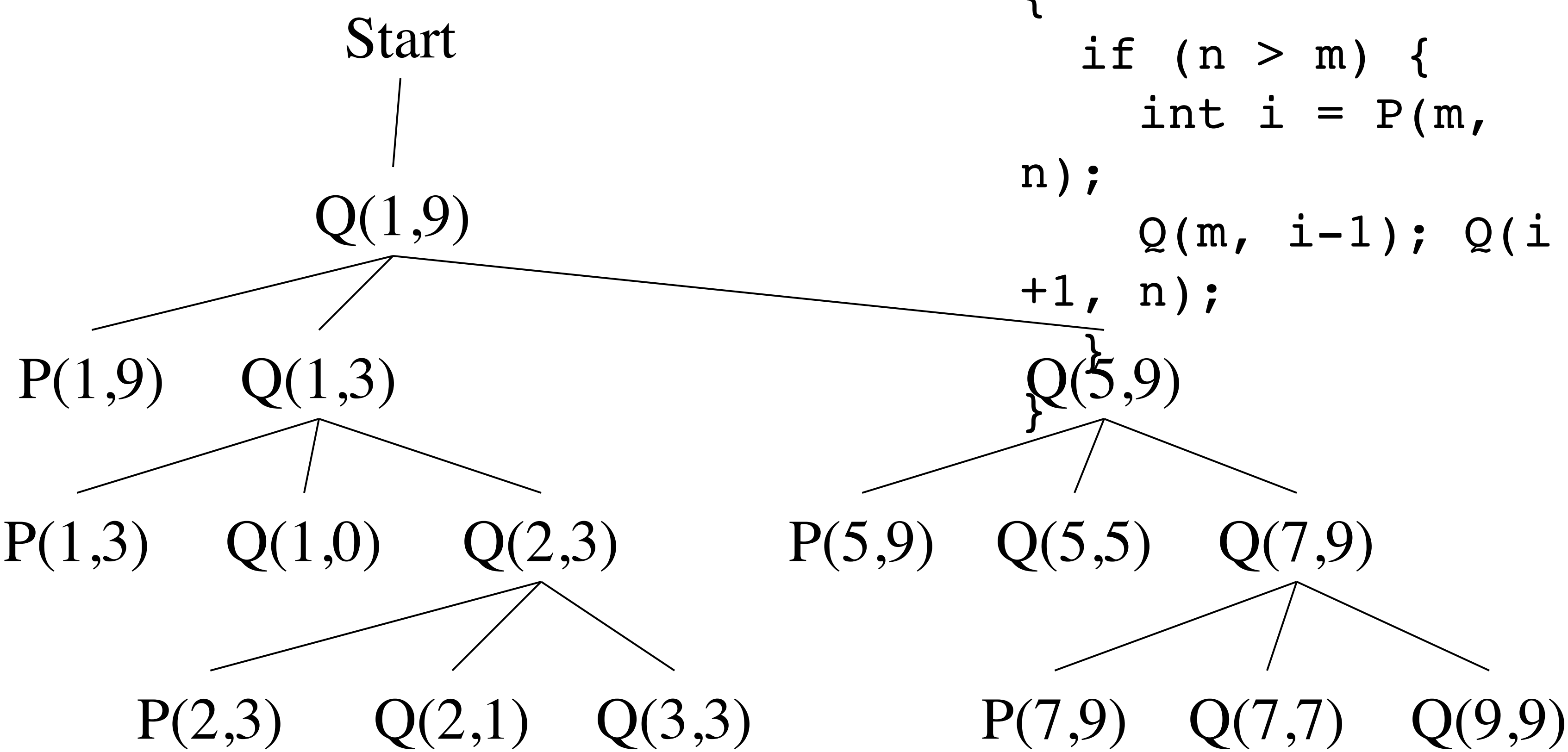
- The lifetime of a variable x is the portion of execution in which x is defined (until x is de-allocated)
- Note that
  - Lifetime is a dynamic (run-time) concept
  - Scope is a static concept

Activation Trees

- Observation
  - When P calls Q, then Q returns before P returns
- Lifetimes of procedure activations are properly nested
- Activation lifetimes (sequence of function calls) can be depicted as a tree: *activation tree*

Activation Tree

```
int Q(int m, int n)
{
  if (n > m) {
    int i = P(m,
n);
    Q(m, i-1); Q(i
+1, n);
  }
}
```



Activation Tree

- The activation tree depends on run-time behavior
- The activation tree may be different for every program input
- Since activations are properly nested, a stack can track currently active procedures

Stack of Active Procedures

```
int Q(int m, int n) {
  if (n > m) {
    int i = P(m, n);
    Q(m, i-1); Q(i+1, n);
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}
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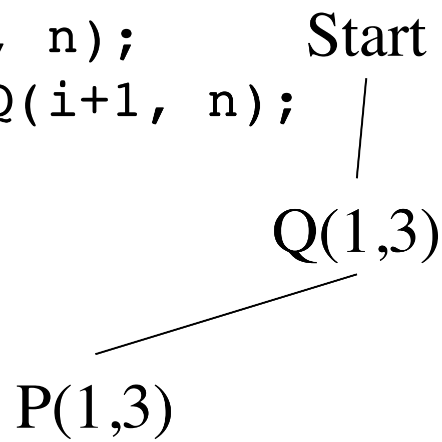

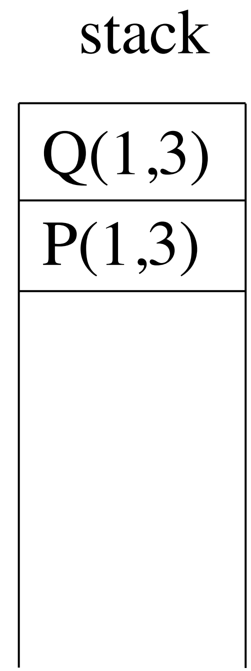

Stack does not keep track of entire activation tree, just active procedures

Stack of Active Procedures

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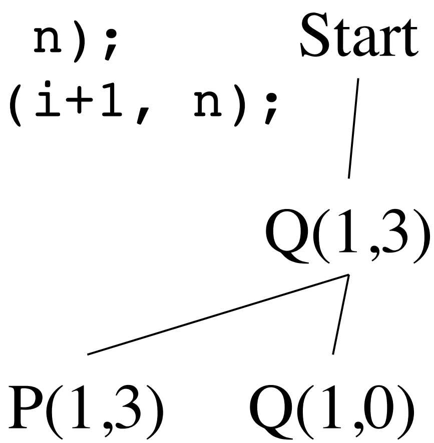

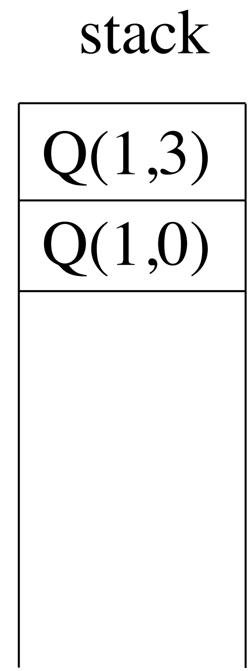

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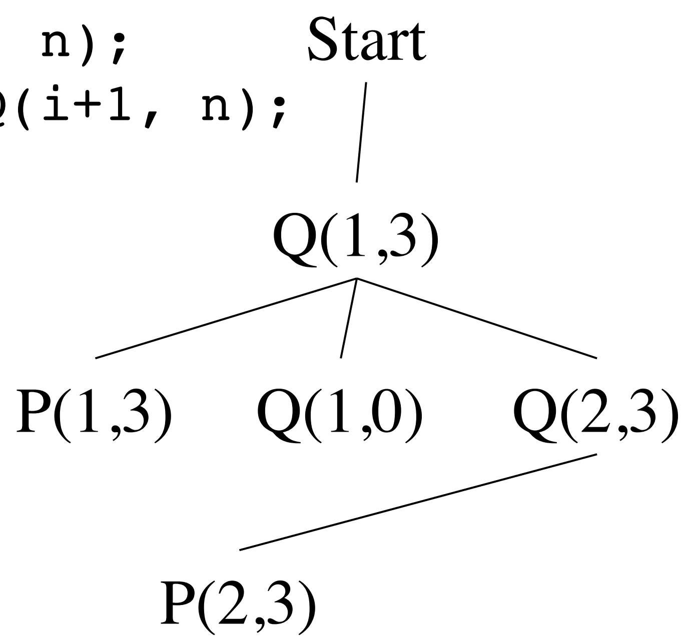

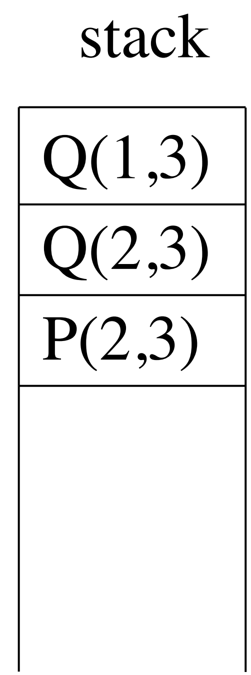

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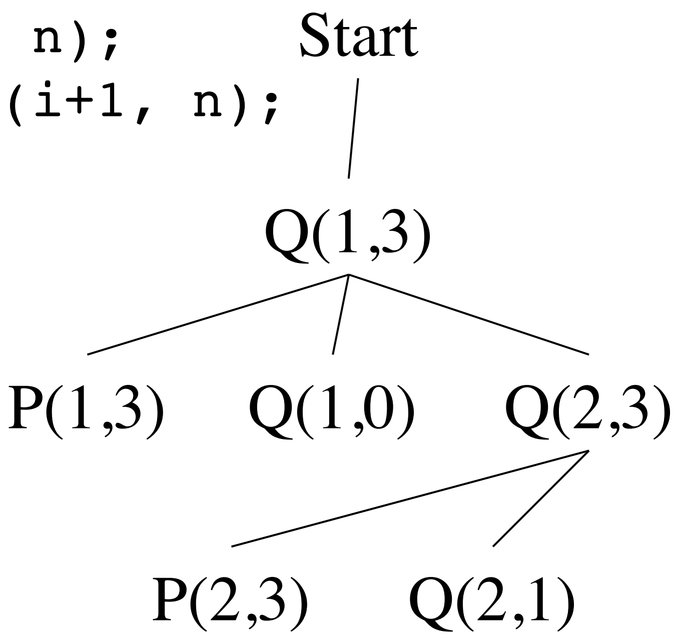

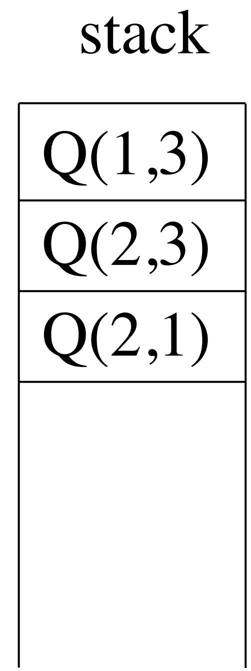

Stack does not keep track of entire activation tree, just active procedures

Stack of Active Procedures

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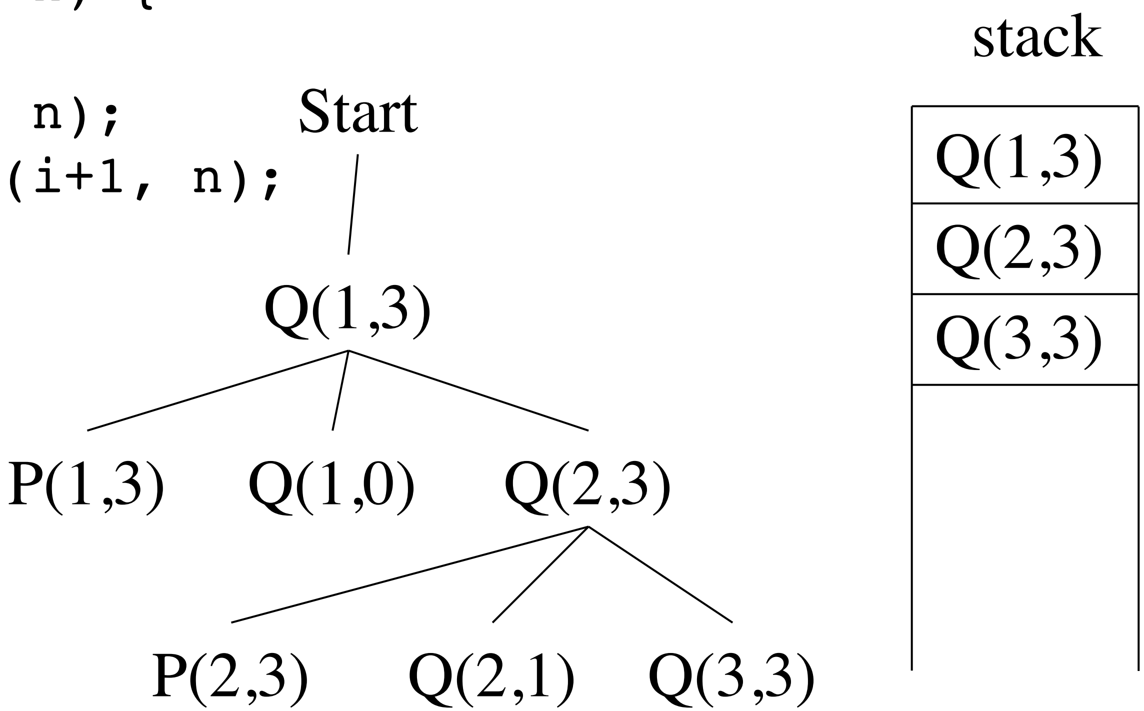

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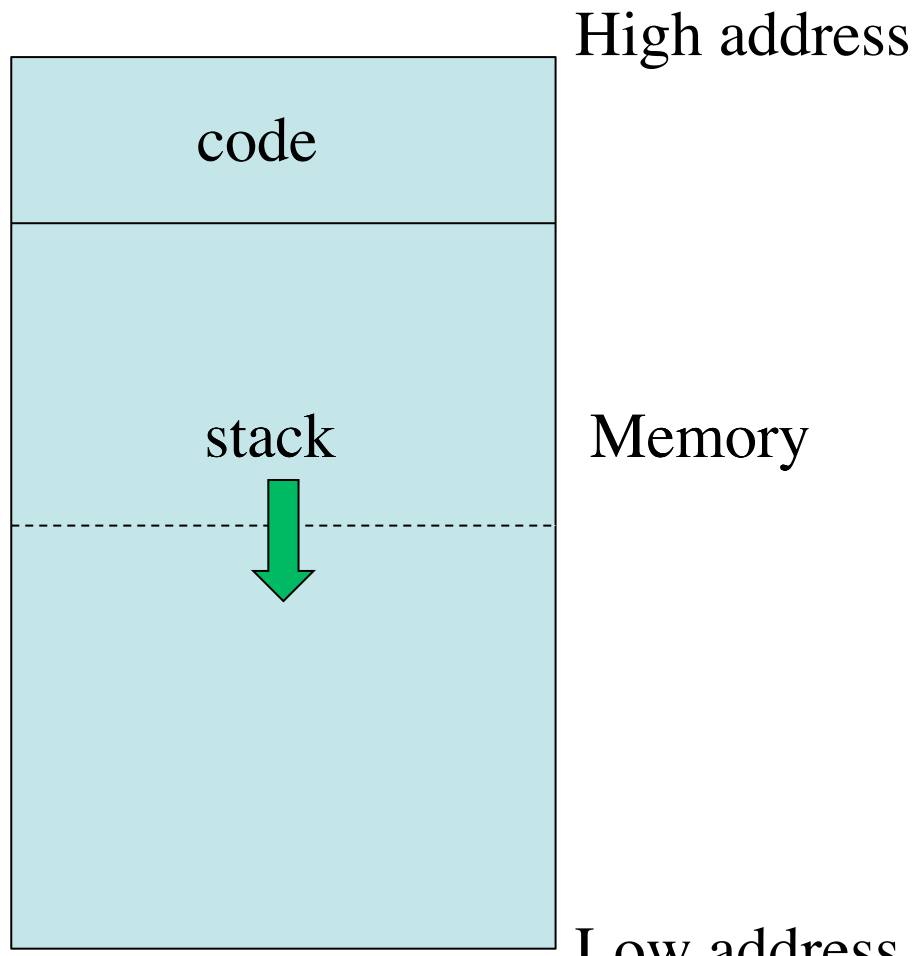
Memory Organization

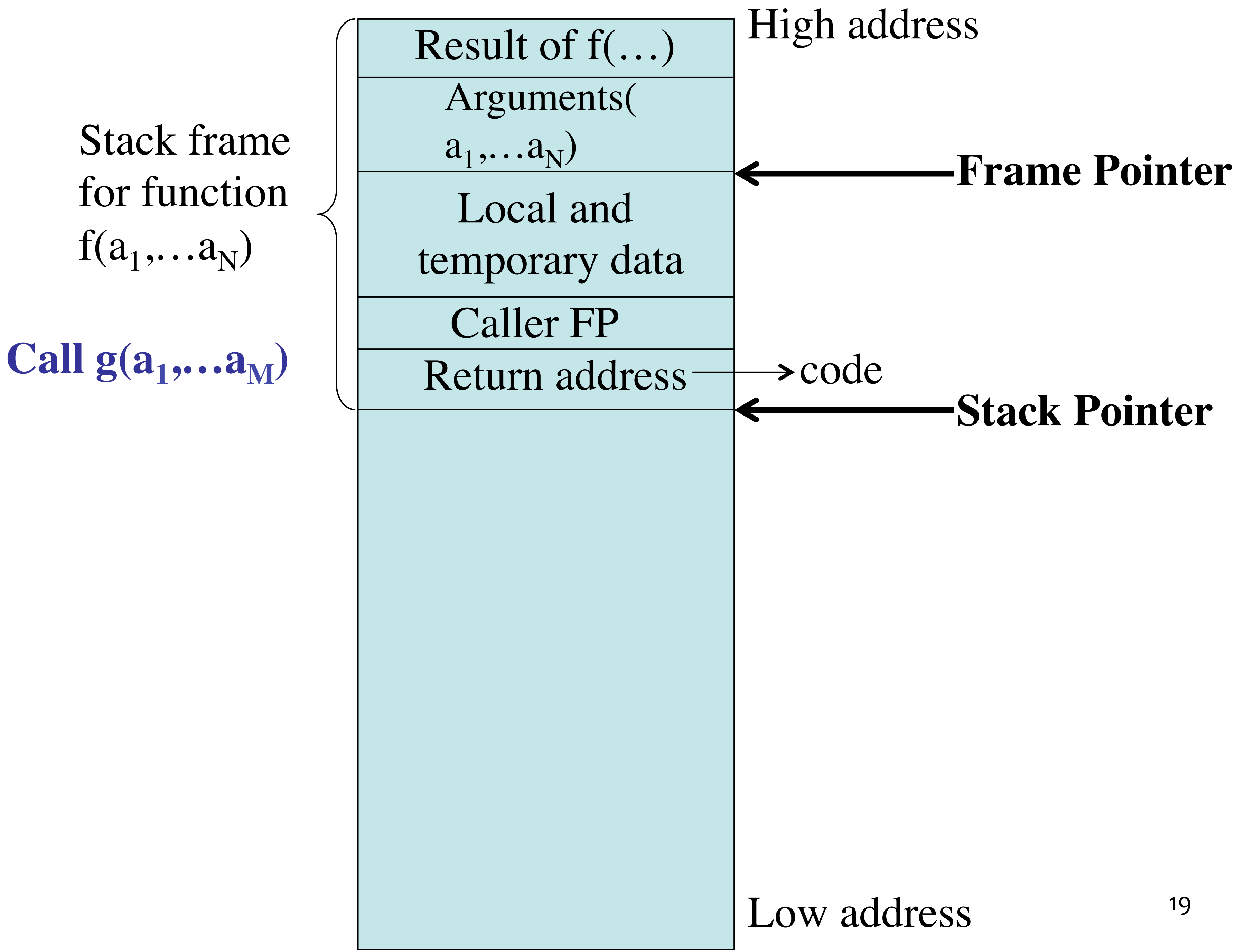


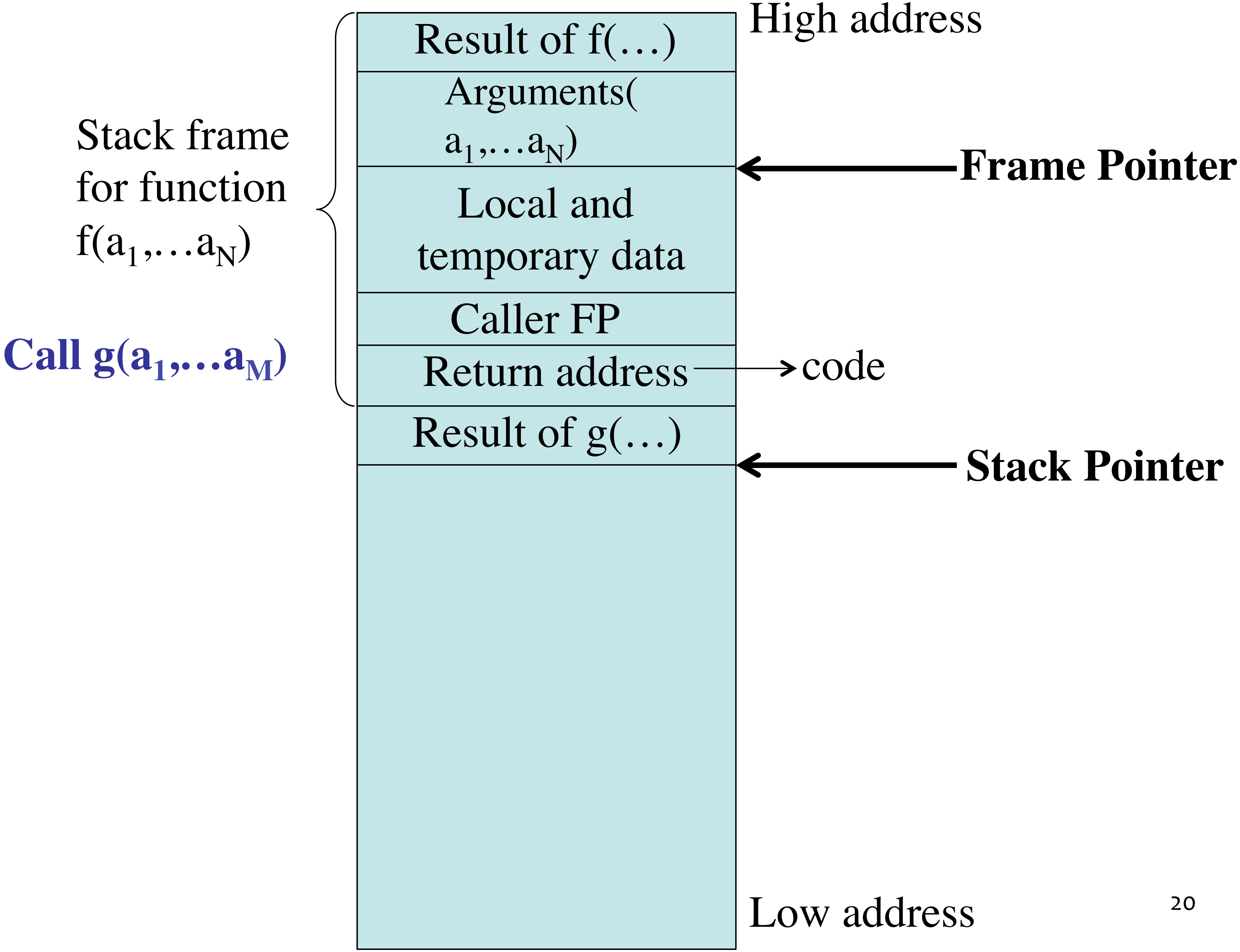
Activation Records

- The information needed to manage one procedure activation is called an *activation record* (AR) or *frame*
- If procedure F calls G, then G's activation record contains mix of info about F and G
- F is suspended until G complete, at which point F resumes
- G's AR contains information needed to
  - Complete execution of G
  - Resumes execution of F

Activation Records

- A frame contains:
  - Control link (pointer to the caller frame)
  - Local data
  - Snapshot of machine state (important registers)
  - Return address
  - Link to global data
  - Parameters passed to function
  - Return value for the caller


High address
Result of f(…)
Arguments($a_1,\ldots a_N$)
Frame Pointer
Stack frame for function $f(a_1,\ldots a_N)$
Local and temporary data
Caller FP
Call $g(a_1,\ldots a_M)$
Return address
code
Stack Pointer
Low address



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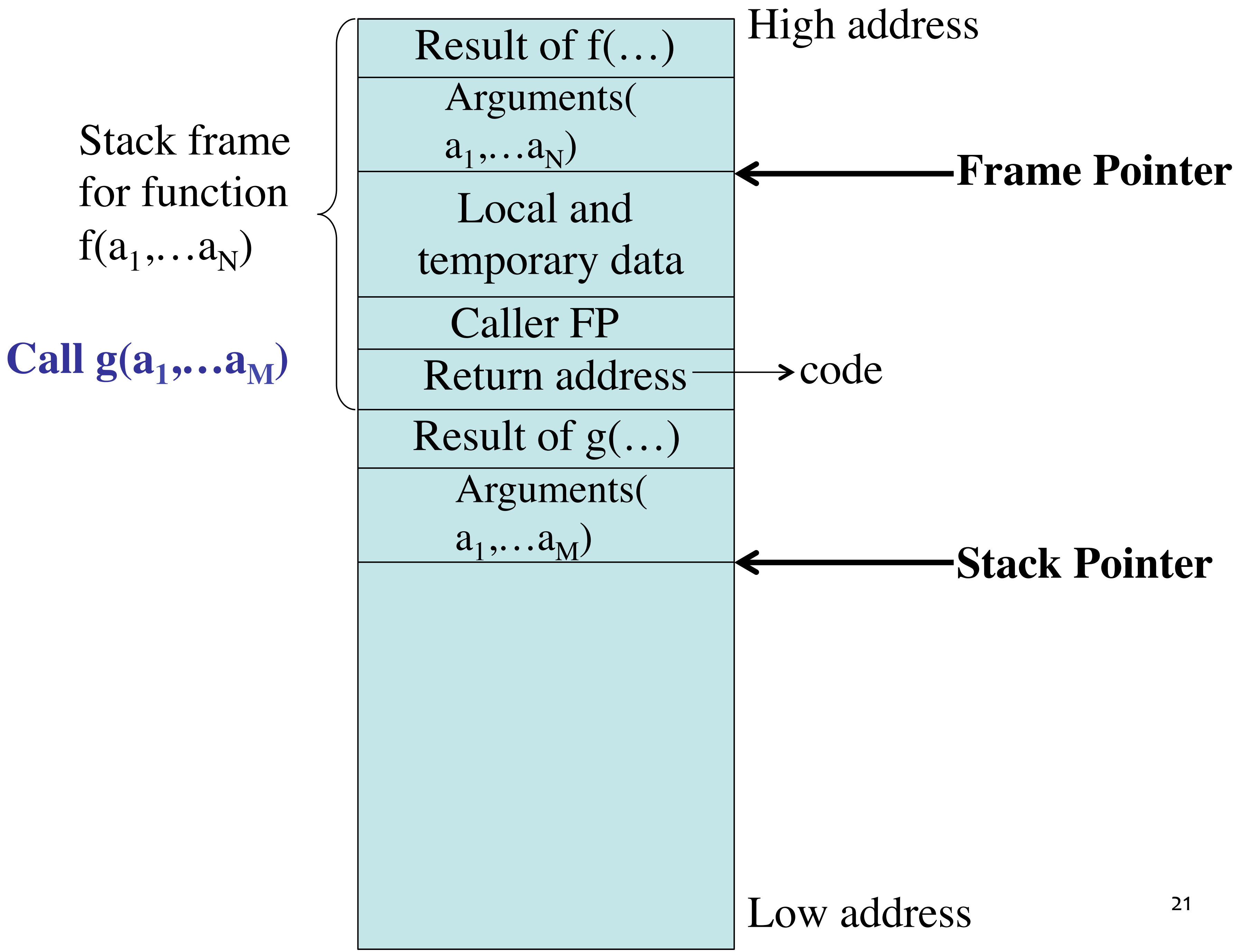
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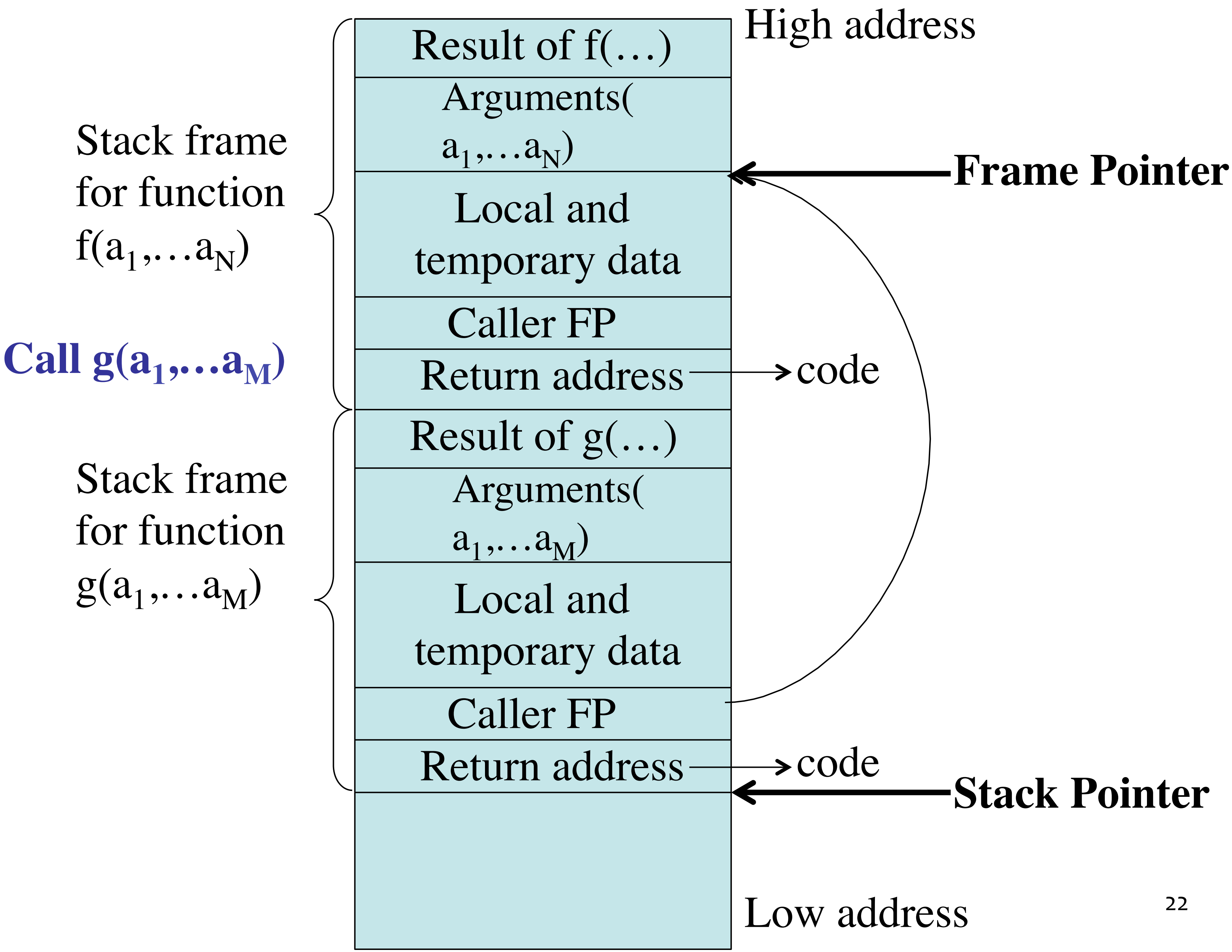
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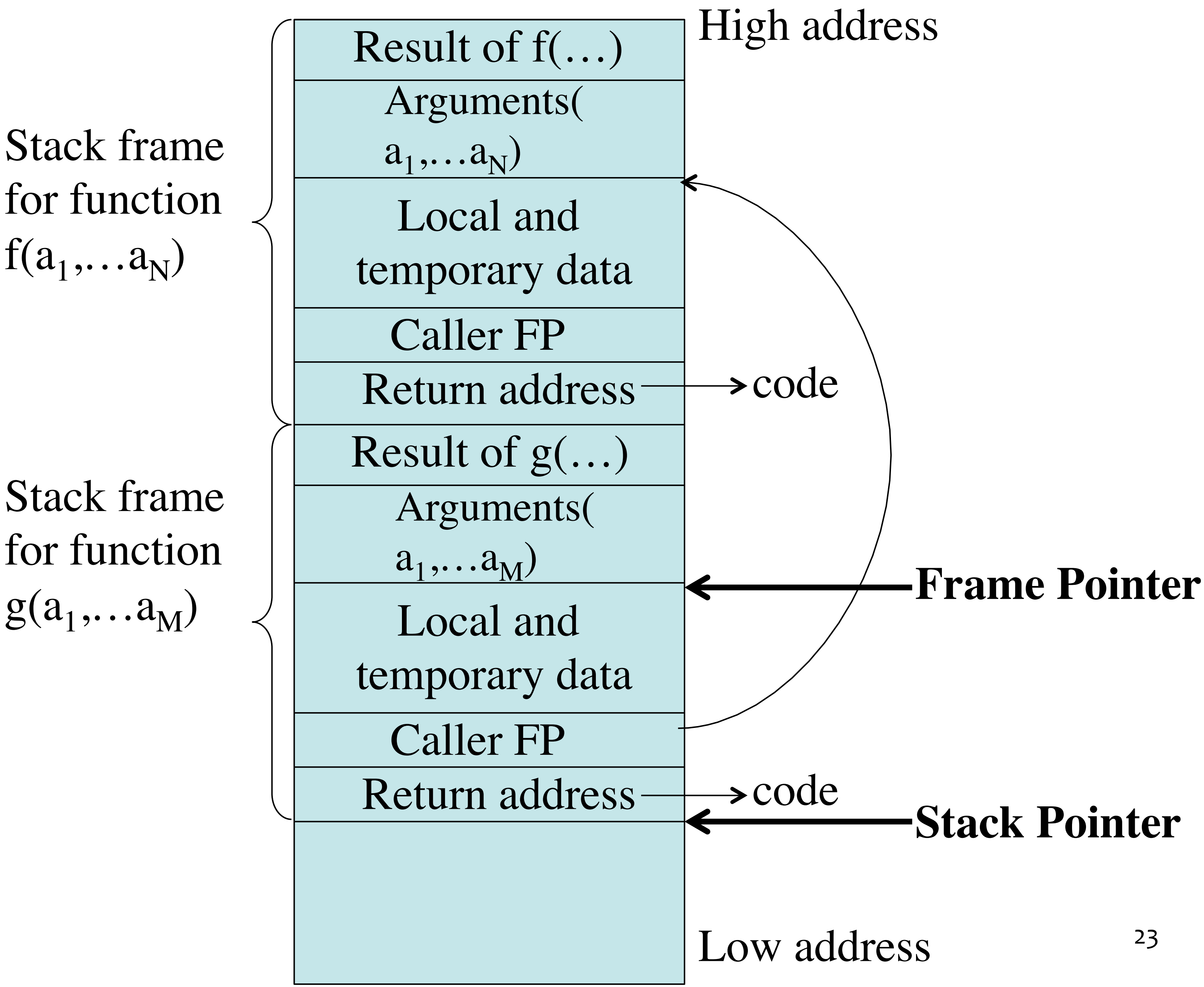
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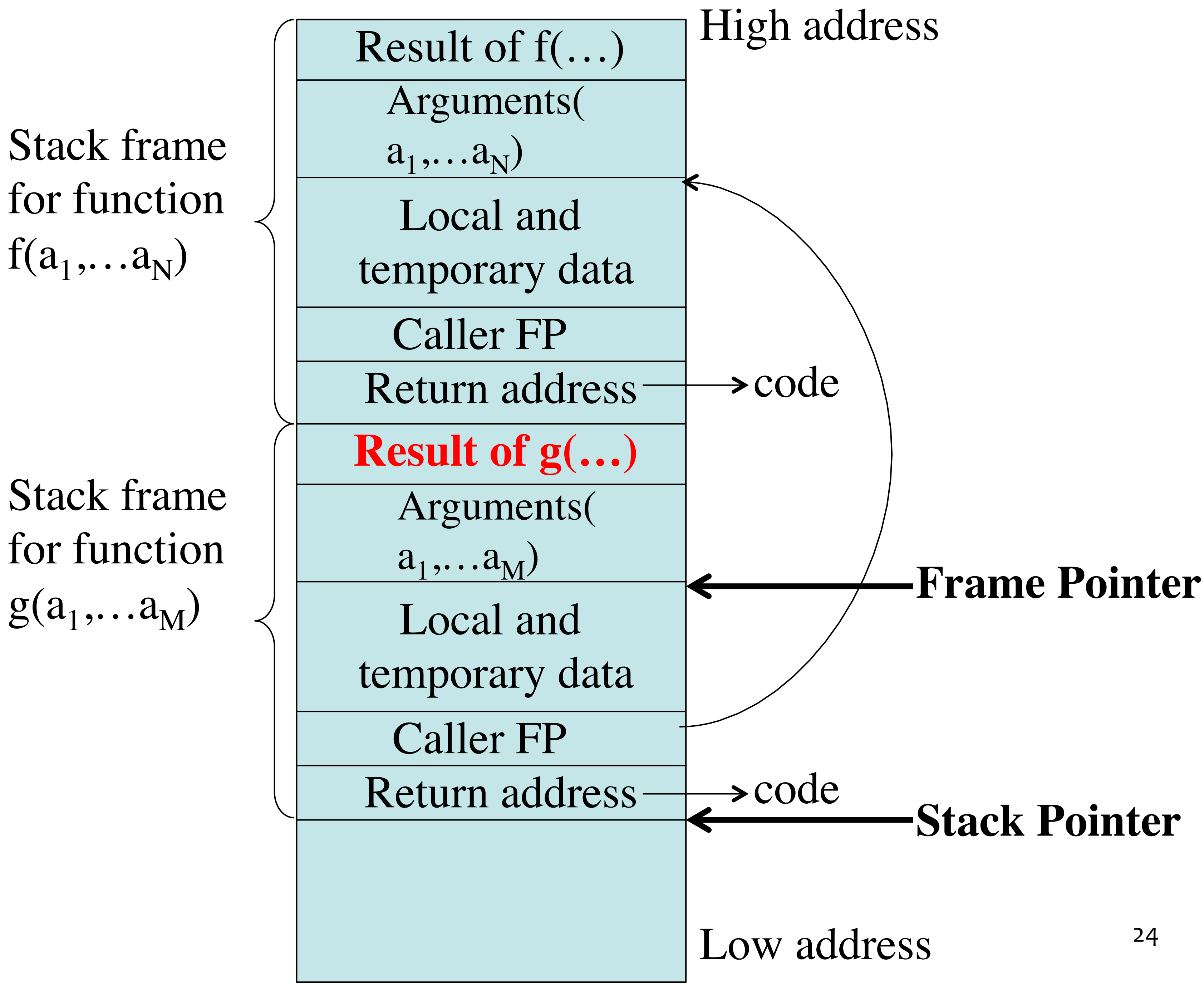
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Stack frame for function f(a1,…aN)
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Return address
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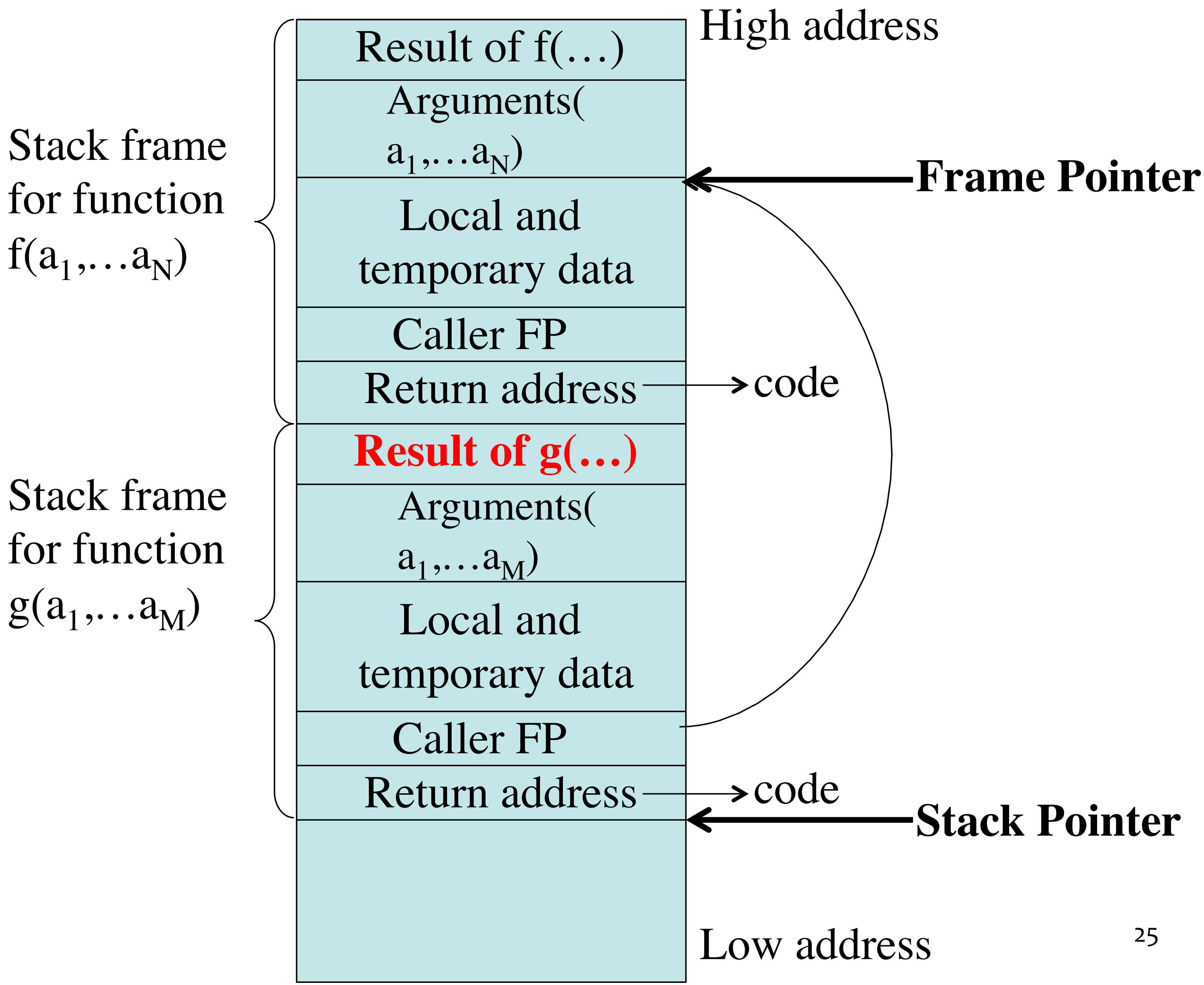
Result of g(…)
Arguments(a1,…aM)
Frame Pointer
Local and temporary data
Caller FP
Return address
code
Stack Pointer
Low address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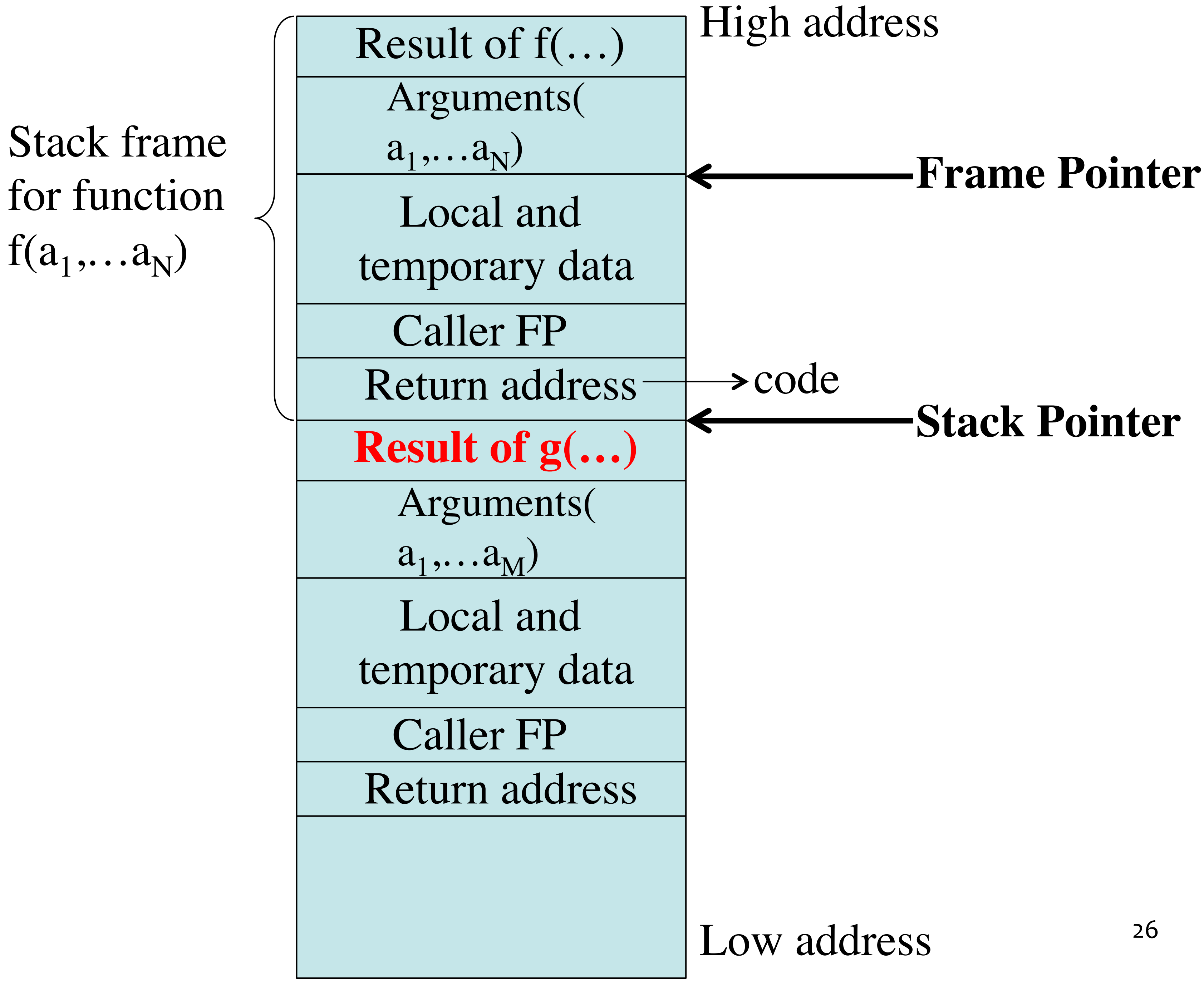
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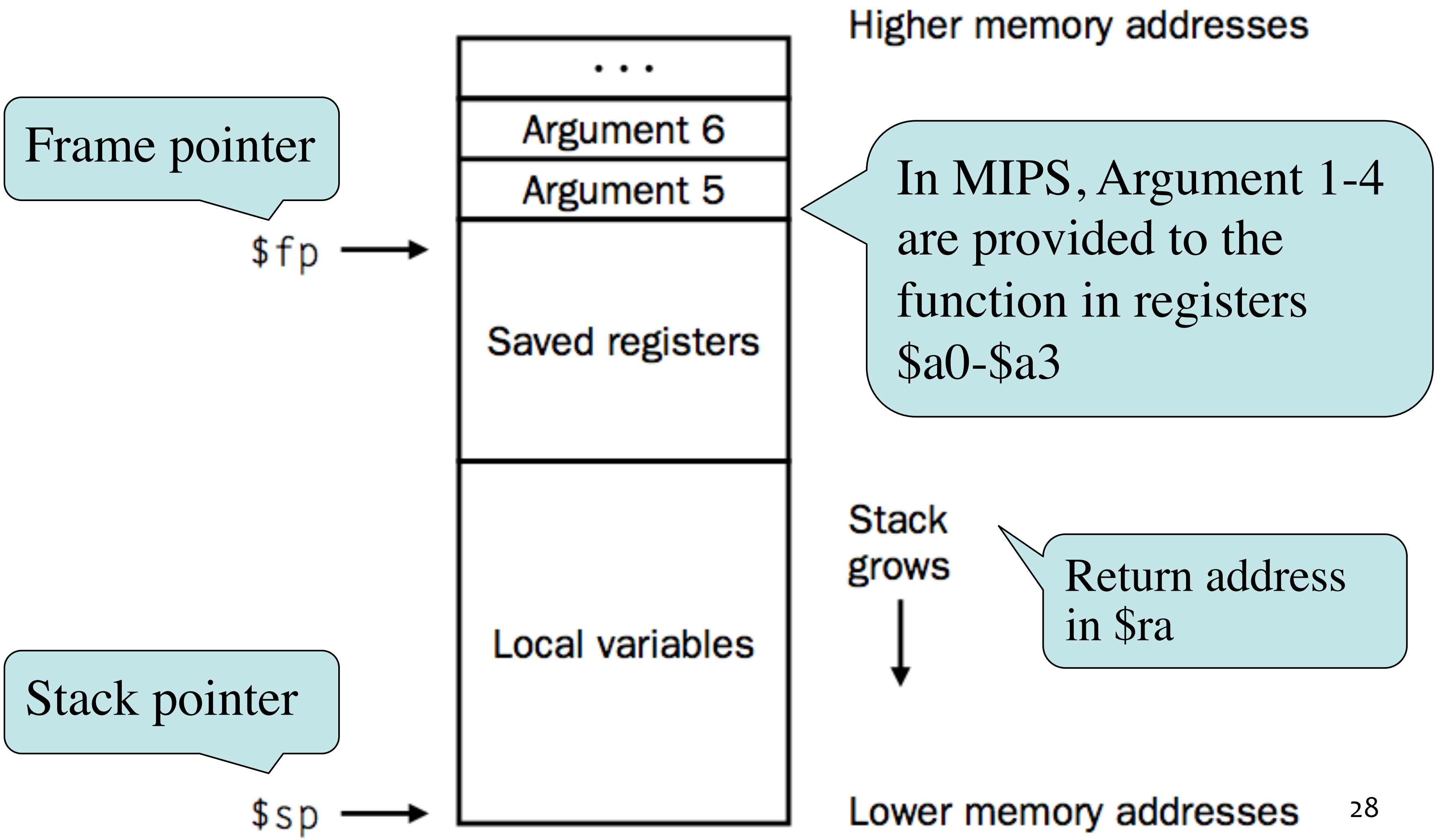
Activation Record Organization

- There is nothing magic about this organization
  - Can rearrange order of frame elements
  - Can divide caller/callee responsibilities differently
  - An organization is better if it improves execution speed or simplifies code generation
- Real compilers hold as much of the frame as possible in registers
  - Especially the method result and arguments

Stack frame

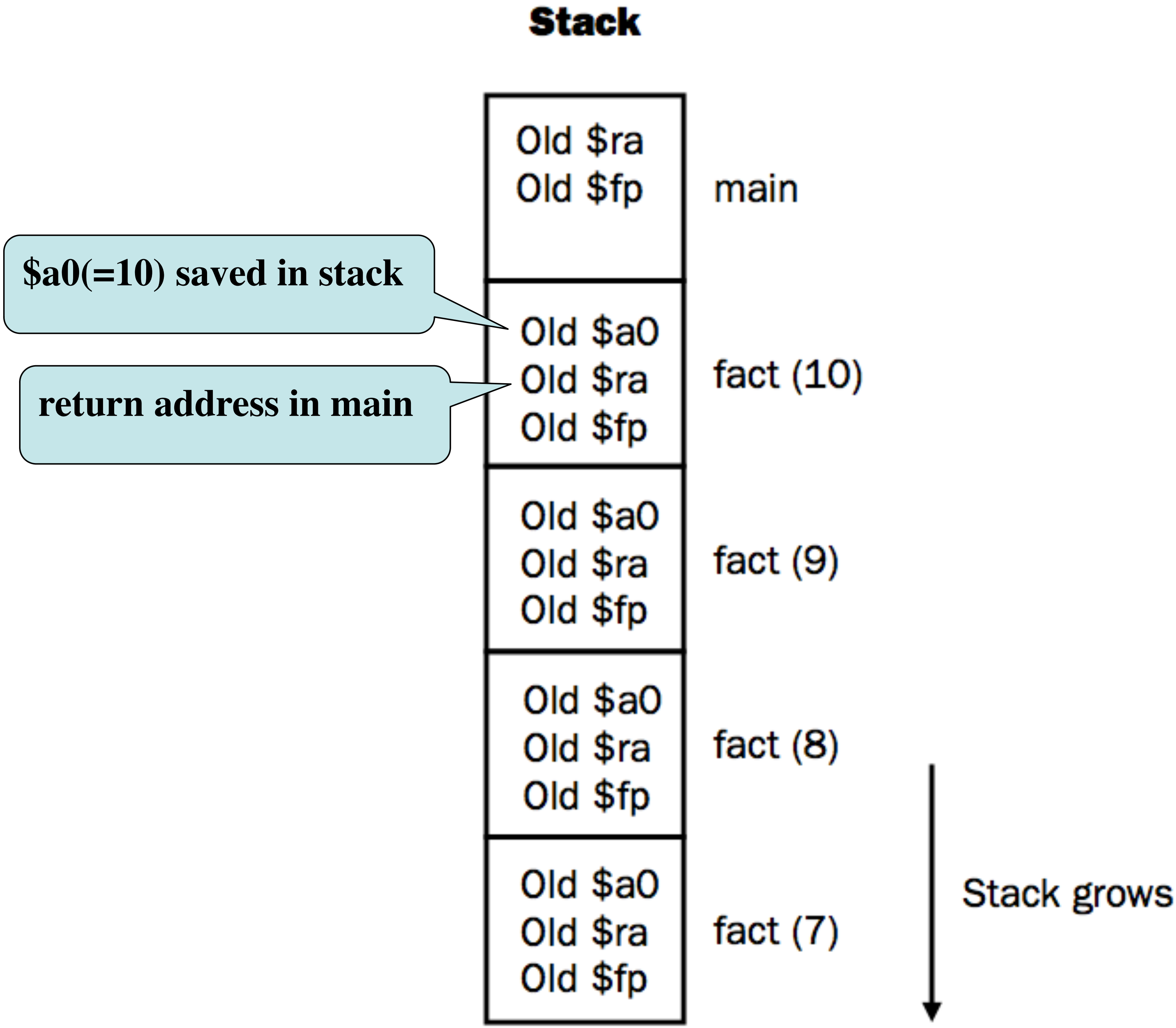


Higher memory addresses
...
Argument 6
Argument 5
Frame pointer
$fp
Saved registers
Local variables
Stack pointer
$sp
Stack grows
Lower memory addresses
In MIPS, Argument 1-4 are provided to the function in registers $a0-$a3
Return address in $ra

```
#include <stdio.h>

main ()
{
    int n = 10;
    printf("The factorial of 10 is %d\n", fact(n));
}

int fact (int n)
{
    if (n < 1)
        return(1);
    else
        return(n * fact(n - 1));
}
```

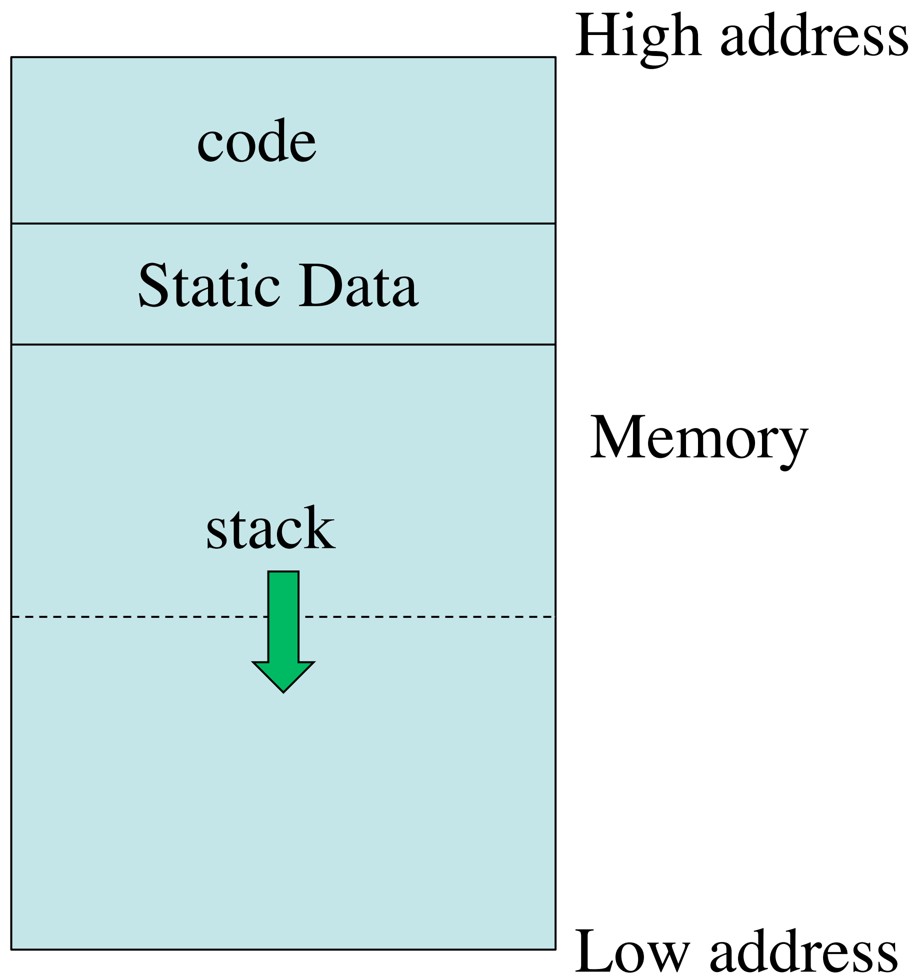


Stack
Old $ra
Old $fp
main
$a0(=10) saved in stack
return address in main
Old $a0
Old $ra
Old $fp
fact (10)
Old $a0
Old $ra
Old $fp
fact (9)
Old $a0
Old $ra
Old $fp
fact (8)
Old $a0
Old $ra
Old $fp
fact (7)
Stack grows

Global Variables

- All references to a global variable point to the same object
  - Cannot store a global in an activation record
- Globals are assigned a fixed address once
  - Variables with fixed address are "statically allocated"
- Depending on the language, there may be other statically allocated values

Memory Organization



Heap Allocation

- Any value that outlives the procedure that creates it cannot be kept in AR

  ```
  int* foo() {int * bar = new int[size]; return bar;}
  ```

  The bat value must survive de-allocation of foo’s AR

- Languages with dynamically allocated data use a heap to store dynamic data

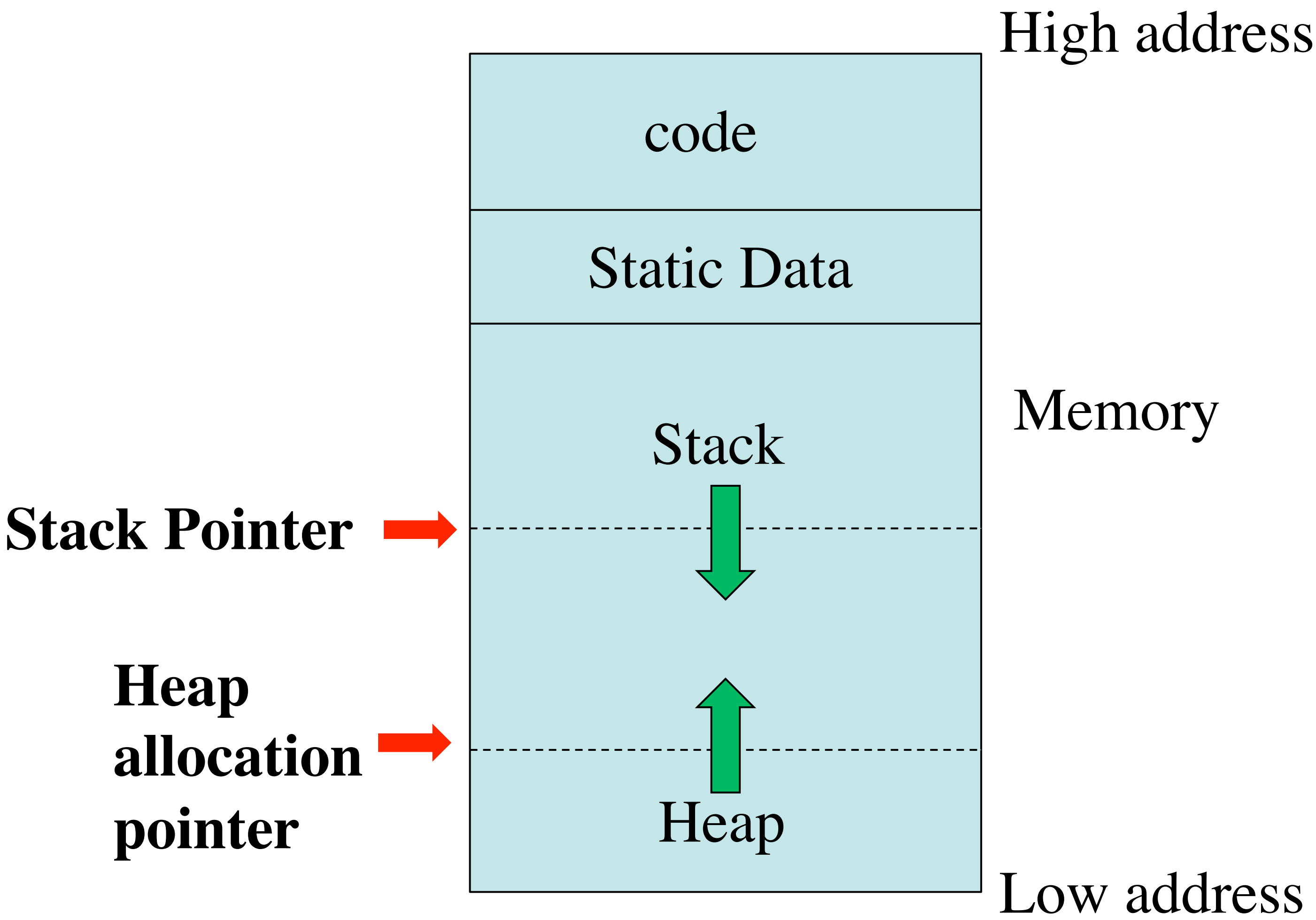
Memory organization

- The code area contains object code
  - For many languages, fixed size and read only
- The static area contain data (not code) with fixed addresses (e.g., global data)
  - Fixed size, may be readable or writable
- The stack contains and AR for each currently active procedure
  - Each AR usually fixed size, contains locals
- Heap contains all other data
  - In C, heap is managed by *malloc* and *free*

Heap and Stack Management

- Both the heap and stack grow
- Must take care that they do not grow into each other
- Solution: start heap and stack at opposite ends of memory and let them grow towards each other

Memory Organization



Alignment

- Most modern machines are 32 or 64 bit
  - 8 bits in a byte
  - 4 or 8 bytes in a word
  - Machines are either byte or word addressable
- Data is word aligned if it begins at a word boundary
- Most machines have some alignment restrictions
  - Or performance penalties for poor alignment

Padding

- Example: A string

  “Hello”

  Takes 6 characters (including a terminating \0)

H	e	l	l	o	\0		

- To word align next word, add 2 “padding” characters
- The padding is not part of the string, it’s juts unused memory

Padding

- Compilers may insert unused bytes called "padding bytes" after structure members to ensure that each member is appropriately aligned.

```
struct widget {
    char m1;
    int m2;
    char m3;
};
```

On a word aligned machine: add 3 bytes of padding after m1 and m3

Summary

- Run-time support for functions
- Dealing with (potentially infinite) recursion
- Activation records for each function invocation
- Storage allocation for activation records in recursive function calls
- Stack allocation is easiest to implement while retaining recursion
- Functional PLs use heap allocation

Extra Slides

Storage Allocation for Functions

- Stack Allocation √
  - Storage for recursive functions is organized as a stack: last-in first-out (LIFO) order
  - Activation records are associated with each function activation
  - Activation records are pushed onto the stack when a call is made to the function
  - Size of activation records can be fixed or variable

Storage Allocation for Functions

- Stack Allocation √
  - Sometimes a minimum size is required
  - Variable length data is handled using pointers
  - Locals are deleted after activation ends
  - Caller locals are reinstated and execution continues
  - C, Pascal and most modern programming languages

Storage Allocation for Functions

- Heap Allocation
  - In some special cases stack allocation is not possible
  - If local variables must be retained after the activation ends
  - If called activation outlives the caller
  - Anything that violates the last-in first-out nature of stack allocation e.g. closures in Lisp and other functional PLs

Storage Allocation for Functions

- Function Composition: (f•g)(x) = f(g(x))

```
class Compose {
        fun sq (int x) { return (x * x); }
        fun f (fun m) { return (m•h); }
        fun h () { return sq; }
        fun g (fun z) { return (sq•z); }
        int main() {
                fun v = g•h;
                print_int((v())(3));
        }
}
```

Storage Allocation for Functions

- Function Composition: (f•g)(x) = f(g(x))

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    fun f (fun m) { return (m•h); }
    fun h () { return sq; }
    fun g (fun z) { return (sq•z); }
    int main() {
        fun v = g•h;
        callout("print_int", (v())(3));
    }
}
```

v = g•h

v() = (g•h)()

v() = g(h())

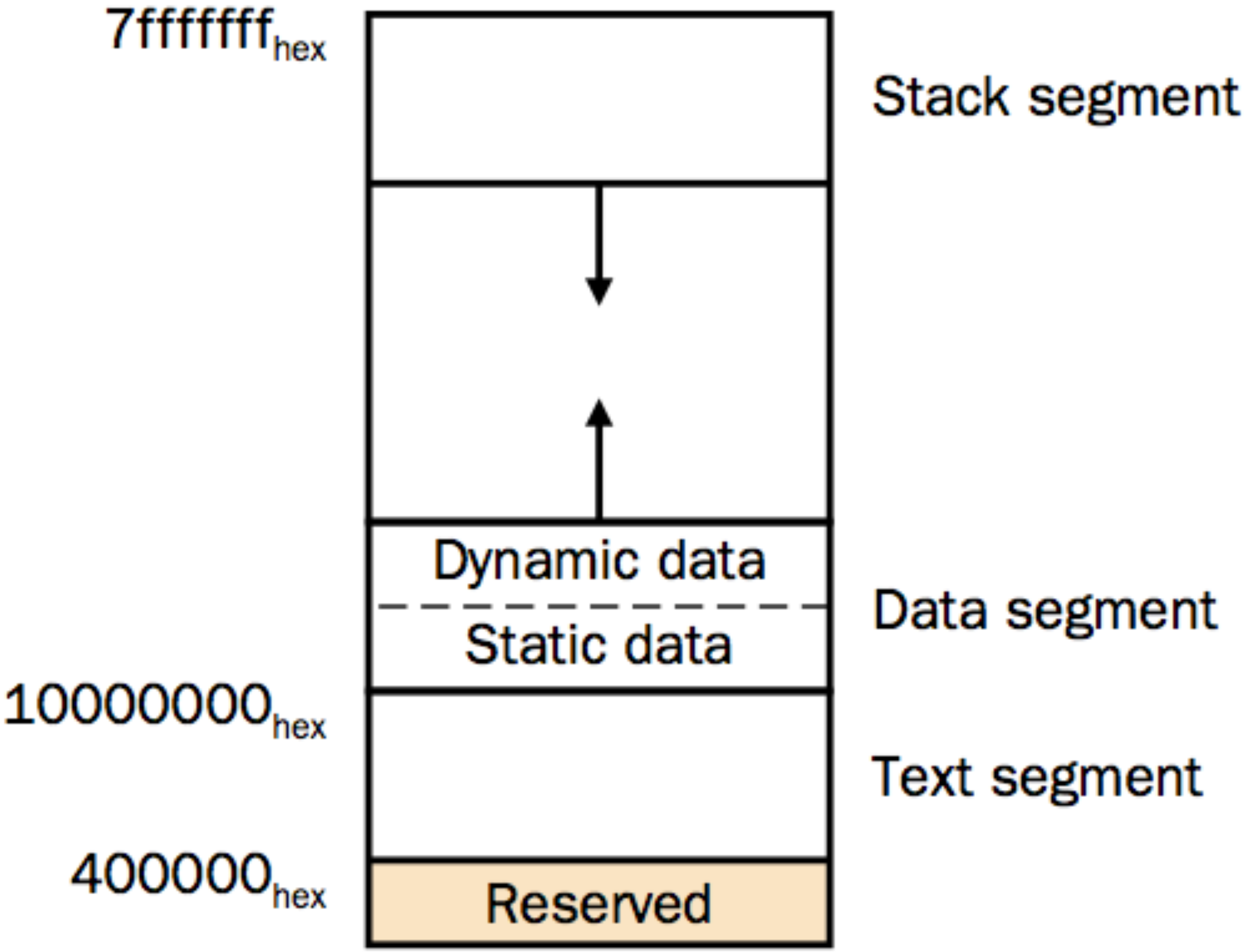
v() = g(sq)

v() = (sq•sq)

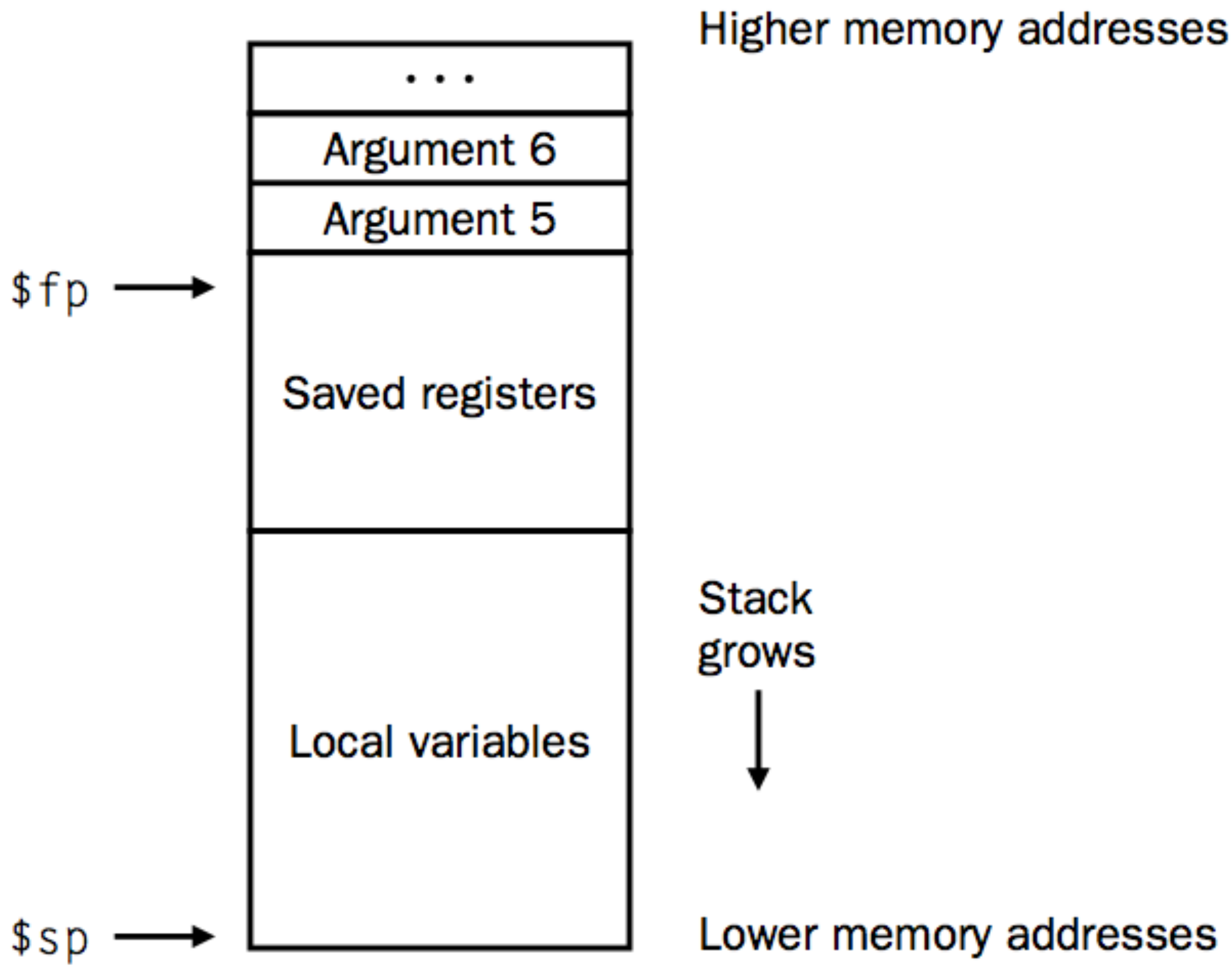
v()(3) = (sq•sq)(3)

v()(3) = (sq(sq(3))

Run-time Memory



Stack frame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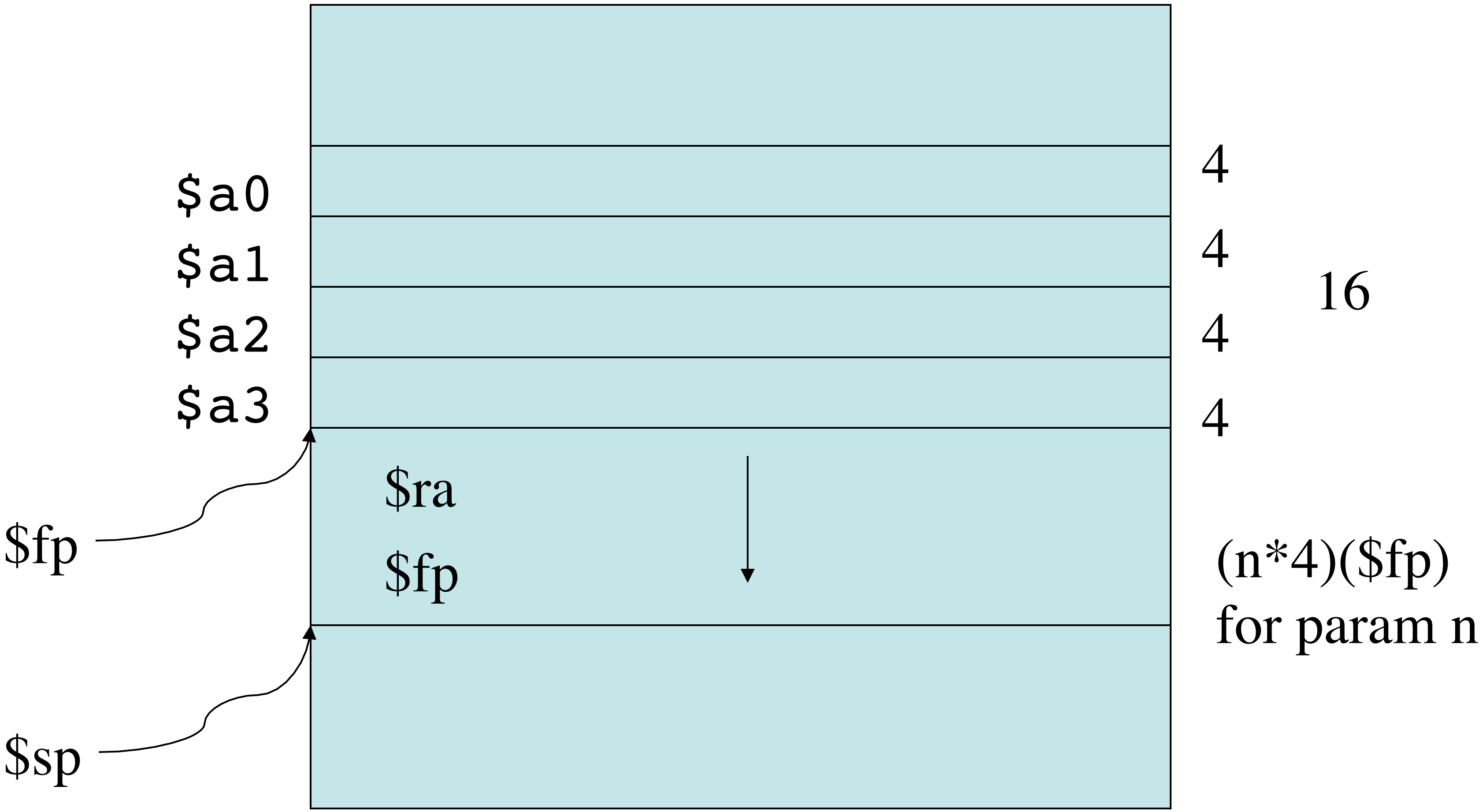
Example: MIPS stack frame



Parameter Passing Conventions

- Differences based on:
  - The parameter represents an r-value (the rhs of an expr)
  - An l-value
  - Or the text of the parameter itself
- Call by Value
  - Each parameter is evaluated
  - Pass the r-value to the function
  - No side-effect on the parameter

Parameter Passing Conventions

- Call by Reference
  - Also called call by address/location
  - If the parameter is a name or expr that is an l-value then pass the l-value
  - Else create a new temporary l-value and pass that
  - Typical example: passing array elements a[i]

Parameter Passing Conventions

- Copy Restore Linkage
  - Pass only r-values to the called function (but keep the l-value around for those parameters that have it)
  - When control returns back, take the r-values and copy it into the l-values for the parameters that have it
  - Fortran
- Call by Name
  - Function is treated like a macro (a #define) or in-line expansion
  - The parameters are literally re-written as passed arguments (keep caller variables distinct by renaming)

Parameter Passing Conventions

- Lazy evaluation
  - In some languages, call-by-name is accomplished by sending a function (also called a thunk) instead of an r-value
  - When the r-value is needed the function is called with zero arguments to produce the r-value
  - This avoids the time-consuming evaluation of r-values which may or may not be used by the called function (especially when you consider short-circuit evaluation)
  - Used in lazy functional languages

Parameter Passing Conventions

- Call-by-need
  - Similar to lazy evaluation, but more efficient
  - To avoid executing similar r-values multiple times, some languages used a memo slot to avoid repeated function evaluations
  - A function parameter is only evaluated when used inside the called function
  - When used multiple times there is no overhead due to the memo table
  - Haskell